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PREFACE

On behalf of the Scientific and Organizational Committee, it is my honor and great pleasure to present the Proceedings of the 4th EUROSА International Conference, held on 13-16 May 2026 in Vrnjačka Banja, Serbia.

The papers contained in this Proceedings represent current scientific and professional informations in the field of Engineering and Occupational Safety Management, Environmental Engineering and Management, Fire Protection Engineering and Management, Engineering and Management of Disaster and Emergency Protection, and Good use of practice in protection and represent a mix of scientific research and professional opinion, shared with us by participants from academia and industry professionals.

We sincerely thank all the conference participants for their contribution, ensuring the success of the conference. Special thanks to all the participants of the round tables and panel discussions, keynote speakers, chairmen of the sessions and of course the reviewers for their invaluable contribution.

Last but not least, I would like to express my sincere gratitude to all members of the Scientific and Organizing Committee, whose efforts and work led to the successful realization of the EUROSА 2026 conference.

Vrnjačka Banja, May 2026

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**GLOBAL PERSPECTIVES ON ENVIRONMENTAL MANAGEMENT SYSTEMS:
EVOLUTION AND PRACTICAL IMPLICATIONS OF ISO 14001:2026**

Perović M 6

AI FOR HEALTH RISK ASSESSMENT IN OCCUPATIONAL SAFETY SYSTEMS

Šunjević M., Šunjević M., Brborić M., Dmitrašinović S., Dubljević S., Kolaković Oliveira
Barreiros S..... 15

**CONSTRUCTION-RELATED PM10 EMISSIONS AND HUMAN HEALTH RISK
ASSESSMENT IN A RAPIDLY URBANIZING AREA OF NOVI SAD**

Šunjević M., Brborić M., Dmitrašinović S., Nakomčić-Smaragdakis B., Obrovski B, Dubljević S.,
Trajkovska N. 24

**ANALYSIS OF OCCUPATIONAL INJURIES IN CONSTRUCTION IN SERBIA FOR
IMPROVING RISK ASSESSMENT AND HSE MANAGEMENT**

Živković Miloš, Marija Ćuruvija, Ilja Stanišević 31

**ANALYSIS OF THE INTERDEPENDENCE OF REGULATORY COMPLIANCE AND
SAFETY CULTURE AS KEY FACTORS IN THE PREVENTION OF
OCCUPATIONAL INJURIES**

Aleksandra Ilić Petković 38

DESIGNING ACOUSTIC COMFORT IN THE WORKING AND LIVING SPACE

Cvetković D., Cvetković M., Dimitrov LJ. 45

**ASSESSING ‘REAL WORLD’ RISK: OVERVIEW OF CUMULATIVE RISK
ASSESSMENT**

Tuğçe Yeşil Ekici, Milena Stošić..... 56

**ASSESSMENT OF PROFESSIONAL RISK FOR FIREFIGHTERS DURING
ELECTRIC VEHICLE FIRE EXTINGUISHING**

Javor D., Krstić D., Zigar D., Javor V., Krstić M., Petrović N..... 64

**CALCULATION AND ANALYSIS OF ELECTROMAGNETIC RADIATION FROM
FIFTH-GENERATION (5G) MOBILE SYSTEMS**

Krstić M., Krstić D., Zigar D., Raičević N., Kostić M., Javor D., Barši A., Raičević S⁵ 73

**COMPARATIVE ANALYSIS OF CRANE INSPECTION REGULATIONS IN THE
EUROPEAN CONSTRUCTION INDUSTRY**

Kužet Ž., Mučenski V., Bošković G., Topalić J., Ilić Mićunović M..... 83

THE NEW REGULATION ON MACHINERY AND THE READINESS OF THE BZNR SYSTEM TO IMPROVE BUSINESS AND COMPETITIVENESS

Cvetković M., Mijailović I., Dimitro vLJ., Cvetković D. 91

DESIGNING GREEN ENGINEERING LEARNING MATERIALS FOR SUSTAINABLE AND DIGITAL TRANSFORMATION

Novaković Bežanović M., Petrović M., Ćirić Lalić D., Bilić I. 102

DETERMINATION OF CRITICAL CONTROL POINTS FROM A FIRE PROTECTION PERSPECTIVE IN SURFACE MINING AND COPPER PRODUCTION

Gicić R., Vasilev A., Trajčev I., Ristić D., Stojković A., Krstić I. 109

DIGITAL TWINS AS A MODERN SOLUTION FOR IMPROVING OCCUPATIONAL SAFETY AND HEALTH

Tankosić M., Bošković G., Zoraja B., Kužet Ž. 120

DIGITALIZATION OF OCCUPATIONAL SAFETY AND HEALTH ELECTRONIC TRACKING AND COMPLIANCE SOLUTION

Živković Miloš, Marija Ćuruvija, Ilja Stanišević 126

BIOMETHANE IN SERBIA: ADVANCING THE CIRCULAR BIOECONOMY AND ENERGY SECURITY

Djatkov Dj., Viskovic M., Nesterovic A..... 134

ECOLOGICAL risk assessment of pesticide use regarding soil contamination

Stojanović D., Đorđević A., Golubović T., Stojković A., Krstić I. 143

EXPOSURE TO ORGANIC SOLVENTS IN THE WORKPLACE

Adamović D., Milotić M. 150

SAFETY AND ETHICAL CHALLENGES OF ARTIFICIAL INTELLIGENCE APPLICATION IN WASTE MANAGEMENT

Istrat D., Lukač J., Kokanović A., Ćulibrk J., Petrović M..... 158

SCENARIO-BASED ASSESSMENT OF ALTERNATIVE FUELS FOR TRANSPORT DECARBONIZATION IN SERBIA

Nesterovic A., Djatkov Dj., Viskovic M..... 167

REGULATORY CHANGES AND SUSTAINABILITY IMPLICATIONS OF THE NEW WASTE MANAGEMENT LAW IN SERBIA

Perović M., Todorović M., Mitrović T. 174

**OCCUPATIONAL HEALTH AND SAFETY EDUCATION FOR EMPLOYABILITY
AND SUSTAINABLE DEVELOPMENT IN SUB-SAHARAN AFRICA**

Petrović M., Novaković Bežanović M., Ćirić Lalić D., Zoraja B., Birungi G., Kyarimpa C. 181

**PROJECT OVERVIEW - AI-ASSISTED MONITORING AND MANAGEMENT OF
INVASIVE PLANT SPECIES IN CROSS-BORDER REGION**

Radić J., Brkić M., Mihajlović I., Obrovski B., Keser T., Roguž M., Vasić I., Nikolić A.,
Živković M.^{2,6} 190

**RISK ASSESSMENT REGARDING TO WHOLE BODY VIBRATIONS OF DUMPER
TRUCK OPERATORS IN A MINING COMPANY**

Šikman D-R., Golubović-Bugarski V., Vranješ B. 196

**SPECIAL WASTE AND OCCUPATIONAL SAFETY IN THE CIRCULAR
ECONOMY: SERBIA CASE STUDY**

Čugalj J., Mihajlović V., Baloš D. 205

**HAZARDS AND HARMFUL FACTORS AT THE WORKPLACE AND IN THE
WORKING ENVIRONMENT**

Ilić M., Petrović M., Savić L. 213

**THE IMPACT OF ERGONOMICS ON THE HEALTH OF EMPLOYEES IN OFFICE
WORK**

Štulić A., Ognjenović V. 220

**ADVANCED TECHNOLOGIES IN FIRE PROTECTION SYSTEMS: PREVENTIVE
AND EMERGENCY RESPONSE MEASURES**

Knežević M., Stojkovski J. 228

**APPLICATION OF UAV TECHNOLOGY IN PESTICIDE SPRAYING:
IMPLICATIONS FOR OCCUPATIONAL HEALTH AND SAFETY**

Rakić B., Đaković J. 237

SUSTAINABLE REUSE OF THERMAL WASTEWATER IN AGRICULTURE

Mihajlović I., Kovačević S., Antović J., Hgeig A., Milovanović D. 247

**THE IMPACT OF DIGITALIZATION ON OCCUPATIONAL SAFETY AND HEALTH
- EMERGING RISKS AND CHALLENGES**

Krstić I., Stojković A., Đorđević A., Stojanović D., Stanisavljević M., ... 254

APPLICATION OF ENVIRONMENTAL PROTECTION SYSTEM ON THE BIOGAS SECTOR IN SERBIA

Viskovic M., Djatkov Dj., Nesterovic A. 263

THE FUTURE OF WASTE MANAGEMENT: STRATEGIC DIRECTIONS AND SERBIA'S GREEN TRANSITION

Kokanović A., Muhadinović M., Kovačević S., Xiaoming W., Stanisavljević N. 274

PLANNING AND IMPLEMENTING MSW SOURCE SEPARATION SYSTEMS: INSIGHTS AND CHALLENGES FROM SERBIA

Batinić B., Stanisavljević N., Berežni I., Marinković T., Vaccari M. 283

APPLICATION OF IoT-BASED ENVIRONMENTAL MONITORING AND HYBRID ANN MODELING FOR AIR QUALITY AND OCCUPATIONAL SAFETY AT CONSTRUCTION SITES

Mrazovac Kurilić S., Nikolić Bujanović Lj., Predrag I., Farooqi Z.U.R. 290

OPERATIONAL FAILURE AND MICROBIOLOGICAL RISKS IN DECENTRALIZED DRINKING WATER SYSTEMS: EVIDENCE FROM TRIPOLI, LIBYA

Aborus N., Hgeig A., Mihajlović I., Abugassa E., Mohammed O. 297

WORKPLACE NOISE ASSESSMENT IN A LABORATORY: A CASE STUDY FROM NOVI SAD, SERBIA

Mihajlović I., Novaković Bežanović M., Birungi G., Kyarimpa C. 305

PREVALENCE OF METABOLIC SYNDROME AMONG BANK EMPLOYEES AND THE IMPORTANCE OF WORKPLACE HEALTH PROMOTION

Perazić O. 313

ANALYSIS OF THE RISK OF ELECTRIC SHOCK IN PUBLIC AREAS DUE TO FAULTY ELECTRICAL INSTALLATIONS – EXAMPLES FROM PRACTICE

Vujić J., Ilić B., Rastovac D. 320

CHRONIC PAIN AND ERGONOMIC INJURIES IN THE WORKPLACE

Tatjana Mladenović, Srđan Novokmet 327

CHRONIC DISEASES AS A CAUSE OF WORK DISABILITY – NEW THERAPEUTIC POSSIBILITIES: A CASE REPORT

Tatjana Mladenović 333

**BIOPHILIC DESIGN STRATEGIES AND USER PSYCHOLOGICAL RESPONSE IN
CONTEMPORARY HOSPITALITY INTERIORS**

Katić T., Čavić A. 339

**HIGH-CAFFEINE STIMULANT BEVERAGES IN THE OCCUPATIONAL
SETTING: ACUTE EFFECTS ON VIGILANCE AND IMPLICATIONS FOR
RECOVERY AND OCCUPATIONAL RISK**

Milidrag Ardea, Mladenović Tatjana..... 344

**SMOKING AS A MODIFIABLE RISK FACTOR IN THE PREVENTION OF
CHRONIC NON-COMMUNICABLE DISEASES - HARM REDUCTION IN FOCUS**

Dr. Aleksandra Jesic 350

GLOBAL PERSPECTIVES ON ENVIRONMENTAL MANAGEMENT SYSTEMS: EVOLUTION AND PRACTICAL IMPLICATIONS OF ISO 14001:2026

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Abstract: Environmental protection is a constantly evolving process, influenced by technological progress, the introduction of new materials and substances, increasing resource consumption, and the generation of more complex waste streams, often with uncertain long-term behavior and limited recycling options. These developments create new challenges that require organizations to continuously adapt and integrate environmental considerations into their decision-making. ISO 14001 has evolved from a focus on regulatory compliance and pollution control to a more structured, risk-based approach, where organizations are expected not only to meet requirements, but to show measurable results. Developed through the participation of 176 countries, the standard represents a shared global approach to environmental management. This paper analyses the key changes introduced in the latest revision of ISO 14001, with a focus on leadership, risk-based thinking, and system integration in practice. It also examines how these changes influence environmental protection and occupational health and safety through more structured risk management. Particular attention is given to the strengthening of lifecycle thinking and supply chain control, the clearer distinction between normal, abnormal, and emergency conditions, and the enhancement of performance evaluation through objective-based auditing and structured management review. The findings highlight the convergence between environmental management and occupational health and safety, especially in the context of risk assessment and emergency preparedness. The paper contributes by interpreting ISO 14001 as both a reflection of global environmental priorities and a practical framework for integrated, evidence-based management.

Keywords: *ISO 14001:2026; environmental management systems; risk-based approach; lifecycle thinking.*

INTRODUCTION

Environmental management is no longer limited to regulatory compliance but can be understood as an integral part of everyday organizational decision-making, with studies showing that environmental management systems influence operational practices and performance (Sroufe, 2003). This transformation is caused and induced by increasing environmental risks, growing societal expectations, and the need to address challenges such as climate change, resource scarcity, and ecosystem degradation. ISO 14001 – Environmental Management Systems – Requirements with Guidance for Use can be considered the most widely applied international standard for environmental management. Besides being used as a technical standard, it is also the reflection of global environmental awareness and a tool for

translating that awareness into structured and measurable organizational practices. The transition to ISO 14001:2026, besides formal requirements, also represents a practical organizational challenge that requires timely planning, resource allocation, and coordination across departments and with certification bodies (ISO 14001, 2015). ISO 14001 has developed over time alongside changes in how environmental management is applied in practice. Early versions were mainly focused on regulatory compliance and pollution control, while later revisions introduced more structured approaches to risk identification, lifecycle thinking, and system integration (ISO, 2004; ISO, 2015; ISO, 2026). This development has also made the link between environmental protection and occupational health and safety more visible. Environmental risks, such as pollution events, resource failures, or emergency situations, often create direct risks for people. In practice, the same issue can affect both the environment and worker safety, which means these risks need to be managed together. For this reason, modern management systems increasingly use integrated, risk-based approaches that address both environmental and occupational aspects, forming what is commonly referred to as integrated management systems (Nunhes et al., 2017).

The ISO 14001 standard was developed by the International Organization for Standardization (ISO), specifically within Technical Committee ISO/TC 207, with the aim of establishing a globally applicable framework for environmental management systems (EMS). The first version, published in 1996, focused primarily on environmental compliance and pollution prevention (ISO, 1996). Over time, the standard evolved through revisions in 2004 and 2015, gradually introducing clearer requirements, improved alignment with other management system standards, and the concept of risk-based thinking. The 2015 revision marked a significant step through the introduction of the High-Level Structure (Annex SL), which aligned ISO 14001 with other management system standards, such as ISO 9001 - Quality Management Systems - Requirements and ISO 45001 - Occupational Health and Safety Management Systems - Requirements with Guidance for Use.

This development clearly shows which aspects the global community now considers essential, defining the areas where organizations claiming effective environmental management, and holding certification, must demonstrate concrete performance and accountability. In this sense, the standard serves as a formalized representation of global environmental thinking, translating complex sustainability challenges into structured and auditable organizational requirements. ISO 14001 can be observed as a framework through which global environmental priorities are translated into practical and verifiable organizational requirements.

Within this context, this paper aims to analyse the key developments introduced in the latest revision of ISO 14001 and to interpret them from both a global and practical perspective. Particular attention is given to the integration of environmental management with occupational health and safety, demonstrating how the standard supports a unified, risk-based approach to managing environmental and human-related risks in organizational practice.

MATERIALS AND METHODS

This study is based on a qualitative and comparative analysis of the ISO 14001 standard, focusing on the evolution of its structure and requirements through different revisions (2015 and 2026). A clause-by-clause interpretative approach was applied to identify key changes, with particular attention to risk-based thinking, lifecycle perspective, and system integration. The analysis considers not only formal differences in requirements, but also their practical implications for organizational implementation and their connection with occupational health and safety management systems.

RESULTS

The ISO 14001 standard is based on a structured framework consisting of ten clauses, organized in accordance with the Plan–Do–Check–Act (PDCA) cycle (Figure 1). Clauses 1 to 3 define the general elements of the standard, including its scope (Clause 1), normative references (Clause 2), and terms and definitions (Clause 3), providing the foundation for its interpretation and application. The core requirements are defined within Clauses 4 to 10, which correspond to the PDCA cycle. Clauses 4 (context of the organization), 5 (leadership), and 6 (planning) represent the “Plan” phase; Clause 7 (support) and Clause 8 (operation) correspond to the “Do” phase; Clause 9 (performance evaluation) represents the “Check” phase; and Clause 10 (improvement) corresponds to the “Act” phase (Figure 1).

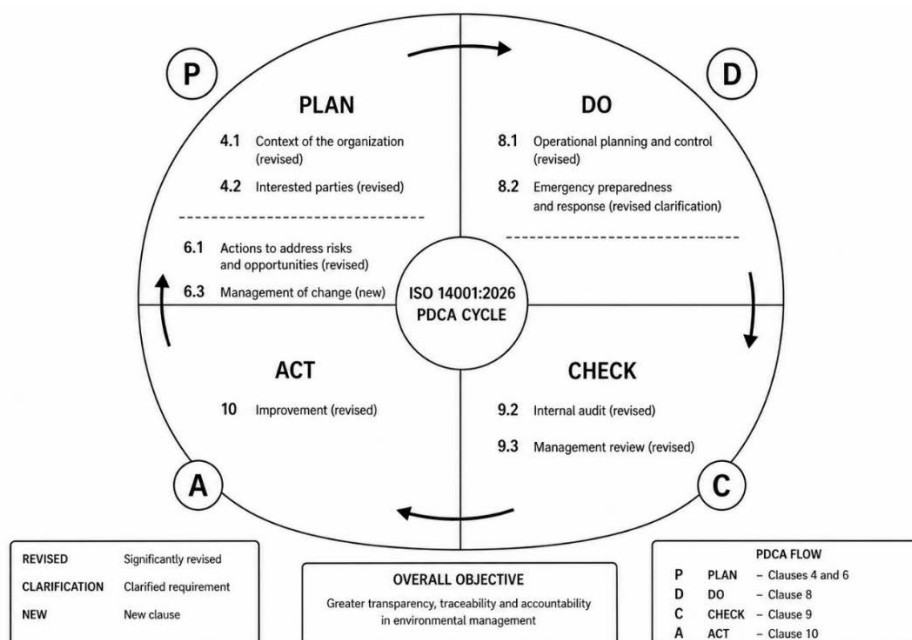


Figure 1. PDCA cycle of ISO 14001:2026 with key revised and new requirements across clauses.

In practice, organizational context (Clause 4) refers to understanding the conditions in which an organization operates and how they affect its decisions. In the revised ISO 14001, this now

clearly includes factors such as climate change, pollution, biodiversity, and resource availability. Organizations also need to identify relevant stakeholders and understand their expectations, since only defined expectations can become compliance obligations. The standard also places more emphasis on communication, moving from simple stakeholder identification toward more active and two-way engagement.

Leadership is increasingly recognized as a central element of environmental management, emphasizing that environmental issues should not be treated solely as a technical responsibility. Instead, top management is expected to integrate environmental considerations into everyday organizational decision-making (Clause 5). Compared to earlier versions, the focus is less on formal commitment and more on actual responsibility and results. In practice, this means ensuring that the system works, providing resources, and encouraging awareness across the organization. Even when tasks are delegated, responsibility remains with top management. Many environmental decisions, such as those related to emissions, resource use, or emergencies, also affect worker safety. For this reason, environmental and safety issues need to be managed together, rather than separately.

Planning within ISO 14001 is based on a structured approach to risk management, taking into account environmental aspects, legal obligations, and the broader organizational context (Clause 6). Although this approach was introduced in ISO 14001:2015, the 2026 revision indicates that relationship between risks, actions, and environmental objectives is more explicit and easier to follow (ISO, 2015; ISO, 2026). In practice, organizations are expected to clearly identify and document risks, explain their origin and significance, and define how they will be managed. The revised version also places stronger emphasis on the lifecycle perspective, encouraging organizations to consider environmental impacts beyond their direct operations, including suppliers, transportation, and product use, even in areas where full control may not exist. Another important addition is Clause 6.3 (Management of Change), which requires environmental impacts to be assessed before organizational or operational changes are introduced. This makes change management more systematic, transparent, and easier to verify. Many of these requirements are closely aligned with occupational health and safety management, where risks are likewise expected to be identified early and managed through a structured and preventive approach. Effective environmental management depends not only on procedures and requirements, but also on the people, resources, communication, and documented information that support the system in everyday practice (Clause 7). Although these elements were included in earlier versions of ISO 14001, the revised approach places greater emphasis on how they function in real organizational conditions. Besides providing adequate training, it is no longer considered sufficient, and organizations are expected to demonstrate that employees understand environmental risks, their responsibilities, and the influence of their activities on environmental performance.

Communication that ensures clear, consistent, reliable, and traceable information is of great importance for effective risk management in both environmental management and

occupational health and safety. Environmental management becomes most visible through everyday operational activities and the way organizations respond to unexpected situations (Clause 8). The revised approach places greater emphasis on practical implementation, including operational control, supplier involvement, and emergency preparedness. Environmental responsibility is no longer limited only to activities within the organization itself; suppliers and externally provided processes are expected to meet environmental requirements as part of procurement and operational control. The standard indicates differentiation between abnormal operating conditions and emergency situations. Routine operational procedures are used to manage abnormal conditions, while emergencies require detailed and adequate response plans, clear coordination, and preparedness measures. Preparedness for emergency situations is continuous process that encompasses primarily identification of potential scenarios, followed by preparation of response measures, testing procedures, and reviewing the effectiveness of actions taken. In addition to what has traditionally been a priority, namely the implementation of emergency drills, greater emphasis is now placed on lessons learned and experience gained in order to support continual system improvement. In both systems, environmental management and occupational health and safety management, emergency preparedness is not viewed as a one-time activity, but as an ongoing process that requires organizations to identify potential risks, test response procedures, analyse weaknesses, and improve preventive and corrective measures based on experience and documented results.

Monitoring and evaluating environmental performance is an essential part of ensuring that the environmental management system functions effectively in practice (Clause 9). This includes measurement, internal audits, and management review, which together represent the “Check” phase of the PDCA cycle. The revised approach places greater emphasis not only on collecting information, but also on demonstrating that implemented processes achieve their intended results. Internal audits are therefore expected to go beyond simple compliance checks and address broader objectives, such as evaluating system effectiveness and verifying whether corrective actions have been successfully implemented. Management review is also presented in a more structured way, with clearer focus on the information used during the review process, how the review is performed, and the decisions and outcomes that follow. Organizations are expected to base decisions on measurable data and translate them to specific actions, including system improvements, operational changes, or allocation of resources. This strengthens transparency, traceability, and accountability, making performance evaluation a more systematic and evidence-based process. Similar principles are widely applied in occupational health and safety management, where monitoring, review, and data-based decision-making are also essential for continual improvement.

Continual improvement is presented as a structured and evidence-based process that focuses not only on correcting problems when they occur, but also on preventing similar issues from happening again (Clause 10). In the revised version of ISO 14001, improvement is more

directly connected to measurable results, meaning that decisions and corrective actions are expected to rely on objective data rather than assumptions or temporary solutions. When environmental problems or nonconformities are identified, organizations are expected to determine their root causes and implement actions that effectively prevent recurrence. The effectiveness of these actions must then be verified through monitoring and documented evidence. In practice, this creates a continuous connection between monitoring activities, internal audits, corrective actions, and management decisions. Results are reviewed, problems are analysed, corrective measures are introduced, and their effectiveness is subsequently evaluated. For example, if monitoring data indicates an increase in pollutant concentration, the organization is expected to identify the underlying cause, such as equipment malfunction or process inefficiency, implement corrective measures, and confirm through additional measurements that the issue has been successfully resolved.

DISCUSSION

The revised ISO 14001 can be interpreted as introducing both gradual updates and more significant changes, including new processes and expanded responsibilities. Environmental and climate issues are no longer treated as separate elements but are integrated across the entire management system. The most significant developments are focused on strengthening risk-based thinking, expanding the lifecycle perspective, and improving the structure and traceability of key processes. Particular emphasis is placed on the integration of climate change and biodiversity into organizational context, a more structured approach to risk identification, and the formalization of change management as a distinct and auditable requirement. The revised standard extends environmental responsibility beyond the organization by placing more emphasis on supply chain control. It also makes a clearer distinction between abnormal situations and emergencies and strengthens performance evaluation through more focused auditing and a more structured approach to management review. The key changes and their practical implications are summarized in Table 1.

Table 1. Key Changes in ISO 14001:2026 and their practical implications.

Clause	Area	Key Change	Practical Implications	Illustrative Example
4.1	Context of the organization	Integration of climate change and biodiversity	Environmental conditions must be considered in decision-making	Including flood or drought risk when planning site operations
4.2	Interested parties	Stronger focus on stakeholder expectations	Expectations must be identified and, where relevant, treated as obligations	Incorporating community concerns about air quality into operational limits
6.1	Risks and opportunities	Clearer structure of risk identification	Risks must be linked to sources and documented	Linking emissions risk to specific process steps in a risk register
6.2	Lifecycle	Strengthened and	Impacts must be	Evaluating

	perspective	more explicit requirement	considered beyond direct operations	environmental impact of raw material sourcing and product disposal
6.3	Management of change	Formal requirement introduced	Environmental impacts must be assessed before implementing changes	Evaluating environmental impact before introducing new chemicals
8.1	Operational control	Expanded to supply chain	Environmental criteria must apply to suppliers	Requiring suppliers to meet environmental standards in contracts
8.1 / 8.2	Operations vs. emergency	Clear distinction introduced	Different approaches required for abnormal operations and emergency situations	Using procedures for process deviations vs. emergency response plans for spills
9.2	Internal audit	Objective-based auditing	Audits must evaluate performance, not only compliance	Conducting an audit focused on energy efficiency improvement results
9.3	Management review	Structured into inputs–process–results	Decisions must be based on data and reasoning	Using monitoring data to justify investment in pollution control equipment
10	Improvement	Root cause focus/ Evidence-based actions	Corrective actions must be based on root cause analysis and measurable evidence	Identifying cause of pollution increase and fixing process failure

The changes introduced in the revised ISO 14001:2026 show that environmental management is transitioning from a primarily compliance-based and pollution reduction approach toward a more performance-oriented and risk-aware system. This shift toward performance orientation is consistent with earlier findings that environmental management systems contribute to improvements in operational practices and environmental performance (Sroufe, 2003). Compared to earlier versions, instead of fulfilling formal requirements the revised standard emphasizes demonstrating the results. The changed expectations for environmental management, with more focus on integration and measurable results, rather than just compliance are observed. One important direction is bringing environmental and social aspects closer together, so that environmental impacts are considered alongside human health, community well-being, and workplace safety during everyday operations. This highlights the need for coordinated management of environmental and safety risks within organizations. Climate change is increasingly treated as a concrete factor influencing planning, risk assessment, and long-term decision-making, rather than a general external condition. Besides managing environmental issues, organizations are expected to clearly demonstrate the process of decision making. They have to document how performance is evaluated, and to enable traceable documented evidence. Environmental management is becoming increasingly data-

driven, with greater reliance on monitoring, analysis, and digital tools to support timely and informed decision-making.

Integration of Environmental Management and Occupational Health and Safety

Although defined by separate standards, in practice environmental management and occupational health and safety to a greater extent rely on the same principles. Environmental risks, such as pollution events, resource depletion, process deviations or operational failures, often become direct risks to people. The distinction between abnormal conditions and emergency situations reflects a similar approach in safety systems, where different types of risks require different responses. In both cases, organizations must have clear procedures, trained personnel, and effective controls. Emergency preparedness shows that these systems together rely on planning, regular testing, and continuous improvement. At the same time, the growing focus on supply chains and lifecycle thinking extends responsibility beyond the organization to suppliers and contractors. Stronger performance evaluation, through audits and management review, supports more integrated decision-making, from the aspects of environmental and safety outcomes. Thus, environmental management and occupational health and safety present closely connected parts of a single, risk-based approach, which is consistent with the concept of integrated management systems (Nunhes et al., 2017) and supported by evidence of their effectiveness in improving organizational performance (Zeng et al., 2010).

CONCLUSION

The latest revision of ISO 14001 shows a clear direction toward a more practical and integrated way of managing environmental performance. The focus is now on understanding risks, considering impacts across the full lifecycle, and using real data to guide decisions. At the same time, the link between environmental management and occupational health and safety is becoming more visible. Many environmental issues also affect human wellbeing, which means these areas are no longer treated separately. Rather than introducing completely new ideas, the 2026 revision builds on existing concepts and makes them more structured, easier to follow, and easier to verify in practice. It reflects a broader shift toward more transparent and accountable management. ISO 14001 is becoming less about formal compliance and more about helping organizations manage real environmental and safety challenges in a clear and consistent way. Future implementation of ISO 14001:2026 will depend on the ability of organizations to translate these structured requirements into measurable and integrated management practices.

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AI FOR HEALTH RISK ASSESSMENT IN OCCUPATIONAL SAFETY SYSTEMS

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Abstract: Occupational health and safety (OHS) management still relies largely on periodic inspection, static documentation and reactive intervention, which limits the ability of OHS professionals to respond to short-term exposure events. This paper proposes a four-layer framework coupling continuous workplace monitoring to artificial-intelligence-supported health-risk assessment, automated workflow and post-intervention verification, instantiated through a construction-site PM10 scenario. Three methodological issues frequently left implicit in real-time OHS monitoring are addressed explicitly: the mismatch between ambient PM10 sampling conventions and the inhalable and respirable conventions on which occupational exposure limits are defined; the requirement that measured and reference concentrations share an averaging time; and the separation of verified engineering controls from respiratory protective equipment in the risk calculation. A dynamic risk index is defined that combines shift-averaged exceedance, short-term peak exceedance, hazard severity and worker vulnerability, attenuated only by verified engineering and organisational controls. A shown example depicts a task whose 8h time-weighted average exceeds an internal action level and constitutes a high-risk condition once short-term peaks are represented. The framework is a conceptual and methodological specification rather than a validated deployed system, and is intended to support rather than replace qualified OHS professionals.

Keywords: *occupational health and safety; AI agents; exposure assessment; PM₁₀; construction sites.*

INTRODUCTION

Occupational health and safety systems protect workers from injury, occupational disease and harmful exposure, yet accidents and work-related disorders remain frequent in construction, manufacturing, mining, transport and waste management, where physical, chemical, biological and ergonomic hazards often act simultaneously (Liu et al., 2023). Conventional risk assessment relies on workplace inspection, expert observation, interviews, measurement campaigns of limited duration and retrospective incident analysis, with results recorded in static forms and isolated databases. These methods are necessary for regulatory compliance but represent workplace conditions only at the moments they are applied, whereas hazards

vary within a shift with activity, plant operation, weather, worker behaviour and exposure duration (Pinto et al., 2011).

Safety management therefore remains predominantly reactive: corrective measures follow an incident, an inspection finding or a documented exceedance. Periodic assessment is poorly suited to short-lived concentration peaks, temporary control failures and rapidly changing site conditions, and manual handling of heterogeneous datasets delays intervention further.

Digitalisation offers a partial remedy. Environmental sensors, wearables, video systems, instrumented plant and building information models can record air quality, noise, vibration, thermal conditions, worker position and task progress continuously. Acquisition alone, however, does not improve safety; measurements must be converted into interpretable risk indicators and timely action. Machine-learning methods have been applied to construction injury prediction (Tixier et al., 2016), accident forecasting (Koc et al., 2022) and hazard-informed site safety (Kim et al., 2024), and computer vision can detect missing personal protective equipment, restricted-area entry and hazardous worker-machine proximity. Reviews nevertheless report that most models are trained retrospectively on incident registers and are rarely integrated with live exposure monitoring or with the decision and documentation workflow that follows an alert (Liu et al., 2023).

Airborne particulate matter at construction sites is a suitable test case. Excavation, demolition, cutting, loading and vehicle movement generate coarse dust whose concentration changes over minutes, and where the material is silica-bearing the health consequence is severe and delayed (Chisholm, 1999; OSHA, 2016). Real-time optical PM10 monitors are now affordable enough for dense deployment, but their output is an ambient-air metric and cannot be treated as an occupational exposure measurement without explicit qualification. The paper specifies an integrated framework linking real-time acquisition, AI-supported analysis, dynamic risk classification, automated response and verification of intervention effectiveness, and instantiates it for construction-site PM10 exposure.

MATERIALS AND METHODS

Framework architecture

The architecture is shown in Figure 1. Acquisition (L1) covers fixed and personal monitors, worker-position and task records, plant and control status, meteorology and existing OHS documentation; validation (L2) applies quality control and aligns records in time and space; assessment (L3) contains the specialised agents and the risk model; and response (L4) issues alerts, routes decisions to human experts and writes the audit trail.

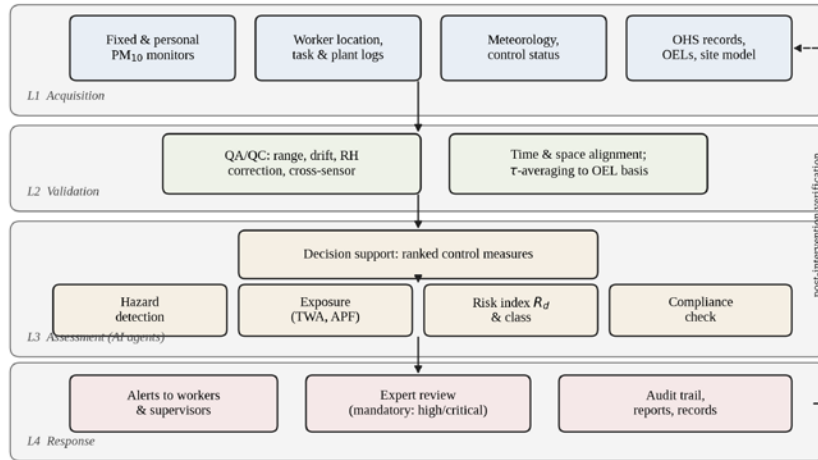


Figure 1. Four-layer architecture of the proposed framework, with the post-intervention verification loop returning to the acquisition layer.

Eight specialised agents operate within L3 and L4: *monitoring* (availability and technical plausibility of incoming records); *hazard detection* (threshold exceedances, abnormal trends, hazardous variable combinations); *exposure assessment* (time-weighted and cumulative exposure per worker or similar exposure group); *risk classification* (operational category); *compliance* (comparison against exposure limits and internal procedures); *decision support* (ranked control measures); *alerting* (notifications, with content differentiated by recipient); and *reporting* (event, recommendation, responsible person, implemented measure, verification outcome). Decomposing the workflow this way keeps each analytical step separately testable and auditable, which matters more for regulatory acceptance than end-to-end predictive performance.

Data acquisition and preprocessing

Each measurement is stored with a timestamp and, where available, position, activity, exposure group and plant status. Preprocessing removes duplicates, flags missing values, rejects technically impossible readings, applies calibration and humidity corrections, synchronises time bases, aligns spatial references, converts units and aggregates to the averaging periods required for comparison with reference values. Readings outside the sensor operating range are flagged for review rather than passed to the risk model as valid conditions, and cross-comparison between sensors is used to detect drift or malfunction.

The step is not a formality for optical particle sensors. Such instruments infer mass from light scattering and are least reliable for exactly the fraction of interest here: they systematically underestimate the coarse fraction that dominates construction dust, and their response depends on aerosol composition, refractive index and relative humidity (Kuula et al., 2020; Crilley et al., 2020). Site-specific gravimetric co-location is therefore a prerequisite for deployment

rather than an optional refinement, and the resulting correction factor is stored with the data so the provenance of every risk decision remains reconstructable.

Size-selective conventions and reference values

A recurring error in real-time occupational dust monitoring is the direct comparison of a PM₁₀ reading with an occupational exposure limit. The two quantities are defined on different sampling conventions. PM₁₀ is an ambient-air metric with a 50 % cut-off at 10 μm aerodynamic diameter (EN 12341), whereas occupational limits for dust are defined on the inhalable and respirable conventions of EN 481, with 50 % cut-offs at approximately 100 μm and 4 μm respectively. PM₁₀ therefore excludes part of the inhalable fraction and includes particles well above the respirable range, and no fixed conversion exists between them, because the ratio depends on the particle size distribution generated by the task.

In the framework PM₁₀ is consequently used as a real-time *indicator* that triggers assessment, escalation and control, while compliance determinations remain based on gravimetric personal sampling against the applicable limits. Table 1 summarises the reference values used, each with its averaging time and sampling convention.

Table 1. Size-selective conventions and reference values used in the PM₁₀ instantiation.

Metric	Convention (d_{50})	Reference value	Averaging time	Role in framework
PM ₁₀	EN 12341 (10 μm)	45 $\mu\text{g m}^{-3}$ (WHO AQC)	24 h	Site/boundary indicator
PM ₁₀	EN 12341 (10 μm)	50 $\mu\text{g m}^{-3}$ (EU limit)	24 h	Regulatory boundary value
PM ₁₀	EN 12341 (10 μm)	Internal action level	8 h and 15 min	Real-time escalation trigger
Inhalable dust	EN 481 (100 μm)	10 mg m^{-3} (typical)	8 h TWA	Compliance (gravimetric)
Respirable dust	EN 481 (4 μm)	4 mg m^{-3} (typical)	8 h TWA	Compliance (gravimetric)
Respirable crystalline silica	EN 481 (4 μm)	0.1 mg m^{-3} (EU BOELV)	8 h TWA	Compliance (gravimetric)

Internal action levels are set below the compliance limits so that escalation occurs before an exceedance is established; they are site-specific and require expert derivation. National limits differ, so the values in Table 1 are indicative (WHO, 2021; European Parliament and Council, 2004, 2008).

Exposure assessment

Cumulative exposure of worker or exposure group i over n monitored intervals is

$$E_i = \sum_{j=1}^n C_j t_j \quad (1)$$

where C_j is the concentration during interval j and t_j its duration. The corresponding time-weighted average over a reference period T is

$$\text{TWA}_T = \frac{1}{T} \sum_{j=1}^n C_j t_j, \quad \sum_{j=1}^n t_j = T \quad (2)$$

The constraint is essential. If monitored intervals do not span T , the remainder must be assigned an explicit value — measured, modelled or conservatively assumed — and the rule applied is recorded. Otherwise, the average is biased low, since dividing a partial exposure integral by a full 8-h reference period implicitly assigns zero concentration to unmonitored time.

Where respiratory protective equipment is worn, the effective exposure is

$$E_{i,\text{eff}} = E_i / \text{APF} \quad (3)$$

where APF is the assigned protection factor. The correction is applied only when the device is of the correct class, fit-tested and confirmed to be in use for the interval concerned; otherwise $\text{APF} = 1$. Because protective equipment is the lowest tier of the hierarchy of controls, the correction adjusts the exposure estimate but never, on its own, lowers the risk category assigned in Section 2.6.

Dynamic risk index and classification

The exceedance ratio for averaging time τ is

$$\text{ER}_\tau = C_{m,\tau} / C_{r,\tau} \quad (4)$$

where $C_{m,\tau}$ and $C_{r,\tau}$ are the measured and reference concentrations for the *same* averaging time. Comparing a short-term reading with a long-term reference value, or the reverse, is not meaningful, and the compliance agent rejects such pairings.

The dynamic risk index combines four normalised components on $[0, 1]$ and is attenuated by verified controls:

$$R_d = \left(\sum_{k=1}^4 w_k x_k \right) (1 - \eta_c), \quad \sum_{k=1}^4 w_k = 1 \quad (5)$$

Here $x_1 = \min(\text{ER}_{8h}/a, 1)$ represents shift-averaged exceedance; $x_2 = \min(\text{ER}_{15\text{min}}/b, 1)$ represents short-term peak exceedance; x_3 is normalised hazard severity, reflecting the toxicological potency of the material, including its crystalline silica content; x_4 is normalised worker or task vulnerability; a and b are saturation constants; and $\eta_c \in [0, 1]$ is the verified

effectiveness of implemented engineering and organisational controls. Including x_1 and x_2 separately is what allows a short peak to raise the risk level even when the shift average is close to acceptable — the behaviour that periodic assessment cannot reproduce. Only controls whose operation has been confirmed by the monitoring agent contribute to η_C ; prescribed but unverified measures are treated as absent.

The index maps to four categories: acceptable ($R_d < 0.25$), moderate (0.25–0.50), high (0.50–0.75) and critical ($R_d > 0.75$). An override rule prevents an assessment from falling below compliance status: if $ER_\tau > 1$ for any τ , the category cannot be lower than moderate. The weights, saturation constants and boundaries are expert-elicited, not empirically derived; their calibration is the principal outstanding validation task.

Categories are linked to predefined responses: *acceptable* — conditions within criteria, controls adequate; *moderate* — increased monitoring frequency and minor preventive adjustment; *high* — immediate corrective action, notification of responsible personnel and assessment of whether work may continue; *critical* — urgent intervention, suspension of the activity, access restriction or withdrawal of workers. OHS professionals may override an automated recommendation where site-specific circumstances warrant, and every override is recorded with its justification.

Workflow automation and case-study definition

A workflow engine connects monitoring, models, communication tools and documentation. A measurement triggers validation, exposure and risk computation, categorisation, alert generation, recommendation of control measures, creation of a digital record and, after implementation, re-assessment against subsequent measurements. Where corrective action is not confirmed within a defined period, the workflow escalates automatically.

Construction sites were selected because particulate concentrations change rapidly with excavation, demolition, cutting, material handling and vehicle movement. Monitoring points are positioned near major emission sources, work zones, site boundaries and circulation routes, with mobile sensors tied to worker or vehicle position where available. Analysis variables are PM₁₀ concentration, time, exposure duration, activity, worker location, distance from source, meteorology, dust-control status, respiratory protection use and number of workers exposed. Candidate controls include water spraying, local extraction, covering of loose material, vehicle speed reduction, route modification, suspension of high-emission activities, worker relocation, exposure-time limitation, increased separation distance, respiratory protection and rescheduling by weather.

RESULTS AND DISCUSSION

The framework defines occupational risk as a state variable rather than a value fixed at a periodic assessment. The estimate is updated whenever concentration, activity, exposure duration, worker position or control status changes, and the verification loop returns post-

intervention measurements to the model, so effectiveness is evaluated from data rather than inferred from the fact that a measure was recorded as implemented.

Because exposure is interpreted together with activity, duration, proximity, control status and protection use, identical measured concentrations can produce different risk categories. This is intended behaviour, and it distinguishes environmental concentration at a monitoring point from effective exposure of a worker. The hazard-identification stage produces a structured record per event and separates two event types: direct exceedances of a predefined value, resolvable by threshold rules; and developing patterns that do not yet exceed a limit — sustained upward trends, repeated short peaks, or co-located moderate hazards — detectable only by trend or anomaly analysis. The first supports compliance assessment, the second earlier intervention.

Illustrative example

Table 2 applies the model to an illustrative concrete-cutting task. The values are hypothetical and are used to demonstrate the arithmetic and the classification logic; they are not measurements.

Table 2. Illustrative application of the dynamic risk index to a concrete-cutting task.

Quantity	Value	Quantity	Value
Task duration / shift	0.75 h / 8 h	ER _{8h} ; ER _{15min}	1.26 ; 4.67
Mean PM10 during task	850 µg m ⁻³	x_1 ($a=3$) ; x_2 ($b=5$)	0.42 ; 0.93
Background, rest of shift	120 µg m ⁻³	x_3 severity ; x_4 vulnerability	0.80 ; 0.50
Highest 15-min mean	1 400 µg m ⁻³	Weights $w_{1..4}$	0.30, 0.30, 0.25, 0.15
8-h TWA	188 µg m ⁻³	Weighted sum	0.68
Action level (8 h / 15 min)	150 / 300 µg m ⁻³	Verified control effect. η_c	0.20
Risk index R_d			0.54 — high

The example illustrates the central argument. Assessed on the shift average alone, the task exceeds the internal action level by 26 % and would plausibly be handled as a moderate finding. Once the short-term peak is represented explicitly, the same task is classified as high risk and triggers immediate corrective action. Averaging over a shift is precisely the operation that removes the information most relevant to acute exposure, which is why x_2 is weighted equally with x_1 .

The example also shows the limits of the indicator. Because the material is silica-bearing, the PM10 reading cannot establish compliance: determination against the 0.1 mg m⁻³ respirable crystalline silica limit requires gravimetric personal sampling in the respirable convention. A

high or critical PM10 classification on silica-bearing material is therefore treated as an automatic trigger for personal sampling, not as a substitute for it.

Comparison with conventional assessment

Conventional assessment records conditions at selected moments, whereas the proposed model updates them continuously and resolves variation within the shift rather than assigning a single level to a task. Conventional systems require manual transfer between measurement, decision and documentation; the proposed workflow links these automatically while retaining mandatory human confirmation for high and critical events. Conventional corrective-action records confirm that a measure was prescribed; the proposed system evaluates whether it reduced exposure. Aggregating events over time also identifies recurrent hotspots — excavation and demolition zones, cutting and loading points, unpaved haul routes, loose-material storage and downwind positions — where repeated elevated readings indicate insufficient controls or a work area requiring reorganisation.

CONCLUSION

The paper proposed a four-layer framework applying artificial intelligence to occupational health-risk assessment, combining continuous monitoring, validation, hazard identification, exposure assessment, dynamic risk classification, specialised agents, workflow automation and post-intervention verification. Its contribution is not the individual components, which exist separately, but their integration into a traceable path from measurement to verified corrective action, together with the explicit treatment of three issues often left implicit: the distinction between ambient and occupational size-selective conventions, the matching of averaging times between measured and reference values, and the separation of verified engineering controls from personal protective equipment in the risk calculation.

The PM10 instantiation demonstrates the framework's operation and its limits. The illustrative example shows that short-term peaks can determine the risk category even when the shift average is near acceptable, which is the principal argument for continuous over periodic assessment; it also shows that a real-time indicator triggers assessment without replacing gravimetric compliance measurement.

The framework does not replace occupational safety professionals but provides faster and more consistent information for their decisions; human supervision remains essential for high-risk situations, legal interpretation and decisions affecting workers' health, privacy or employment. Future work should implement the framework on an instrumented site, calibrate the index parameters against expert classifications and health-surveillance outcomes, and report false-alarm rates and response times.

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CONSTRUCTION-RELATED PM₁₀ EMISSIONS AND HUMAN HEALTH RISK ASSESSMENT IN A RAPIDLY URBANIZING AREA OF NOVI SAD

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Abstract: Large-scale urban construction is an intense, spatially concentrated source of particulate matter, but it is not represented in Serbia's air pollutant registry as a distinct source, and its local exposure burden is rarely quantified. The research models PM₁₀ emissions from a 60,000 m² apartment-construction site in a rapidly urbanizing district of Novi Sad, Serbia, and translates them into ambient concentrations and human health risk. Emissions were estimated with the US EPA Tier 1 method as adopted in the EMEP/EEA Guidebook, using a soil silt content of 35.4% measured at the nearest monitored construction site. The central estimate is 24.6 t PM₁₀ over the nine-month build (range 2.5–73.7 t across the emission-factor confidence interval). Modelled 24-hour concentrations at the nearest homes, 50 m from the boundary, reached 135 µg m⁻³ - about three times - giving a residential hazard quotient of 6.2. On-site worker exposure (704 µg m⁻³ as an 8-hour mean) remained an order of magnitude below the occupational limit (HQ 0.07) while exceeding the ambient 24-hour guideline, exposing a substantial regulatory asymmetry between occupational and public-health frameworks.

Keywords: PM₁₀; construction dust; health risk assessment; urbanization.

INTRODUCTION

Urban construction generates fugitive particulate matter through land clearing, excavation, material handling, on-site vehicle movement and wind erosion of exposed surfaces. Unlike combustion sources, these emissions are diffuse, uncontrolled, highly variable in time, and largely uncontrolled unless mitigation is actively imposed. They are weighted towards the coarse fraction, which makes construction a disproportionate contributor to PM₁₀ relative to PM_{2.5}, and they are released at or near ground level directly adjacent to receptors — the combination that produces the steepest near-field concentration gradients of any common urban source.

A significant share of construction takes place in densely populated areas, so a large number of people may be exposed to the resulting emissions. Serbia's urban centers are undergoing rapid redevelopment, with tracts of land moving from industrial or vacant use into high-density residential construction over compressed timeframes, yet the national air pollutant

registry does not yet recognize construction sites as distinct PM sources. The site examined here is characteristic: roughly 60,000 m² of land under intensive earthworks and apartment construction, embedded directly within an established low-rise residential neighborhood, with dwellings along the southern and eastern boundaries separated from active works by little more than the site fence and a single carriageway (Figure 1).



Figure 1. Observed location – rapidly urbanizing area in Novi Sad, Serbia

MATERIALS AND METHODS

Location

The observed site is an apartment-construction area of approximately 60,000 m² (6.0 ha) in a rapidly urbanizing district of Novi Sad (Figure 1). It is bounded to the north by an arterial road and commercial/light-industrial land use, and to the south and east by established low-rise housing. Works comprise land clearing, bulk excavation and earthmoving, material handling and stockpiling, and construction-vehicle movement on unpaved internal routes. The 60,000 m² is the affected area, including accessory haul roads. No routine dust control was applied.

Emission modeling

Emissions were estimated with the US EPA Tier 1 method as adopted in the EMEP/EEA Guidebook (2019) for NFR 2.A.5.b:

$$EM_{PM10} = EF_{PM10} \cdot A_{aff} \cdot d \cdot (1-CE) \cdot 24 / PE \cdot s / 9\%$$

where EF is the construction-type emission factor, A_{aff} the affected area, d the duration, CE the control efficiency, PE the Thornthwaite precipitation–evaporation index, and s the soil silt content. The 24 and 9% are the reference PE and silt values of the original US measurements, so the last two terms normalise the site to those baseline conditions.

For apartment construction the guidebook PM10 emission factor is $0.30 \text{ kg m}^{-2} \text{ yr}^{-1}$ (95% confidence interval 0.03–0.90), with a default duration of 0.75 yr. No control was applied (CE = 0). Silt content value of $s = 35.4\%$ was used based on the fine-particle content measured by laboratory analysis at the nearest monitored construction site (Šunjević et al., 2023). The Thornthwaite index was computed from the Novi Sad 1991–2020 climate average (mean annual temperature $12.2 \text{ }^{\circ}\text{C}$, annual precipitation 670 mm) using the metric form given in the guidebook, giving PE = 51.9 (sub-humid). The resulting moisture correction ($24/PE = 0.46$) roughly halves the emission relative to the semi-arid reference conditions.

Dispersion modelling

Emissions were converted to concentrations in two stages. On-site worker exposure was estimated with a box model, $C = Q / (u \cdot W \cdot H)$, where Q is the emission rate during working hours, u the mean wind speed (2.5 m s^{-1}), W the equivalent square side of the site (245 m) and H the near-field mixing height (10 m); this yields an 8-hour working mean. Off-site concentrations were estimated by representing the site as a ground-level area source (virtual point approximation, Briggs urban coefficients, neutral stability) and evaluating the Gaussian ground-level equation $C(x) = Q / (\pi u \sigma_y \sigma_z)$ at downwind receptors. Plume-centerline values were converted to 24-hour and construction-period averages using a working-hours duty cycle and a prevailing wind-sector frequency of 0.30. This is a screening-level treatment, deliberately conservative, and not a substitute for AERMOD or ADMS with site-specific hourly meteorology.

Health risk assessment

Risk was characterized following US EPA RAGS Part F inhalation methodology, with exposure concentration $EC = (CA \cdot ET \cdot EF \cdot ED) / AT$ and hazard quotient $HQ = EC / RfC$. PM10 is a criteria pollutant without an IRIS reference concentration, so the WHO 2021 Air Quality Guideline values were adopted as reference concentrations — $15 \text{ } \mu\text{g m}^{-3}$ (annual) and $45 \text{ } \mu\text{g m}^{-3}$ (24-hour) — and this substitution is treated as a limitation. The occupational scenario used the ACGIH TLV-TWA for inhalable particulate not otherwise specified, 10 mg m^{-3} (Table 1.).

Table 1. Input parameters

PARAMETER	VALUE	UNIT
AFFECTED AREA	60,000	m ²
CS TYPE	Apartments	–
EMISSION FACTOR	0.30 (0.03–0.90)	kg m ⁻² yr ⁻¹
DURATION	0.75	yr
CONTROL EFFICIENCY	0	–
SILT CONTENT	35.4	%
PE INDEX	51.9	–
MOISTURE CORRECTION	0.46	–
SILT CORRECTION	3.93	–
MEAN WIND SPEED	2.5	m s ⁻¹
MIXING HEIGHT	10	m
WIND-SECTOR FREQUENCY	0.30	–
EXPOSURE FREQ., RESIDENTIAL	350	d yr ⁻¹
EXPOSURE TIME, RESIDENTIAL	24	h d ⁻¹
RFC (ANNUAL / 24-H)	15 / 45	µg m ⁻³
OEL (INHALABLE)	10	mg m ⁻³

RESULTS

Modelled concentrations

Emission rates during active working hours were 0.28, 2.83 and 8.48 g s⁻¹ for the lower, central and upper cases.

Table 2. Modelled on-site concentration (8-hour working mean)

Case	On-site PM10 (µg m ⁻³)	× WHO 24-h AQG (45)	HQ vs ACGIH OEL
Lower CI	70	1.6	0.004
Central	704	15.6	0.07
Upper CI	2,111	46.9	0.21

Table 3. Modelled off-site 24-hour mean PM10 (µg m⁻³), central case

Distance (m)	24-h mean	× WHO 24-h AQG (45)
25	255.8	5.7
50	134.6	3.0
100	67.0	1.5
200	31.1	0.7
500	9.1	0.2

WHO 2021 24-h AQG = 45 µg m⁻³; EU daily limit value = 50 µg m⁻³ (35 exceedances permitted).

Table 5. Modelled construction-period mean PM10 (µg m⁻³), central case

Distance (m)	Period mean	× WHO annual AQG (15)
25	185.0	12.3
50	97.4	6.5
100	48.4	3.2
200	22.5	1.5
500	6.6	0.4

WHO 2021 annual AQG = 15 $\mu\text{g m}^{-3}$; EU annual limit value = 40 $\mu\text{g m}^{-3}$.

At the nearest homes (50 m) the modelled 24-hour concentration is about three times the WHO 24-hour guideline and exceeds the EU daily limit value. The EU daily limit is exceeded out to roughly 100 m and the WHO 24-hour guideline out to beyond 100 m.

Residential (nearest receptor, 50 m). The construction-period exposure concentration is 93.4 $\mu\text{g m}^{-3}$, giving a hazard quotient of 6.2 against the WHO annual guideline; the 24-hour hazard quotient is 3.0. Both exceed unity by a wide margin, indicating a health concern for residents immediately adjacent to the site for the duration of construction.

The on-site 8-hour mean of 704 $\mu\text{g m}^{-3}$ gives a hazard quotient of 0.07 against the ACGIH inhalable limit — an order of magnitude below the occupational threshold — yet the same exposure is 15.6 times the WHO 24-hour ambient guideline.

DISCUSSION

Emission magnitude and uncertainty. The central estimate of 24.6 t PM₁₀ from a single six-hectare site over nine months is substantial for a source that the national registry does not track. The dominant uncertainty is the emission factor itself, whose confidence interval spans a factor of 30; by contrast the two correction terms are well constrained here, because the silt content is measured at a neighbouring site and the PE index is computed from local normals rather than assumed. The prior validation of this method against Novi Sad monitoring (Šunjević et al., 2023), which found the Tier 1 PM₁₀ predictions required essentially no correction, gives some confidence that the central estimate is not systematically biased, even though the present study includes no new measurements of its own.

The occupational–ambient asymmetry. Workers are modelled at 704 $\mu\text{g m}^{-3}$, comfortably within an occupational limit of 10,000 $\mu\text{g m}^{-3}$ while simultaneously breathing roughly sixteen times the WHO 24-hour ambient guideline. The same air that constitutes occupational compliance inside the fence would constitute a serious air-quality episode outside it. This is not an error in either framework — occupational limits are set for healthy adults over a 40-hour week with medical surveillance, whereas ambient guidelines protect an entire population continuously, including the susceptible — but it means occupational compliance provides essentially no assurance of health protection on a construction site. Given that PM₁₀ shows no identified threshold for cardiopulmonary effects, exposures at these levels warrant concern even where they are legally compliant.

Residential exposure and susceptible groups. A residential hazard quotient of 6.2 at 50 m indicates that the population living along the site boundary is exposed, for the duration of the build, to concentrations well above health-based guidelines. Children, the elderly and people with pre-existing cardiopulmonary disease are more susceptible at a given exposure; the AQI assessment of Novi Sad construction sites in Šunjević et al. (2023) reached comparable conclusions from measured concentrations, classifying nearby air quality as harmful to unhealthy on most days.

No dust control was applied at this site. Routine watering achieves an overall control efficiency of about 50% (WRAP, 2006), which would roughly halve every concentration and hazard quotient reported here — bringing the residential 24-hour hazard quotient from 3.0 to about 1.5, still above unity at the nearest homes. Reaching the WHO guideline at 50 m would require substantially higher combined control: watering plus perimeter barriers, wheel washing, stockpile covering, haul-route stabilisation, and scheduling of the most emissive operations away from adverse wind conditions.

CONCLUSIONS

A 60,000 m² apartment-construction site in Novi Sad is estimated to release about 24.6 t PM₁₀ over its nine-month construction period (range 2.5–73.7 t), using measured local silt content and a locally modelled climate correction.

Modelled 24-hour concentrations at the nearest homes (50 m) reach 135 µg m⁻³, about three times the WHO 24-hour guideline and above the EU daily limit value, with a residential hazard quotient of 6.2. While on-site worker exposure complies with the occupational limit by an order of magnitude (HQ 0.07) while exceeding the ambient 24-hour guideline roughly sixteen-fold, demonstrating that occupational compliance is not a proxy for health protection.

Construction sites should be recognised as a distinct, trackable PM source in the Serbian air pollutant registry, given its magnitude and its concentration in populated areas.

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ANALYSIS OF OCCUPATIONAL INJURIES IN CONSTRUCTION IN SERBIA FOR IMPROVING RISK ASSESSMENT AND HSE MANAGEMENT

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Abstract: This paper examines the extent to which publicly available data on occupational injuries in the construction sector of the Republic of Serbia can be used as a basis for effective risk management and the improvement of preventive action. The empirical basis consists of annual reports of the Administration for Occupational Safety and Health for the period 2022–2024, while the methodological framework includes descriptive and comparative analysis of trends, with supplementary application of the Kinney method for prioritization of hazards under conditions of limited data granularity. The results indicate an increase in the absolute number of analyzed injuries, with a relatively stable share of the construction sector in the overall structure of occupational injuries, confirming the continuity of elevated risk levels. At the same time, a key systemic issue is identified: the aggregated nature of the available data does not allow consistent correlation between causes, workplaces, exposures, and consequences, which significantly limits the operational applicability of the analyses and the accuracy of risk assessment. Based on these findings, the paper concludes that the existing record-keeping model does not provide a sufficient level of informational support for proactive safety management. A necessary direction for improvement is the introduction of an electronic, structured, and continuous record-keeping system in the field of occupational safety and health, enabling detailed analytical processing, dynamic updating of risk assessments, and more effective preventive action. The contribution of this paper is reflected in establishing the link between empirical injury indicators, the limitations of the existing record-keeping system, and the need for digitalization as a prerequisite for the development of a genuinely proactive HSE approach.

Keywords: *construction; occupational injuries; risk assessment; Kinney method; preventive action.*

INTRODUCTION

The construction sector is classified among activities with elevated occupational risk due to variable working conditions, work at height, the use of machinery, the presence of multiple contractors, and frequent organizational changes on construction sites. In such a working environment, occupational injuries represent not only an indicator of the state of safety, but also an important source of information on weaknesses in the existing system of preventive action. Contemporary research indicates that the analysis of incidents and injuries attains its

full value only when used for identifying patterns, isolating priority hazards, and directing targeted preventive interventions, rather than merely for ex post recording of consequences.

The subject of this paper is the analysis of occupational injuries in the construction sector of the Republic of Serbia in the period 2022–2024, with the aim of linking injury trends to the improvement of risk assessment documentation and the development of a more proactive HSE approach. The main thesis of the paper is that publicly available data, although aggregated and limited, can be sufficiently informative to indicate the need for revising priorities in preventive action.

In theoretical terms, the paper relies on three complementary foundations: incident analysis as a basis for recognizing risk patterns, quantitative approaches to risk prioritization, and contemporary concepts of proactive safety management. In practical terms, the paper is grounded in the national regulatory framework, according to which the risk assessment document represents the central document for hazard identification, risk evaluation, and the definition of preventive action.

Despite the availability of official reports, the existing system for recording occupational injuries is largely based on aggregated and partially structured data, which limits their use in more advanced analyses and operational decision-making. In this context, one of the key questions implicitly raised by this paper is whether such a record-keeping model can support the development of a proactive safety approach, or whether the introduction of electronic systems enabling more detailed, integrated, and time-updated data is necessary.

Theoretical and regulatory framework

Relevant literature confirms that incident analysis in the construction sector enables the identification of dominant causes, injury occurrence patterns, and areas where targeted interventions are required. Particular importance is attributed to studies that combine the analysis of incident databases with the classification of high-risk hazards and the proposal of hazard-specific preventive action. In parallel, systematic reviews of quantitative risk assessment methods indicate that structured approaches contribute to more transparent prioritization and more rational selection of control measures.

Recent approaches further shift the focus from reactive to proactive safety management. Within such an approach, injury data are not only lagging indicators, but also a basis for early identification of organizational and technical deficiencies, correction of procedures, and improvement of supervision and training. Digital HSE tools can support this approach through incident recording, tracking of corrective measures, trend analysis, and training management; however, they do not replace professional risk assessment nor the regulatory obligations of the employer.

In the Republic of Serbia, the regulatory framework consists of the Law on Occupational Safety and Health, the Rulebook on the Method and Procedure for Risk Assessment at the

Workplace and in the Working Environment, and specific regulations governing safety at temporary or mobile construction sites. Within this framework, the risk assessment document has an operational function: based on identified hazards and assessed risks, it defines measures, responsible persons, deadlines, and methods for monitoring their implementation. Therefore, the analysis of injury trends may have direct practical significance for the periodic review of risk assessments in the construction sector.

MATERIAL AND METHODS

The empirical basis of this paper consists of publicly available annual reports of the Administration for Occupational Safety and Health for the years 2022, 2023, and 2024. The analysis is limited to aggregated data on analyzed occupational injuries in the construction sector and their share in the overall structure of analyzed injuries. The normative part of the paper includes the applicable regulations of the Republic of Serbia governing risk assessment and preventive action at construction sites.

The methodological framework includes: (Newaz, M. T., Jefferies, M., & Ershadi, M., 2025) descriptive analysis of injury volume, (Kumi, L., Jeong, J., & Jeong, J., 2024) comparative analysis of year-to-year changes, (Awolusi, I., Marks, E., Hainen, A., & Alzarrad, A., 2022) interpretation of findings in relation to the risk assessment document, and (AlMarri M, Al-Ali M, Alzarooni M, AlTeneiji A, Al-Ali K, Bahroun Z., 2024) supplementary application of the Kinney method (Stanković, M., Stanković, V., 2013) for ranking priority hazards. In this paper, the Kinney method is not used for the reconstruction of each individual event, but rather as a transparent framework for translating injury trends into priorities for preventive action.

The Kinney method is based on the formula

$$R = V \times U \times P \quad (1)$$

where R represents the level of risk, V the probability of occurrence of an undesired event, U the frequency, i.e. exposure to the hazard, and P the severity of consequences. Its practical value in this paper does not lie in replacing detailed assessment of each workplace, but in enabling consistent ranking of hazard groups that require priority attention within the revision of the risk assessment document. Such application of the method is particularly justified when publicly available data are sufficient to identify trends, but insufficient for in-depth incident reconstruction.

RESULTS

The analysis indicates that the number of analyzed occupational injuries in the construction sector of the Republic of Serbia increased over the observed period. In 2022, 74 analyzed injuries were recorded in construction, 91 in 2023, and 104 in 2024. This represents an increase of approximately 23.0% in the period 2022–2023 and 14.3% in the period 2023–2024, i.e. a total increase of 40.5% over the three-year period.

At the same time, the share of the construction sector in the total number of analyzed injuries remained relatively stable: 6.57% in 2022, 6.88% in 2023, and 6.25% in 2024 (**Table 1.**). This finding indicates that construction consistently maintains a significant position within the overall structure of occupational injuries, even when the increase in the absolute number of injuries is observed in the broader context of the overall growth in analyzed injuries across all sectors.

Table 1. Overview of analyzed injuries, (*Annual report, 2024*)

Year	Total number of analyzed injuries	Injuries in construction	Share (%)	Trend
2022	1,127	74	6.57	—
2023	1,322	91	6.88	increase
2024	1,588	104	6.25	increase

The practical significance of the results lies in the fact that the increase in the absolute number of injuries represents a sufficient signal for a functional revision of risk assessment. Although publicly available reports do not allow full and consistent cross-referencing of sector, type of event, causes, and consequences for each year, they nevertheless clearly indicate that construction remains a sector requiring continuously enhanced preventive attention.

DISCUSSION

The obtained findings do not justify the claim that there has been an unambiguous structural deterioration of all working conditions in the construction sector. However, they reliably indicate the continuity of elevated risk and an increase in the absolute number of analyzed injuries. From the perspective of safety management, such a pattern is sufficient to treat risk assessment not as a static document, but as an instrument that must be periodically revised based on real-world indicators.

The application of the Kinney method in this paper further supports such an interpretation, as it enables the relationship between injury trends and risk assessment to be established in a structured and verifiable manner. When aggregated data indicate the stable presence of construction among sectors with a significant share of total injuries, it is methodologically justified to rank priority hazards according to the combination of probability, exposure, and severity of consequences, and subsequently to define appropriate technical, organizational, and training measures.

An important limitation of the study relates to the level of detail in publicly available data, which are predominantly aggregated and do not allow consistent linking of key elements of each incident, such as the specific workplace, type of activity, immediate cause, level of exposure, and severity of consequences. Such a data structure prevents deeper analysis of cause–effect relationships and significantly limits the application of more advanced risk assessment and prediction methods.

Consequently, the application of the Kinney method in this paper necessarily has an approximative character, as the ranking is based on trends and general patterns rather than on precise micro-level data. This clearly indicates that the problem is not exclusively methodological, but systemic—related to the manner of data collection, structuring, and record-keeping in the field of occupational safety and health.

Under such conditions, risk assessment remains partially limited in its operational function, as it is not based on continuously updated and finely structured data from practice. This reduces the ability to timely identify changes in injury patterns, as well as to precisely direct preventive action.

These findings indicate that without systemic improvement in the methods of data recording and processing, it is not possible to achieve the full capacity of proactive safety management. In this context, the introduction of an electronic record-keeping system, enabling standardized data collection at the level of individual events, their integration, and continuous analysis, represents not only a technological improvement but also a methodological prerequisite for the development of a modern occupational safety and health system.

PROPOSAL FOR IMPROVING PREVENTIVE ACTION

Based on the results of this study, a three-level model for improving preventive action can be proposed. The first level includes technical measures, such as control of work at height, protection against falling objects, safe use of machinery and electrical energy, and improvement of collective protective measures. The second level consists of organizational measures: clearer definition of responsibilities, stricter supervision of work execution, consistent incident recording, and more frequent review of work procedures. The third level relates to training and safety culture, i.e. targeted training programs, availability of instructions, and continuous monitoring of the implementation of corrective measures.

In practical application, the results of injury analysis and Kinney-based ranking should be incorporated into a priority matrix within the risk assessment document. For each priority hazard, it is necessary to define a responsible person, a deadline for implementation, and a control indicator. This reduces the gap between formally prepared risk assessment documentation and its actual management capacity at the construction site.

Digital HSE tools can provide additional support to this model through incident recording, tracking of corrective measures, trend analysis, and training management. Their role in this context is not to replace the risk assessment document, but to improve data timeliness, transparency of measure implementation, and continuity of preventive action.

In this regard, electronic record-keeping systems should provide at least the following functionalities: (1) structured recording of incidents at the level of individual events, including workplace, type of activity, cause, and consequences; (2) linking incidents with identified hazards and measures defined in the risk assessment document; (3) automatic risk ranking

through the application of standardized methods; (4) monitoring the implementation of corrective measures and their effectiveness over time.

Such an approach enables the transition from a static and periodic risk assessment model to a dynamic system that is continuously updated based on real-world data, thereby significantly improving the capacity for preventive action.

CONCLUSION

The analysis of occupational injuries in the construction sector of the Republic of Serbia for the period 2022–2024 shows a clear increase in the absolute number of analyzed injuries, accompanied by a stable share of this sector in the overall structure of injuries, confirming its continuously elevated risk level. However, the key finding of this paper goes beyond the descriptive level and relates to the limitations of the existing record-keeping system.

It has been demonstrated that aggregated and insufficiently structured data do not allow consistent linking of causes, exposure, workplaces, and consequences, thereby directly limiting the possibility of accurate risk assessment and effective preventive action. Under such conditions, risk assessment remains a partially static document, whose operational value depends more on expert judgment than on systematic data analysis.

Based on this, it can be concluded that the existing record-keeping model in the field of occupational safety and health is not adequate for the needs of modern, proactive safety management. The introduction of an electronic, structured, and continuous record-keeping system emerges as a necessary step, as it enables data integration, real-time analysis, and dynamic improvement of risk assessment.

This creates the conditions for transitioning from a reactive to a genuinely proactive, data-driven management model, in which preventive action are not defined solely on the basis of periodic analyses, but through continuous monitoring and optimization. In this sense, the digitalization of record-keeping does not represent merely a technological improvement, but a key prerequisite for the development of an effective and sustainable occupational safety and health system.

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ANALYSIS OF THE INTERDEPENDENCE OF REGULATORY COMPLIANCE AND SAFETY CULTURE AS KEY FACTORS IN THE PREVENTION OF OCCUPATIONAL INJURIES

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Abstract: Reducing the number of occupational injuries represents a strategic objective of the Republic of Serbia, recognized in all relevant national regulations. This paper examines the interdependence of legal regulation and safety culture as significant determinants of occupational injuries. The research analyzes the relationship between formally established rules governing the behavior of stakeholders within the occupational safety and health system and the actual behavior of employees and employers.

Drawing on a review of relevant scientific literature, the paper indicates that the effective implementation of regulations, including their consistent enforcement and sanctioning, contributes to reducing the risk of occupational injuries. However, the findings also show that the level of development of safety culture—encompassing attitudes, values, risk perception, and everyday practices of employees and employers—has a crucial impact on actual safety in the work environment.

Based on the research, it is concluded that an integrated approach, which implies alignment between the implementation of legal regulations and the development of safety culture, represents the most effective model for the prevention of occupational injuries.

Keywords: occupational safety and health, legal regulation, safety culture, occupational injuries, prevention

INTRODUCTION

For many decades, scientific literature has demonstrated the existence of a direct relationship between occupational safety and health and work productivity. Extensive research has demonstrated that effective work organization has a positive impact on occupational safety and health and, consequently, on employee productivity.

A prerequisite for the full health of workers is the existence of a healthy working environment, as the “quality”—and especially the “lack of quality”—of the working environment strongly affects the health and well-being of employees (Petrović, 2019). This is also the direction of the European Union’s policy, which aims to achieve a “vision zero” for occupational injuries (Ilić Petković, Stratijev, 2023).

Achieving such ambitious goals requires continuous monitoring and alignment with contemporary legal regulations in this field, particularly those of the European Union, with

which the Republic of Serbia is obliged to harmonize its policies and legislation under the Stabilisation and Association Agreement (2008). It can be observed that, over the past several years, Serbia has not experienced significant changes in the number of occupational injuries—neither a notable increase nor a decrease (Labour Inspectorate, 2026). This indicates that, in addition to the ongoing process of improving legal regulations, there is a need for additional measures and mechanisms that would contribute to reducing the number of occupational injuries, particularly fatal ones. This serves as a basis for examining the issue of safety culture.

The goal of every employer is to ensure that everyone in the organization can recognize and understand real or potential hazards and associated risks, to prevent or control operational hazards and related risks, and to train employees at all organizational levels so that they can demonstrate the importance of correcting potential hazards to which they may be routinely exposed, as well as how to protect themselves and others (Lugar, Varičak, Primužak, 2022). In this context, it becomes evident that clearly defined and well-communicated safety roles and responsibilities at all levels of the organization constitute an issue that deserves special attention in scientific research.

NORMATIVE APPROACH TO OCCUPATIONAL SAFETY AND HEALTH

If the goal is to achieve minimal or no risk to the safety and health of employees, their protection must be approached from the perspectives of multiple scientific disciplines (Joldžić, 2021a). Such an approach should be complemented by considerations from various social sciences and humanities, where legal sciences clearly find their place and significance. This is further supported by the fact that some of the fundamental legal elements of occupational safety and health originated in the last century, for example in 1919 as part of the Treaty of Versailles. The legal approach to occupational safety and health began a century ago and has been in a constant process of development. All international legal documents in this field should be observed within the context of the continuous improvement of legislative structures, which is directly conditioned by the development of various sciences, not only legal ones (Joldžić, 2021b).

Regulation in the field of occupational safety and health in the Republic of Serbia represents a system of legal norms and provisions that define the rights and obligations of employers and employees in ensuring safe and healthy working conditions. This regulatory framework is based on laws, bylaws, national strategies, and international conventions ratified by the Republic of Serbia. The primary and overarching legal act in this field is the Law on Occupational Safety and Health (2023). This relatively recent law is accompanied by a number of bylaws, primarily rulebooks and decrees, which regulate procedures such as risk assessment, safety in construction, protection when working with hazardous substances, protection from workplace noise, radiation protection, and others.

The legal framework of the Republic of Serbia in this area is subject to dynamic changes, and occupational safety experts are expected to continuously and actively monitor these developments. In this context, an important question arises as to whether, and to what extent, changes in regulation influence awareness of occupational safety and health, or whether additional mechanisms and the involvement of other scientific disciplines are necessary to shape awareness and, consequently, the behavior of stakeholders within the occupational safety and health system.

SAFETY CULTURE AS A FACTOR IN THE PREVENTION OF OCCUPATIONAL INJURIES

Safety, as a concept, encompasses a function, organization, condition, and perception that enable the uninterrupted functioning of business systems without the risk of disruption due to injuries or other hazards. A safety system is designed to protect people, property, and business processes from unauthorized access, damage, injuries, and illnesses (Živković, Rađenović, 2025).

The objectives of occupational safety and health are multifaceted and include various aspects of the work environment, employee health, and the improvement of working conditions. These objectives can be observed through several key areas (Kineber et al., 2023). The prevention of occupational injuries implies avoiding injuries that may occur as a result of work activities. This includes the implementation of measures such as adequate training, the use of personal protective equipment, and regular health check-ups for employees.

In this regard, factors influencing the occurrence of occupational injuries can be divided into objective and subjective factors (Živković, Todorović, 2018). Objective factors include physical factors (work environment: type of work, lighting, temperature, noise, workload, and work pace; equipment and tools), social factors (socio-psychological climate, communication), and organizational factors (work organization, safety culture, policies and procedures, employee training). Subjective factors include human factors (education, abilities, fatigue, health condition of employees, employee behavior, issues related to specific abilities, emotional factors), psychological factors (motivation and job satisfaction, risk perception), and socio-demographic factors (age, background, experience, gender, years of service, habits, prejudices).

Errors and accidents often occur due to subjective factors such as insufficient employee preparation, lack of appropriate knowledge and habits, or inadequate levels of such knowledge and habits, a mismatch between individual psychological characteristics and job requirements (i.e., low professional competence), indiscipline and negligence shaped by attitudes toward work, temporary reductions in work capacity due to illness or fatigue, adverse working conditions (cold, heat, lack of oxygen, glare), and inherent dynamics in the development of work habits (Mihailović, 2010).

One of the important subjective factors contributing to occupational injuries is risk perception (Rundmo, 1996). It refers to how employees assess hazards in their work environment and how this assessment influences their safety-related behavior. The way employees respond to risk depends on how serious they perceive its consequences to be. If they perceive the risk as high, they are more likely to take precautionary measures. However, if they perceive the risk as low, they may be more inclined to ignore safety measures, thereby increasing the likelihood of accidents (Harris, Hahn, 2011).

Closely related to the concept of safety is the concept of safety culture. It refers to the collective values, attitudes, perceptions, and behaviors related to safety shared by individuals within an organization, encompassing organizational commitment to safety and practices that ensure the prevention of accidents and incidents. Safety culture can be understood as a product of individual and group values, attitudes, perceptions, and behavior patterns that determine how an organization approaches safety (Lee, Harrison, 2000; Cole, Stevens-Adams, Wenner, 2013).

Safety culture is primarily people-oriented and focuses on their understanding of what safety is, why it is important, and how to act in ways that ensure safety (Fahim, 2018). Every organization possesses some form of safety culture, whether strong or weak. Safety culture is particularly important because people often represent the weakest link in any system.

From a psychological perspective, safety culture emphasizes individual and group attitudes toward risk, safety communication, and management commitment to safety. Research highlights the importance of psychological climate—how employees perceive safety-related aspects of their work environment—and its influence on safety behaviors and outcomes. In contrast, the engineering approach focuses more on formal and managerial aspects and systems affecting safety. This approach tends to be more practical and oriented toward change and improvement of occupational safety and health performance, with the aim of creating a safer work environment. It focuses on structural and procedural aspects of safety management. Defining safety culture therefore requires a combination of psychological and engineering perspectives, where understanding human behavior and ensuring reliable safety systems are equally prioritized to create a safe working environment (Guldenmund, 2000; Živković, Todorović, 2018).

Changing safety culture requires the engagement of all members of an organization. Changes are necessary at both employee and managerial levels, as safety culture shapes attitudes, values, and behavioral norms (Anderson, Lorber, 2006). The issue of responsibility for initiating changes in safety culture is crucial when examining who drives transformations within the occupational safety system. Responsibility primarily lies with the employer, i.e., management and leadership, as they play a key role in shaping organizational values and leading change processes. Effective leadership, combined with clear communication and employee engagement, is essential for adopting a new safety culture (Johnson, 2011; Reader,

O'Connor, 2014; Hochberg, Merkeley, Fahey, Shah, 2019). This is equally applicable in the context of safety culture in occupational safety and health.

CONCLUSION

This paper integrates concepts and notions in the field of occupational safety and health that may initially appear unrelated—safety culture and legal regulation. However, through the analysis of relevant scientific literature, it has been concluded that these concepts are interdependent and strongly interconnected.

Thus, the foundation of this study is the concept of occupational safety and health in terms of linking safety culture and legal regulation in this field. The starting assumption was that both safety culture and legal regulation are key factors in the prevention of occupational injuries and that they complement each other. Based on this premise, several conclusions can be drawn.

Both legal regulation and the development of safety culture play a significant role in preventing occupational injuries, which directly corresponds to prevention as a strategic objective of the occupational safety and health system of the Republic of Serbia, as defined in the Occupational Safety and Health Strategy (2024). Occupational injuries cannot be viewed solely as a consequence of non-compliance with regulations or individual employee errors, but rather as the result of a complex interaction between legal regulation and safety culture within an organization. Although the legal framework represents a necessary foundation for establishing an occupational safety and health system, its effectiveness largely depends on consistent implementation, enforcement, and the willingness of organizations to integrate it into everyday practice.

A well-developed safety culture plays a crucial role in injury prevention, as it influences attitudes, behavior, and the level of responsibility of all employees, including management. Organizations that foster open communication, continuous education, and active employee participation in safety-related matters achieve significantly better results in reducing the risk of occupational injuries.

In conclusion, it can be emphasized that improving occupational safety and health requires an integrated approach that ensures alignment and synergy between legal regulation and safety culture. Only through a combination of normative measures and the development of awareness regarding the importance of safe behavior is it possible to achieve long-term and sustainable results in reducing occupational injuries.

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DESIGNING ACOUSTIC COMFORT IN THE WORKING AND LIVING SPACE

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Abstract: Acoustic comfort in the context of the harmful effect of noise on human health in an industrial or residential area of a residential building, if analyzed based on the definition of the World Health Organization (WHO), according to which health is "a state of complete physical, spiritual and social comfort". Essentially, health action does not mean only physical damage to health, but also impaired subjective comfort, which in a long period of damage can lead to physical damage to health.

This paper presents a view of one position to improve the process of establishing evidence of noise exposure in the environment of an industrial or residential building and to contribute to a more objective presentation of evidence on the consequences of disturbing acoustic comfort with content that violates privacy and human health.

The growing influx of complaints about the phenomenon of noise in the environment, as well as its impact on mental and physical health, requires a higher level of professional attitude towards a complex multi-dimensional problem and a layered analysis of the spectrum of negative effects that imply auditory and extra-auditory disturbances, above all the disruption of cognitive activities and sleep function. Achieving acoustic comfort is a complex, multi-functional problem, which includes numerous external and architectural factors such as purpose of space, nature of noise in the environment, acoustic performance of building structures and materials.

Keywords: *Noise; acoustic comfort; user satisfaction; public health.*

INTRODUCTION

The concept of working and living space, in the context of acoustic comfort, does not fundamentally differ, although the time of occupation and activities of a mental or physical nature differ significantly. An industrial facility is understood to mean a facility or its parts, which are used for production (production, processing, refining, preparation of production technology, control, distribution, etc.), handy storage of raw materials, semi-finished products, products, tools and auxiliary materials, storage of non-combustible goods in non-combustible packaging, associated side rooms and similar parts - all in the function of production. Industrial construction is a specialized field of construction that focuses on the design, development and construction of facilities intended for industrial use. These facilities include factories, production halls, warehouses, distribution centers, refineries, power plants, waste

processing facilities, logistics centers and other facilities that support industrial processes and production activities. Industrial construction requires cooperation between various professionals, including architects, engineers, builders, occupational health and safety experts, environmental protection experts and other professions in accordance with the purpose.. Precise planning, coordination and execution are key to the successful construction of industrial facilities that meet customer requirements and industry standards.

As a rule, industrial facilities are designed in such a way as to enable the efficient and smooth running of production processes. This includes a thoughtful layout of rooms, appropriate routes for transporting materials, installations for the distribution of energy, water, gas and other working fluids. Modern industrial construction increasingly emphasizes energy efficiency and sustainability. This includes the use of energy-efficient heating, cooling and ventilation systems, insulation, renewable energy sources and other sustainable practices. In addition, the industrial facility must comply with environmental protection requirements, current regulations and standards. These include measures to reduce emissions, waste management, protection of visible resources as well as other measures that reduce the negative impact on the environment. Unfortunately, nowhere did I come across an explicit request for adequate sound protection of the working environment or the environment, although positive regulation and how it treats the phenomenon of noise at the international and national level.

When it comes to the construction of living space in residential buildings, the situation is not significantly different, although the requirements are significantly different. Providing living space in a residential building is a matter of choice: location, apartment size, spatial orientation, construction method, etc. Apartment buyers are ready to pay significant sums of money for their living space and rightly expect high quality in return. Unfortunately, buyers of new apartments complain the most about acoustic comfort. How to prevent this practice, and what to do if you have already moved into a noisy apartment? Objectively, numerous examples of "bad practice" are known where buyers only noticed all construction defects hidden under the luxurious surface after moving in. Comments are heard every day: *"I paid thousands of euros for a square meter and I hear my neighbor talking on the phone, snoring while sleeping, how many times he uses the toilet during the night, etc."*

The terminological explanation of the term "*acoustic comfort*" is based on the meaning of the term "*comfort*" which implies comfort, ease and everything that makes life comfortable and pleasant. What is actually "*acoustic comfort*", when objectively there are several types of comfort when it comes to ambient space. The answer could be derived from the Rulebook on Energy Efficiency of Buildings, which considers potential comfort conditions necessary for living comfort, and consists of four basic prerequisites: thermal, air, visual and acoustic comfort. According to the stated position, acoustic comfort represents conditions in which the level of noise in the living space is such that it does not cause a feeling of discomfort. Good acoustic comfort does not mean achieving complete silence in the housing unit, which in itself can often be unpleasant, but achieving an acceptable level of noise from the outside environment and the immediate environment. In other words, the sounds coming from the

surroundings, corridors, neighboring rooms or the outside environment must be reduced to a level that must not in any way disturb privacy and the daily rhythm of life..

The increased demands of buyers and users of real estate, not only in terms of reducing noise from the environment, as well as from installations in the building, have led to the fact that the question of the quality of sound insulation in the environment of "*living or working space*" is being raised more and more often. Achieving the required level of acoustic comfort is a technologically complex task, which includes numerous external and architectural factors: the purpose of the construction object, the acoustic zone of the location, the spectral content of noise in the environment, the use of building systems and materials, the design skills in the materialization of these requirements, the implementation and observance of standards in order to satisfy the comfort needs of the users of the ambient space.

In practice, unfortunately, providing adequate acoustic comfort is not in the interest of the entities that define the construction conditions, but it is in the investor's interest. In the case of the former, the reason is lack of expertise and insufficient knowledge of the problem, and in the case of others, it is material interest, because acoustic quality costs money. Acoustic comfort is defined as a psychophysical state in which a person, in a certain environment, has a sense of well-being in relation to a certain activity that he has, which implies:

- **Protection against noise**, because noise is defined as any unwanted sound, so acoustic comfort means providing protection against interference with sound originating from sources outside the building and inside the building;
- **Protection of privacy**, because it implies the provision of protection against eavesdropping between rooms, that is, spaces; and
- **Adequate quality of the desired sound content**, which means ensuring adequate acoustic quality of rooms or spaces in accordance with the requirements of the quality of the sound image (intelligibility and aesthetics).

Unfortunately, in practice, it usually happens that solutions for acoustic defects when it comes to public spaces: offices, meeting rooms, hospitals, schools, children's institutions, etc. they only look for it when the object is finished and when the acoustic defects are felt in the interaction with the space in the phase of use.

THE IMPORTANCE OF ACOUSTIC COMFORT

Noise as a phenomenon of acoustic activity unequivocally has a negative impact on human health and well-being, and at the same time it encourages the scientific and professional public to be more and more concerned in the search for acceptable solutions in protection. The latest report of the European Environment Agency (EEA)[1] confirms that exposure to noise has an important impact on people's mental and physical well-being. It is estimated that noise pollution affects at least 20% of the European population living in urban areas where the level of noise generated by traffic (road, rail and airplane) is harmful to people's health. It is

also estimated that in Europe over 113 million people are exposed to long-term noise levels from road traffic during the day and night period (Lden), with a value of at least 55dB. To this data should be added the fact that in Europe, according to estimates from 2020, 80% of citizens live in or near cities. [2] with increased demand for road, rail and air transport. Simultaneously with the increase in noise sources, one can expect increased exposure and associated adverse health effects. Noise was found to be the cause: 48,000 cases of chemical heart disease, 12,000 cases of premature death. According to estimates from the EEA - European Environment Agency report, 12,500 European students suffer from learning disabilities resulting from noise generated by air traffic. Seen through the prism of time and the activities undertaken, the number of people exposed to noise sources has been stable from 2012 to the present day, which can be judged that the main goal of the vision of the Environmental Noise Directive 2002/49/EC for the year 2020, "that no person should be exposed to a level of noise that can endanger health and quality of life", has not been achieved“.

Sources from the literature studied for the purposes of this paper suggest that there are four key non-physical factors that influence the perception of noise in the environment [3]: - work activity; context and attitude; perceived control and predictability; personality and mood. The interpretation of the sound that has taken on the phenomenon of "**noise**" depends on the personality and a number of other dependent factors and circumstances. This means that individual people will react differently to the same acoustic challenges in their environment, which is another reason for layered consideration of noise disturbance and valuing individual differences in the context of acoustic content in order to reach the required level of "*acoustic comfort*".

Making a conclusion about the harmfulness of noise to human health must first take into account the sensitivity to noise, which is based on general attitudes about noise [4,5], and is an important variable to explain the discrepancy between exposure and individual anxiety response. This fact raises the question of whether individuals who are sensitive to noise are simply those who complain more about their environment.

Health as a valuable asset is worthy of legal protection, and that is why it is the duty of the national legislation to regulate the obligations related to sound insulation, which is a prerequisite for acceptable "*acoustic comfort*", by law and under legal regulations. In the comments of the legal doctrine, it is stated, among other things:

That the intimate area is specially protected, which includes the sphere of human life characterized by great isolation from the engagement of other people (with the exception of family).

That the apartment in the narrower sense is part of the private, intimate sphere. Bearing this in mind, the need for the inviolability of the home to be a right that aims to guarantee the

individual "elementary quality of living space", the right "to enjoy peace", in terms of his human dignity and in the interest of personal free development.

When it comes to ambient comfort: *"The building must be designed and built so that the noise felt by the tenants or people nearby is maintained at a level that is not dangerous to health and in which satisfactory conditions are provided for night rest, leisure and work."* Acoustic comfort in buildings is achieved if unwanted sounds (noise) are not noticed, if people's privacy is ensured, which means that their activities cannot be heard by the environment, and if everything that is wanted to be heard, for example speech, is effortlessly recognized and understood (when desired) [6, 7]. In order to achieve this, construction objects must be provided with their physical properties and materialization:

adequate sound insulation from airborne and structural sound inside the building,

adequate insulation of the facade, which ensures an acceptable level of ambient noise coming from the outside environment,

a system of installations in the building that does not produce noise and does not impair other measures to achieve sound comfort,

privacy in areas where it is necessary,

adequate acoustic response of interior spaces that determines the sensibility and quality of useful sounds.

The objectification of "acoustic comfort", which at its root has a very pronounced subjective component, must rely on standards and respect for construction technology (selection of location, purpose of the building, materialization of the architectural project, control over construction processes) in order to increase the level of satisfaction.

STANDARDS IN THE FUNCTION OF ACOUSTIC COMFORT

In today's living conditions and accompanying risks highlighted in the introduction of this paper, "acoustic comfort" has become an unavoidable segment of our reality, especially in the spaces where we spend the most time, the place where we live or work (apartment or office). It is not a rare case that being in an office, restaurant, hospital, hotel, industrial plant, cinema, swimming pool, kindergarten or your child's school is a place where the acoustic content in the environment did not please you and you experienced it as noise [8]. This can be especially important in different environments such as offices, classrooms, restaurants, concert halls, hospitals or homes. Maintaining acoustic comfort can involve the application of various techniques such as the use of acoustic materials, designing spaces with optimal acoustic properties, using sound insulation systems or implementing noise reduction strategies.

Sound insulation standardization is a key element in ensuring "acoustic comfort" - sound quality in construction projects. International organizations for standardization (ISO, EN) as

well as national institutions of the most developed countries in Europe create the necessary but not sufficient conditions for achieving the ultimate goal of complete acoustic comfort:

- **DIN** - "*Deutsches Institut für Normung*"; Sound insulation is considered in DIN standards through various aspects to ensure that buildings and building materials meet certain standards for noise protection. The first version of the standard sheet DIN 4109 "*Sound insulation in construction*", provides the basis for the calculation and gives the minimum specifications for sound insulation. The main goal is health protection [9]. However, this is often not enough in terms of today's user requirements, behavior and lifestyle.

- **VDI** - „*Verein Deutscher Ingenieure*“, is an association of German engineers that also develops technical guidelines and standards, similar to the German Institute for Standardization (DIN). One of the most important VDI standards related to acoustics in buildings is VDI 4100. This standard covers various aspects of acoustics in buildings, including design and measurement of sound insulation, noise control in interior spaces, as well as criteria for assessing acoustic comfort.

- **DEGA** - The German Society for Acoustics, "*Deutsche Gesellschaft für Akustik*", carries out accreditation or certification that confirms that a product or service meets certain standards in the field of acoustics. Their standards and guidelines are often used in the industry to ensure acoustic quality in various environments, such as music rooms, concert halls, offices, or industrial spaces.

- **AFNOR** - "*Association Française de Normalisation*". One of the most famous French standards related to sound insulation is NF S 31-080: This standard specifies methods for measuring the sound insulation of walls, floors and ceilings in buildings. It also provides guidelines for the design and installation of materials and structures to achieve appropriate levels of sound insulation. NF EN ISO 717; NF EN ISO 14; a series of standards defines the procedure for measuring sound insulation of walls, floors and ceilings in buildings. These standards are in line with international ISO standards and are often used in French construction projects.

- **BSI** - "*British Standards Institution*" is the institution from which the most famous standards for sound insulation originate. BS 8233: a standard that provides guidance on the design of sound insulation in buildings to ensure a comfortable environment for occupants. It includes factors such as external noise, internal noise, vibration and acoustic comfort. BS 6472: standard specifies procedures for measuring vibrations transmitted through ground and structures in buildings. Vibrations can be a source of discomfort and disturbance, so their measurement and control is important to maintain acoustic comfort.

- **BREEAM** – „*Building Research Establishment Environmental Assessment Method*“ is a building sustainability rating system used worldwide to assess the environmental performance of construction projects. BREEAM, as a building sustainability rating system, also considers acoustic comfort as part of its rating criteria. Acoustic comfort plays an important role in the

quality of life of building users, so it is important to take this area into account when designing, constructing and managing buildings.

In our country, the Institute for Standardization of Serbia is a national standardization body, which, among other things, adopts, develops, reviews, changes, supplements and withdraws Serbian standards and related documents; ensures compliance of Serbian standards and related documents with European and international standards and related documents.

In the field U 043 "acoustics in construction", the current number of standards that are available to the public is 151, (published standards, standards for which the review procedure has been completed, and standards for which the review procedure has begun), and the number of new projects is 8 (eight).

The existence of standards created the conditions for design, execution and control processes to be carried out without restrictions, for sound insulation to be performed in accordance with the recognized rules of construction technology and in a way that guarantees that "air and structural" sound insulation in and around buildings is a reliable guarantor of "acoustic comfort" in the interest of protecting the health of users. Unfortunately, one gets the impression that listening to the ambience of significant architectural achievements, that the materialization of the space was realized without a sense of how that space will sound and how many chances it will give us to enjoy it with all our senses.

By definition, a standard is a document that provides conditions, specifications, guidelines or characteristics that can be used to ensure that materials, products, processes and services are fit for purpose. Standards are established by consensus and approved by recognized bodies. *The application of Serbian standards is voluntary, which means that there is no automatic legal obligation to apply them. However, laws and technical regulations may refer to standards, making compliance with them mandatory.*

That the standard is necessary, but not decisive in reaching the goal, is evidenced by disputes regarding acoustic comfort and sound insulation as disputed facts. The update of DIN 4109 has no impact on current court practice. In support of the claim: The Federal Court of Justice (BGH - Bundesgerichtshof), in its judgment of June 14, 2007 - VII ZR 45/06, BG HZ 172, 346, does not base its judgment on the requirements for sound insulation according to DIN standards, but on the level of noise insulation agreed upon by the contracting parties. In the verdict BGH VII ZR 45/06 of 14.06.2007. the court's position is that: Requirements for sound insulation are subject to dynamic changes. On the one hand, they are based on people's current needs for peace and individual isolation in their own living space, and on the other, they depend on the ability of construction and the construction industry to provide the widest possible noise protection, taking into account the economic interests of both contracting parties.

The conclusion of the expert public is: The dimensions of sound insulation specified in private technical regulations cannot be used as recognized rules of technology if there are

economically acceptable construction methods that are in accordance with the recognized rules of technology and which easily achieve greater dimensions of sound insulation.

WHICH WAY TO SATISFACTION AND ACOUSTIC COMFORT

The fact that the national legislation, as well as the technical regulations, do not recognize the concept of "acoustic comfort", which does not mean that it is less important and that it cannot be the subject of consideration and dispute for the reason that the threat of noise in the work-living space is an undeniable fact, which is easily proven, and derives from the END - Environmental noise directive 2002/49/EC, the Law on Protection from Noise of the RS and other acts of positive law that deal with noise as a phenomenon, especially its subjective dimension.

Scientific experts emphasize the existence of four key non-physical factors that influence the perception of noise in the environment: - work activity; context and attitude; perceived control and predictability; personality and mood. The interpretation of a sound as "noise" depends on personality and a number of other factors and circumstances. This means that individual people will react differently to the same acoustic challenges in their environment [10]. This is another reason for looking at noise disturbance in layers and valuing individual differences, through the context of acoustic content.

On the basis of my personal, scientifically professional knowledge and skills in relation to noise in the environment, after studying the contents of documents from the literature [11, 12], the experience achieved in improving acoustic comfort in accordance with the explicit requirement of the civilized needs of users in the environment of the living space in relation to the existing practice, I impose lines of thinking:

The expected level of acoustic comfort depends on the precision of the agreed level of sound insulation from noise between the designer-contractor and the client.

Compliance with the minimum sound insulation standards is not sufficient in the civil law sense, but only the construction works performed at the time of acceptance, which corresponds to judicial practice.

Responsibility for an inadequate level of acoustic comfort cannot be avoided, regardless of the fact that in the chain from the purchase contract to the handover of the building, omissions are made in the interest of the investor, and to the detriment of the user.

The only question is, which mechanisms in construction have lost their function and how to assign a management structure to them in order to transform an inert system from a "pathological" into a proactive construction system that seeks the interests of the customer. Therefore, it is a rational dilemma, what is the role of the "coordinator for safety and health at work in the project development phase" if he does not recognize the risk factors in the facility being built in the Plan of preventive measures for safety and health at work. The Law on Planning and Construction in Article 3a requires: "*Technical documentation ensures that the*

*facility as a whole, that is, in each separate part, is suitable for the intended use, as well as that during the economically acceptable period of use, the facility meets the following basic requirements: item 5. **noise** protection."*

How to explain the fact that in the first step of the project implementation, the investor is not informed in the "*Information on the location for the cadastral plot*" by the competent local government body on whose territory the construction of the building is planned, in which acoustic zone the cadastral plot is located, even though each local community as a subject of environmental protection against noise is obliged to carry out: acoustic zoning, determine quiet zones, as well as prohibiting and limiting measures in its territory and this by decision of the competent authority, in accordance with the Law;

How to explain the fact that the project for obtaining a building permit does not contain an Elaboration on the sound protection of the building, and when it is a school, kindergarten, home for the elderly, hospital, etc. and can be located in one of the five acoustic zones, which certainly results from the provisions of the Law on Planning and Construction.

How to explain the fact that in the overall documentation from the conceptual project to the finished project, there is not a single detail that considers any acoustic problem, and the same object is subject to acoustic tests. On the other hand, how to prove that the noise problem has been treated, if there are no valid records in the project and construction documentation.

With the legalization of the JUS U J6 201 standard ("sl. list SFRJ", no. 21/90) in the Rulebook on technical norms for the design and execution of final works in construction, catches were created to make the essence of the standard mandatory:

"This standard establishes the technical conditions that must be met: a) during design, b) during construction or reconstruction, c) when testing sound protection during the reception of buildings intended for human habitation.

The provisions of this standard are also applied to the reconstructed parts of the building, as well as to rooms whose purpose has been changed")

Realistically, today, after 34 years, there is no trace of such an obligation in Serbian construction. This situation deterred many institutions from accrediting the method for field measurement of sound insulation, even though they invested significant funds for the purchase of rather expensive equipment, for staff training and accreditation. And that's not the end, on August 25, 2015, a Decision was signed by the Deputy Prime Minister on "A working group is being formed to draft a proposal for a regulation on sound comfort in buildings (hereinafter: Working Group) composed of:" but there is no Regulation.

Unlike other engineering disciplines in the design process, regulations based on standards cannot be an absolute guide for all details important for sound comfort. It is expected that the user of the living space has the right to demand the desired level of sound comfort, from the minimum prescribed. This naturally follows the task of the designer to seek the help of an acoustic consultant

to unify and optimize requirements in the initial design phase in order to achieve a successful design outcome, to the satisfaction of users and investors.

INSTEAD OF CONCLUSION

It is a logical expectation that just as the user chooses the quality of ceramics in the bathroom or the size of the apartment, the investor should also determine the level of construction from the aspect of sound comfort in the same way. In support of this statement is the fact of intensive housing construction in the last ten years, as well as the way of life, so sound comfort has become a serious design, engineering, scientific-professional, economic and sociological challenge.

Acoustics, as one of the engineering disciplines in the design and construction of buildings, has the task of ensuring the expected level of sound comfort in the built space. That specific type of comfort has several dimensions:

- that a person in the working and living environment is not disturbed by sounds coming from the outside environment and from neighboring rooms, as well as that the sounds he produces do not disturb other people in and around the building. In this way, the desired and necessary privacy is ensured.
- to enable quality sound communication in rooms where necessary, which implies good intelligibility and audibility of speech and music.

Unlike other engineering disciplines in the design process, regulations based on standards cannot be an absolute guide for all details important for sound comfort. It is expected that the customer has the right to demand a sound comfort level higher than the minimum prescribed by the regulation. This naturally follows the designer's task to seek the help of an acoustic consultant to consolidate and optimize the requirements in the initial design phase in order to achieve a successful design outcome, to the satisfaction of users and investors.

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ASSESSING 'REAL WORLD' RISK: OVERVIEW OF CUMULATIVE RISK ASSESSMENT

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Abstract: The rapid expansion of chemical production and use in the twenty-first century has led to increasingly complex exposure scenarios, particularly in occupational settings where workers are routinely exposed to multiple chemical and non-chemical stressors. Traditional risk assessment approaches, based on evaluating individual substances against occupational exposure limits (OELs), are insufficient to capture the realities of combined exposures. This paper examines the concept of cumulative risk assessment (CRA) as a more comprehensive framework for evaluating health risks arising from simultaneous or sequential exposure to mixtures of chemical, physical, and psychosocial agents. CRA integrates multiple exposure routes and considers interactions such as additive, synergistic, or antagonistic effects, which may result in adverse outcomes even when individual exposures remain below established thresholds. Special attention is given to chemical mixtures, whose combined effects remain one of the major uncertainties in toxicology, as well as to non-chemical stressors such as noise and psychosocial stress, which can increase individual susceptibility through mechanisms such as allostatic load. The paper highlights practical challenges in occupational settings, including limitations in experimental data, difficulties in identifying appropriate biomarkers, and the complexity of incorporating lifestyle and individual variability into assessments.

Keywords: Cumulative risk assessment (CRA), Chemical mixtures, Occupational exposure

INTRODUCTION

Life in the twenty-first century, alongside remarkable technological progress, has also brought a dramatic increase in both the number and volume of chemical substances that are synthesized and intentionally or unintentionally released into the environment as products of natural and anthropogenic activities. All biological systems are continuously exposed to complex combinations of chemicals, primarily through air, water, and food. In the context of occupational health and safety, the rapid technological development has been accompanied by a substantial expansion in the production and use of chemical substances across industrial sectors. Large numbers of chemicals are synthesized, processed, transported, and applied in workplaces, where they may be intentionally used as raw materials, intermediates, or finished products, or unintentionally generated as by-products of technological processes. As a result, working populations represent one of the groups most intensively and systematically exposed to chemical agents.

From Risk to Cumulative Risk

Toxicology has evolved into a "risk assessment" discipline aimed at protecting and maintaining human and environmental health. Historically, the concept of poison has been known since ancient times, and the science of toxicology has evolved over centuries. In the 16th century, Paracelsus emphasized the importance of dose in the response; however, today, the concept of response is examined at the molecular level, investigating micro-responses such as identifying changes in RNA expression. On the other hand, the traditional approach to risk assessment, which focused on evaluating the risks of each chemical or physical agent independently and individually, has been found insufficient in addressing the "real world's" needs nowadays (Yeşil, 2022).

Hazard refers to an agent's ability to cause adverse effects, while risk refers to the probability of this hazard occurring under specific exposure conditions. Risk assessment itself is a structured, science-based, multi-step process aimed at estimating the likelihood of adverse effects under defined exposure conditions. The four fundamental components of the risk assessment process are hazard identification, hazard characterization (determining dose-response relationships), exposure assessment, and finally, risk characterization, with exposure assessment being a critical step (Faustman and Omenn, 2010).

The synthesis, production, and use of new chemicals have been increasing logarithmically worldwide. Workers may encounter complex combinations of substances through inhalation of contaminated air, dermal contact with liquids and dust, or, less frequently, inadvertent ingestion (Anderson and Meade, 2014). In addition to occupational exposure, individuals are simultaneously exposed to chemicals in the general environment and through consumer products such as pharmaceuticals, cosmetics and various everyday products. Historically, occupational contamination was often associated with a limited number of well-defined hazards present at relatively high concentrations within specific industries. In contrast, contemporary workplaces are characterized by a broader spectrum of chemical agents, frequently present at lower concentrations but in diverse and variable combinations, reflecting the globalized and highly dynamic nature of modern production systems (EPA, 2025). Moreover, it is common to be exposed to the same agent through different sources and routes (aggregate exposure). Socioeconomic factors and related psychosocial stress also complicate risk assessment by increasing the vulnerability of certain populations to adverse effects. As a result, regulatory authorities are under pressure to take a broader approach to public health, considering chemical and non-chemical risks, vulnerable populations, and multiple exposure routes. They are making efforts to advance traditional risk assessment approaches (Sexton, 2012). In this new holistic approach, termed cumulative risk assessment, cumulative risk is defined as the combined risk resulting from aggregate exposure to multiple chemical, biological, or physical agents. Cumulative risk assessment thus involves analyzing, characterizing, and potentially measuring the cumulative risk to human and environmental health (EPA, 2003).

Occupational risk reality

From an occupational health perspective, assessing the toxicological implications of all possible combinations of chemicals encountered in the workplace is practically impossible. Experimental evaluation of even a small number of co-exposures is technically and resource demanding. For this reason, occupational exposure assessment and regulatory frameworks have traditionally relied on evaluations of individual substances, typically through the establishment of occupational exposure limits (OELs). However, real-world occupational settings rarely involve exposure to a single chemical. Workers are commonly exposed to multiple agents simultaneously or sequentially, often through more than one route of entry into the body (Dinca et al., 2023).

Within occupational health science, such scenarios are described using the concept of a “chemical mixture,” referring to the co-occurrence of two or more substances that may collectively contribute to adverse health outcomes in exposed workers (Wilbur et al., 2004). Some mixtures are intentionally formulated and used as such, for example, certain pesticide products, cleaning agents, coatings, or metalworking fluids. More frequently, however, workers are exposed to unintentional mixtures generated during production processes, combustion, welding, painting, or other industrial activities. These mixtures are often variable in composition and may include constituents originating from different raw materials, intermediates, degradation products, or environmental contaminants (Bloch et al., 2023).

In the field of occupational health and safety, recognizing and appropriately managing exposure to chemical mixtures is therefore essential. Focusing solely on single-substance assessments may underestimate the actual health risks present in complex work environments, where combined exposures represent the rule rather than the exception (EPA, 2003).

Chemical mixtures represent one of the greatest unknowns in toxicology. They may be classified according to the mode of action of their components. One category includes mixtures whose constituents share the same or a similar mechanism of action. Examples include polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and organophosphate pesticides. Because these substances act through comparable biological pathways, it is generally assumed that each component contributes to the overall toxic effect, even when present at concentrations below its individual no observed adverse effect level (NOAEL) (Bloch et al., 2023). In contrast, other mixtures consist of chemicals that act on different molecular targets within the organism. For many years, scientific debate has addressed whether simultaneous exposure to multiple substances with different mechanisms of action, each at doses below its NOAEL, poses a health risk. Opinions have ranged from the view that low-level environmental mixtures may significantly affect human health, to the assertion that mixtures composed of substances below their NOAEL values are unlikely to present any risk (Carpy et al., 2000). Nevertheless, accumulating empirical evidence indicates that exposure to mixtures containing chemicals at individually non-toxic levels may still result

in adverse outcomes, even when the components do not share the same mechanism of action (Bloch et al., 2023). For this reason, the health implications of chemical “cocktails” remain an important and unresolved issue in toxicological research, underscoring the non-negligible impact of combined exposures on human health.

In addition to the uncertainty surrounding chemical mixtures, the combined effects of biological and physical agents, along with psychosocial stress, remain significant unknowns, necessitating the development of methodologies to assess their impacts (Lewis et al., 2011). Regardless of whether chemicals share similar or distinct mechanisms of action, they may interact in ways that enhance (synergism or potentiation) or diminish (antagonism or inhibition) each other’s biological effects (Klaassen, 2018). Different factors can lead to a common risk through different mechanisms of action or through independent mechanisms of action. Understanding or measuring the individual contributions of an agent in simultaneous exposure is one of the foremost challenges. In some cases, the combined effect is additive, meaning that each substance acts independently and the overall response corresponds to the sum of individual effects. However, chemicals may also interact in less predictable ways, leading to responses that are either weaker or stronger than those anticipated under a simple additive model. Failure to adequately account for such interactions represents one of the main limitations of additive approaches in mixture risk assessment, whether applied to substances with similar or dissimilar mechanisms of action.

Other significant limitations in measuring cumulative risk include the determination of endpoints and biomarkers, as well as considering different sources in multi-exposure (aggregate) scenarios (Rider et al., 2014). As can be seen, the nature of cumulative risk assessment is extremely complex, and crafting an effective evaluation framework necessitates a collective scientific consensus on effective solutions at each stage of the assessment where the traditional approach has been inadequate, as well as good problem formulation. Over the past 20 years and still today, regulatory authorities, industry and researchers have been working towards developing cumulative risk assessment methodologies.

Cumulative risk in occupational settings

In occupational practice, identified hazards are generally assessed separately by comparing measured exposure levels with the relevant occupational exposure limits (OELs) or other health-based reference values. Systematic evaluation of the combined risk arising from simultaneous exposure to multiple stressors, whether occupational or non-occupational, is still uncommon (Niemeier et al., 2020). Moreover, individual or lifestyle-related factors that may influence the effects of workplace exposures (age, sex, obesity, smoking, alcohol intake, physical and mental health status, the use of prescribed pharmaceuticals, drug abuse or nutritional status) are rarely incorporated into standard occupational risk assessments (Schulte et al., 2012). Consequently, there is a clear need for structured guidance on how to identify, assess, and manage complex multi-exposure scenarios in occupational environments.

Two key elements distinguish cumulative risk assessment. First, the assessment must include at least two chemical and/or non-chemical stressors, across all relevant exposure routes, that contribute to a common health outcome, whether through similar or different biological mechanisms. Second, the overall health impact of concurrent exposures must be characterized in an integrated manner (EPA, 2007).

A widely used method for evaluating cumulative occupational risk involves the application of occupational exposure limit (OEL) mixture principles. When workers are exposed to two or more substances that produce similar toxicological outcomes—meaning they affect the same target organ or physiological system—each exposure is first expressed as a ratio of the measured concentration to its respective OEL. These individual ratios are then summed to estimate overall hazard (Niemeier et al., 2020).

The general form of the Threshold Limit Value® (TLV®) mixture calculation is (Equation 1) (Niemeier et al., 2020):

$$\text{Mixture} = C_1/T_1 + C_2/T_2 + C_3/T_3 + \dots + C_n/T_n \quad (1)$$

where: C_n represents the measured exposure concentration of a given substance; T_n represents the corresponding TLV® for that substance.

Although the result does not represent a strict cutoff, a summed value below 1 is generally interpreted as unlikely to present a health concern for most workers, whereas a value exceeding 1 suggests an increased probability of adverse effects. This approach is particularly important because individual substances may each be present at levels below their respective exposure limits, yet their combined effect may surpass an acceptable threshold when evaluated collectively (Bloch et al., 2023).

As an illustration, in an automotive paint shop, workers may be exposed simultaneously to two aromatic solvents, toluene and ethylbenzene, both of which act as organic solvents and share the same critical health effect, namely central nervous system (CNS) depression. Due to their similar mode of action, involving disruption of neuronal membrane function as a consequence of their lipophilic properties, their effects can be considered dose additive. According to Serbian occupational exposure limits, the GVI for Toluene is 50 ppm, while for Ethylbenzene it is 100 ppm. If an 8-hour time-weighted average exposure is 12 ppm for toluene and 85 ppm for ethylbenzene, the individual exposure ratios would be 0.24 for toluene (12/50) and 0.85 for ethylbenzene (85/100), both below their respective limit values (Official Gazette of the Republic of Serbia, 2021). However, when assessed using the hazard index approach, the sum of the ratios is 1.09, exceeding 1 and indicating that, although each solvent individually complies with its occupational exposure limit, the combined exposure may still pose a potential health risk to workers.

Workplace exposures to different chemical and non-chemical agents can lead to the same adverse health effect, and the combined impact of multiple exposures may be greater than

predicted when considering each agent separately, even under assumptions of additive effects. Classic examples include the elevated risk of lung cancer observed in individuals exposed both to asbestos and cigarette smoke (Liddell et al., 2002), as well as the increased potential for hearing impairment when workers experience both occupational noise and exposure to chemicals that are toxic to the auditory system, also called ototoxicants (Niemeier et al., 2020).

Research suggests that ongoing psychosocial stress can increase a person's vulnerability to the harmful effects of chemical and physical exposures. This heightened sensitivity is thought to arise through the accumulation of allostatic load, in which chronic stress disrupts immune, hormonal, and metabolic systems (van Huyssteen et al., 2025). Consequently, employees who experience persistent or high levels of stress at work may suffer greater adverse health effects from the same physical or chemical hazards than their less-stressed colleagues. Workplace psychosocial stressors currently lack formal occupational exposure limits. Stress is a non-specific, multi-system process driven by perception, and no single biomarker reliably reflects exposure or effect (Bamert et al., 2025). Assessing psychosocial stress is challenging because its impact varies between individuals, depending on how they perceive and respond to a stressor. Although some biomarkers, such as cortisol, are sometimes used to indicate stress, they are unreliable, especially under chronic conditions where hormone patterns may change. Despite these difficulties, psychosocial stress can influence workers' susceptibility to chemical and physical hazards, and its potential contribution to cumulative risk should be considered qualitatively in occupational risk assessments (Niemeier et al., 2020).

CONCLUSION

Cumulative Risk Assessment represents a crucial step in modern occupational risk evaluation, particularly in workplaces where employees are exposed to complex combinations of chemical and non-chemical agents. Traditional approaches, based on the assessment of individual substances against occupational exposure limits (OELs) or threshold limit values (TLVs), are insufficient to reflect real-world working conditions. Workers are frequently exposed simultaneously or sequentially to multiple agents, including chemical mixtures, physical stressors such as noise or heat, and psychosocial stressors, potentially resulting in cumulative effects that exceed the risks predicted from individual exposures.

In addition to chemical and physical agents, psychosocial stress is an increasingly relevant factor in cumulative risk assessment. Chronic stress can enhance worker susceptibility to harmful exposures through allostatic load, which disrupts immune, endocrine, and metabolic functions. Assessing psychosocial stress is challenging due to its subjective nature and lack of reliable biomarkers. Nevertheless, considering stress in cumulative risk evaluations can provide valuable insight into vulnerable populations and help identify workers who may require additional protective measures.

Overall, a holistic approach to occupational health, accounting for multiple exposure routes and combined effects, is essential. CRA provides a framework to identify, characterize, and, where feasible, quantify total risk from combined exposures. Its application allows regulators and employers to recognize situations where individual exposure limits may not fully capture risk, facilitating implementation of preventive measures that address both chemical and non-chemical stressors. Despite methodological and technical challenges, including assessing psychosocial stress and complex agent interactions, evidence indicates that cumulative exposure can substantially increase health risk. Continued research and development of CRA guidance are necessary to create safer and healthier workplaces that reflect realistic exposure scenarios and meet the needs of diverse worker populations.

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ASSESSMENT OF PROFESSIONAL RISK FOR FIREFIGHTERS DURING ELECTRIC VEHICLE FIRE EXTINGUISHING

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Abstract: Due to the increased number of electric vehicles (EVs), firefighting procedures and strategies for EV fires extinguishing are analysed in this paper. Besides environmental consequences, inhaling smoke, vapours and toxic gases, presence of various metals, as well as organic compounds and water soluble anions in soot and ash, pose potential danger for human health. The assessment of professional risk for firefighters is based on experimental results for toxic gases released during vehicle fire testing. Best-Worst Method (BWM), as a weighting method, is used to obtain weight coefficients for toxic gases based on their emissions (CO₂, CO, NO₂, HF, HCl, HCN) during vehicle fire tests and exposure limits for these gases. These are used as criteria for applying the PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations), as multi-criteria decision making method, to rank the vehicle fire hazard for firefighters and vehicle drivers.

Keywords: *Electric vehicles fires; Firefighter exposures; Occupational risk; Combustion products.*

INTRODUCTION

In 2023, transport participated with 32% of the final energy consumption in the EU, in which road transport was dominant with 73.4%. Gasoline and diesel fuel participate with nearly 90% in road transport energy, but the share of electric vehicles (EVs) is growing every year (Eurostat, 2025). Electric car sales exceeded 17 million globally in 2024, reaching a sales share of more than 20%, but internal combustion engine vehicles (ICEVs) are still dominant. Consequently, ICEV fires are more common than EVs fires.

ICEV fires can often be extinguished quickly once fuel is cut off. EV fires have greater intensity and burn longer than ICEVs because of sustained thermal runaway. Although EVs show much lower fire rates than ICEVs, they present greater challenges for firefighters with

long duration burning, dangerous toxic emissions, and severe insulation requirements. Standard extinguishing methods may fail as EV fires differ in several ways from ICEV fires. EV fires can reignite hours and days later, demand immersion or heavy water loads, and release harmful compounds and heavy metals. Because of these differences, EV fleet operators, recycling centres, and storage facilities face unique suppression challenges.

EV drivers should be familiar with the precautions to take in the event of a battery thermal overheating alarm. If sparks, smoke or flames appear from the vehicle, the driver should turn off the vehicle, exit the vehicle, move to a safe distance, and inform the fire department of the location and type of the vehicle: BEV (Battery EV), HEV (Hybrid EV), or PHEV (Plug-in Hybrid EV). The safest place for vehicle occupants is off the road and, if possible, uphill and upwind so to avoid inhaling smoke, vapours and gases that may be hazardous to human health (Figure 1).

A particular danger is the spread of EV fires in enclosed spaces (RISE, 2023) such as tunnels and multi-car parking garages. For fires in partially enclosed above-ground and underground garages, the necessary fire protection measures are: installed fire detection systems, fixed firefighting systems (FFFS), wider parking spaces, reduced fire cell sizes, water jets and smoke exhaust fans. In the event of a fire due to a collision in tunnels, stopping traffic is very important, as is the installation of a fire detection system, FFFS, marked fire routes, accessible portable extinguishers, emergency call systems and smoke exhaust fans.



Figure 1. Tesla Model S fire in Austria on October 17th, 2017 (Electrek, 2017)



Figure 2. EV-caused fire in the parking garage in Incheon, Korea (The Korea Times, 2024)

In the South Korean city of Incheon on August 5th, 2024, there was a huge fire caused by an electric car battery. The fire broke out on a Mercedes-Benz EQE car in the underground garage of the residential complex, and firefighters spent eight hours extinguishing the fire. 140 cars were destroyed and damaged, while 23 people were hospitalized due to smoke inhalation. The electricity also went out in the residential complex, so more than 120 people had to move to temporary shelters. Local authorities announced that the car was not connected

to the charger at the time of the fire. A surveillance camera captured the moment the fire broke out and the thick white smoke came out of the car (The Korea Times, 2024).

For fires in closed garages, the necessary fire protection measures are: installed fire detection systems, FFPS, wider parking spaces, hand-held extinguishers, maintenance and inspection of electrical installations, safe routes, safe charger design that prevents the use of faulty charging equipment, fire curtains, as well as smart parking management system in the garage (Artificial intelligence/machine learning based system - AI/ML system) that uses sensors, cameras and artificial intelligence to ensure safe distances between vehicles.

Due to the increased number of electric vehicles and more complicated fire extinguishing procedures, it is necessary to train firefighters for these interventions.

PROCEDURES IN CASE OF ELECTRIC VEHICLE FIRES

In extreme working conditions and in case of traffic accidents, batteries in electric vehicles (EVs) are subjected to different external influences: thermal, mechanical and electrical (Sun, 2020), (He, 2020). A battery monitoring system (BMS) monitors temperature and voltage to maintain optimal conditions. In the event of a failure in the BMS, batteries may overheat, burst, throw sparks, release flammable gases and toxic fumes, which can further lead to ignition and fire, throwing flames and gas explosions (Lecocq, 2012). Typical electric vehicle fires include: spontaneous combustion fires, fires during charging, traffic accident fires, re-ignition fires, and external factor fires. The first necessary information about vehicle fire is whether it is an electric car, what is the type and capacity of the battery of that vehicle. It is important to identify, as soon as possible, which drive system is used: internal combustion engine, electric vehicle, gas or hydrogen. That is the basic information to take appropriate measures. QR code with manufacturer's safety instructions or some mobile application can be used to get the information for the car (Figure 3). For example, Euro Rescue application gives information for all types of vehicles as shown in Figure 4.

Symbol	App/Code
	QR code with manufacturer's safety instructions
	Euro Rescue (App)
	RescueCode (App)

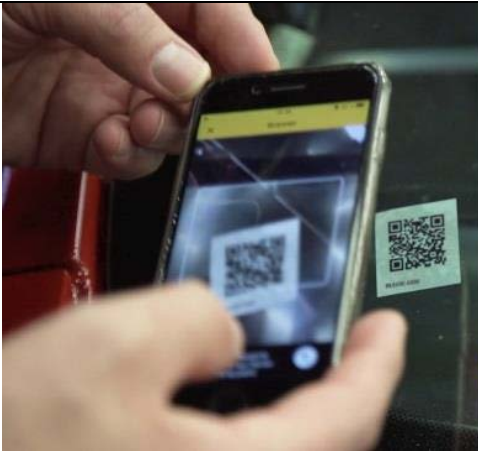
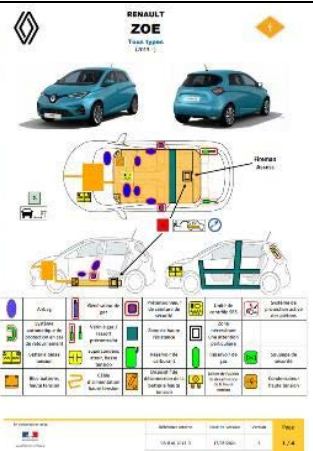



Figure 3. Identification of vehicle type

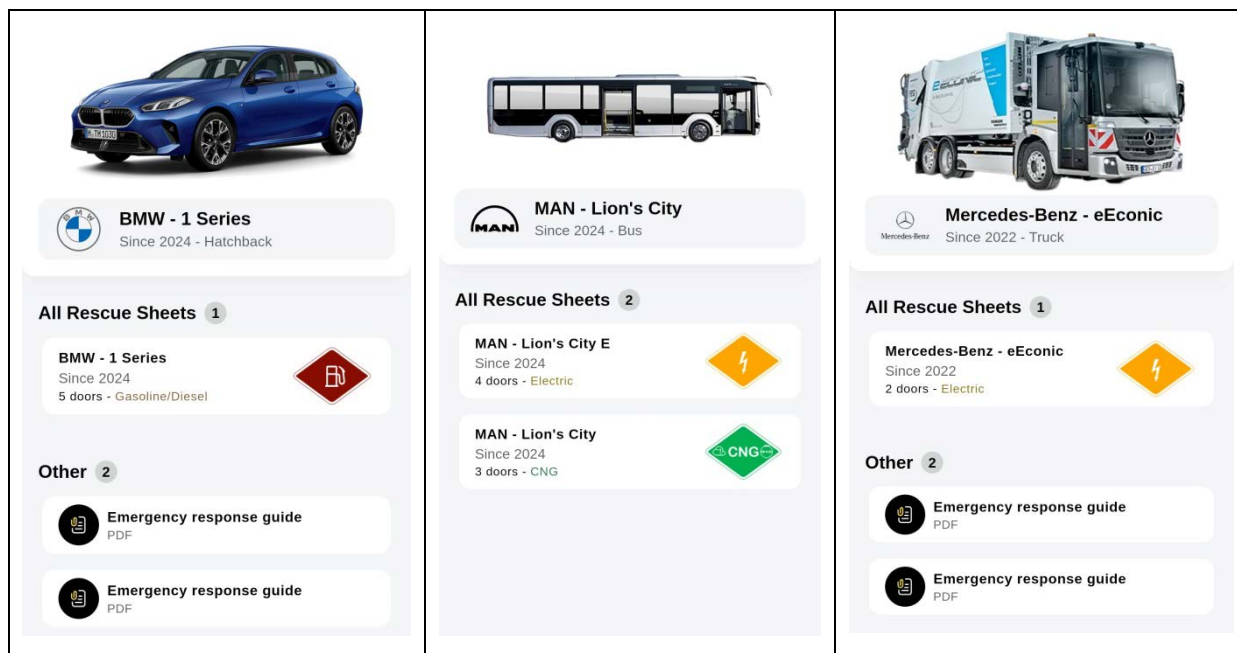


Figure 4. Euro Rescue vehicle type data

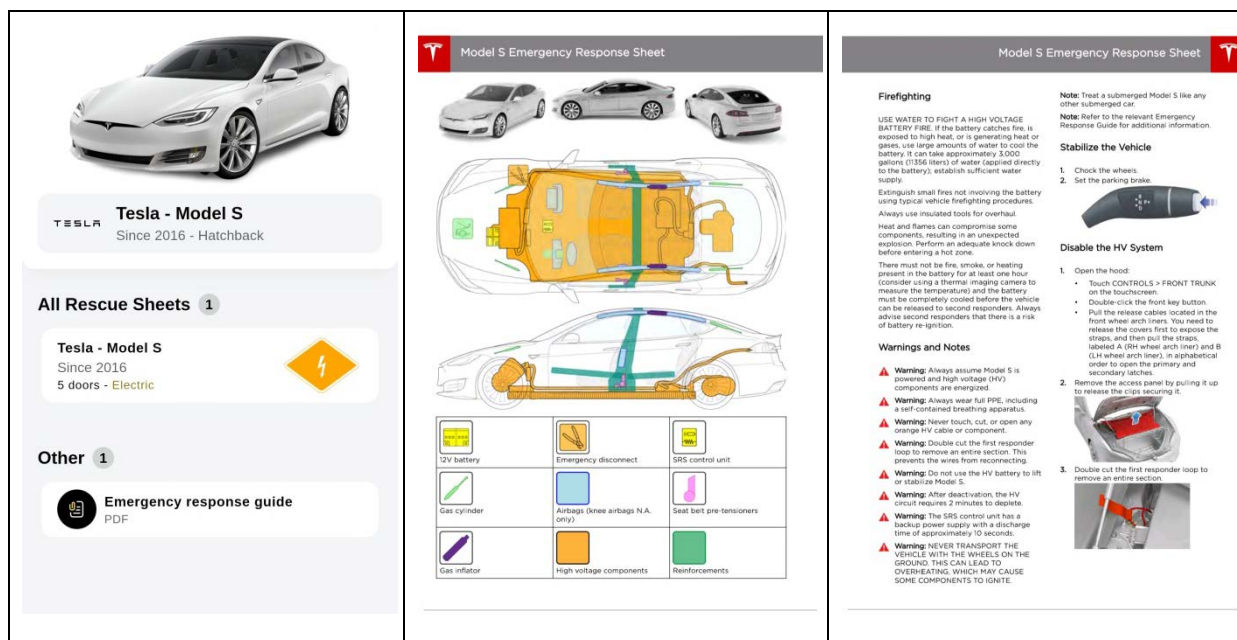


Figure 5. Euro Rescue emergency response guide for Tesla Model S

Euro Rescue emergency response guide for Tesla Model S is given in Figure 5 showing positions of high voltage and low voltage components, emergency disconnect points, etc. It also gives instructions to firefighters, warnings and instructions how to stabilize and disable the HV system.

Then, a fire extinguishing strategy should be determined based on the situation. First, people should be protected and, if necessary, the vehicle should be immobilized. If the vehicle is on

the charger, the power supply should be disconnected, if possible. The vehicle should not be moved until the fire is out. An EV that is switched on (ready to drive) does not produce the typical sound of an ICEV, so the firefighter is not sure whether the vehicle is switched on or off. Most electric vehicles have the ability to cut off the power supply. In the event of a traffic accident, the system automatically disconnects the voltage and the connection of the electric motor to the high-voltage battery. In the event of a very serious accident, various parts of the vehicle may be under voltage that is dangerous to people without protective equipment. It is not allowed to touch or cut the high-voltage cable (orange coloured), as it can be at 800 V DC. A touch voltage of 120 V DC for long shock duration (>3s) should not be exceeded in healthy adults, otherwise a life-threatening condition may occur. Some problems may be solved manually, by turning off all the fuses and disconnecting the battery.

Water is not used to suppress an electric battery fire, because the lithium from the battery would intensify the fire in chemical reactions with water. The fire is extinguished in accordance with standard operating procedures for fire suppression and water is used to cool the material around the battery, but only after the fire has been extinguished by other means. Large amounts of water are needed to cool the battery. For example, it can take approximately 11000 litres of water for cooling Tesla S battery on fire as given in emergency response guide. The battery housing cover must not be opened or removed during firefighting, as there is a high risk of serious injury to firefighters. Everyone within 15 m of an electric car on fire must have full personal protective equipment (suit and mask), especially since various toxic gases are released during a fire.



Figure 6. Extinguishing of high-voltage battery with fireman access mechanism



Figure 7. Extinguishing of high-voltage battery without fireman access mechanism

A sufficient number of replacement air cylinders must be provided, as extinguishing a fire can take several hours. A vehicle with damaged or partially burned Li-Ion batteries should be moved away from other vehicles or any flammable material by a distance of more than 15 m, until sufficient time has passed for the battery to be removed from the car according to the manufacturer's instructions and by qualified personnel, and then disposed of or recycled. In the case of an intervention on an electric/hybrid vehicle, it should be taken into account that

the drive system consists of a combination of an internal combustion engine (gasoline, diesel) and an electric motor with an associated high-voltage battery, so during rescue and firefighting operations there are problems with both drive systems. In the event of an accident, however, it can be assumed that the problems will be almost identical to those of an EV. In the case of a high-voltage battery with a fireman access mechanism, the interior of the battery should be filled with water to stop the combustion (Figure 6). In the case that the high-voltage battery does not have a fireman access mechanism, and the flammable electrolytes of the EV battery produce flashes (Figure 7), water should be introduced into the internal part of the battery through all visible openings (air openings / slot of the protective case).

If the vehicle is submerged in a container or submersion pool, the extinguishing water should be treated as toxic waste and must be treated before being released into the environment.

HEALTH RISKS FOR FIREFIGHTERS FROM ELECTRIC VEHICLE FIRES

EV and HEV fires are usually followed by vapour cloud explosions which can be very dangerous for firefighters. Modern passenger vehicles increasingly use flammable metals in their construction to reduce weight, which increases the danger during firefighting. Some challenges and difficulties (Table 1) during EV fire extinguishing were noticed by experienced firefighters (Hazard control technologies, 2026). Amounts of CO₂, CO, THC – total hydrocarbons, NO, NO₂, HF, HCl, HCN, HBr, SO₂ were measured during testing of two EVs and two ICEVs fires (Lecocq, 2012). Inhaling these gases can be very dangerous and cause fainting, headache, coma and even death (Table 2). Gas emissions vary depending on the manufacturer and battery type. The tests found that HF concentrations were higher in lithium-iron-phosphate (LFP) cells than in lithium-nickel-manganese-cobalt (LNMC) and lithium-manganese-oxide (LMO) cells, which emitted more gas in a shorter time, while the total amount of HF released was approximately the same.

Table 1. Challenges and difficulties during EV fire extinguishing.

Challenge	Difficulty
Thermal runaway	Self-sustaining chemical reaction spreads heat across battery cells
High temperatures and explosions	Fires exceed 650°C causing explosive ruptures and spreading flames
Toxic gas emissions	Releases hydrogen fluoride, carbon monoxide, and flammable gases
Prolonged combustion	Fires can last hours and reignite days later due to residual energy
Water ineffectiveness	Water cannot penetrate compartmentalized battery packs, requiring excessive volumes
Compartmentalized battery design	Heat and gases get trapped in multiple modules, prolonging fire spread
Lack of standardized protocols	Suppression guidelines vary by jurisdiction and manufacturer

Table 2. Common toxic gas components during EV fires, hazards and exposure limits (Health and Safety Executive, 2020).

Substance	Hazard	Exposure Limit, 8h (mg/m ³)	Exposure Limit, 15' (mg/m ³)
CO ₂	Cause headaches, dizziness, confusion, loss of consciousness, and asphyxiation at high concentrations	9150	27400
CO	Toxic if inhaled, causes damage to organs through prolonged exposure and is an extremely flammable gas	23	117
H ₂	Extremely flammable	/	/
THC	Flammable	/	/
HF	Fatal if swallowed, is fatal in contact with skin, is fatal if inhaled and causes severe skin burns and eye damage	1.5	2.5
HCl	Severe skin burns and eye damage, is toxic if inhaled, may cause damage to organs through prolonged or repeated exposure, may cause respiratory irritation and contains gas under pressure and may explode if heated	2	8
HCN	Fatal if swallowed, in contact with skin, if inhaled, causes damage to organs through prolonged exposure, is very toxic to aquatic life (with long lasting effects) and is an extremely flammable liquid and vapour	1	5
NO ₂	Fatal if inhaled, causes severe skin burns and eye damage; and may cause or intensify fire (oxidizer)	0.96	1.91
SO ₂	Severe skin burns and eye damage, toxic if inhaled	1.3	2.7

The presence of various metals in the soot was also determined, such as: Al, Cd, Pb, Co, Cr, Cu, Li, Mn, Ni, Zn, as well as organic compounds and water-soluble anions: F⁻, Cl⁻ and Br⁻, present in soot and ash. The data for six toxic gases are given in Table 3 and used as criteria for ranking the hazard of their toxicity. The most important criterion is HF due to its toxicity and combustion product weight. It is marked as “the most important” with the grade 1. The least important criterion is HCN with the grade 9. Other criteria grades are given in Table 3.

Table 3. Toxic gases released in vehicle fire tests, exposure limits, rates of toxicity, criteria grades and weight coefficients.

Gas	Emissions of gases per vehicle fire test (kg)				Average emission per vehicle fire (kg)	Exposure limit, 15min (mg/m ³)	Rate of toxicity	Grade	Weight coefficient (%)
	EV1	EV2	ICEV1	ICEV2					
CO ₂	460	618	508	723	577,25	27400	47,47	9	3,52
CO	10,4	11,7	12,0	15,7	12,45	117	9,40	5	9,72
HF	1,540	1,470	0,621	0,813	1,111	2.5	2,25	1	40,16
HCl	2,060	1,930	1,990	2,140	2,030	8	3,94	2	24,31
HCN	0,113	0,148	0,167	0,178	0,152	5	32,90	8	6,08
NO ₂	0,198	0,349	0,307	0,410	0,316	1.91	6,04	3	16,21

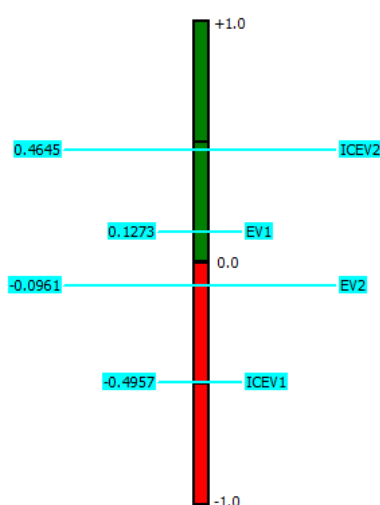


Figure 8. PROMETHEE II results for net flows and ranking of vehicle fire hazard

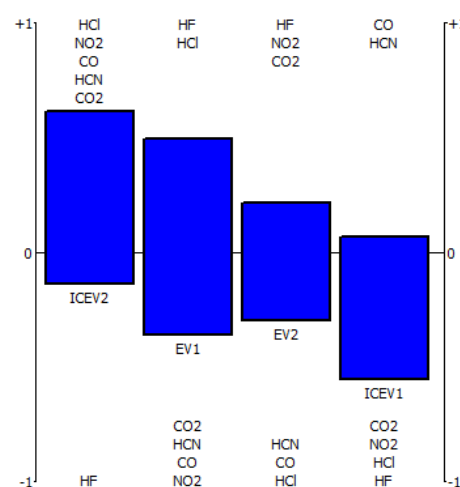


Figure 9. The PROMETHEE II rainbow shows the most dangerous gases (listed above) and the least dangerous gases (listed below) for vehicle fires

Based on these, BWM method (Rezaei, 2015) is applied to obtain the criteria weights given in Table 3. Four vehicle fires hazards are ranked by using PROMETHEE II (Brans, Mareschal, 2024) according to measured emissions for 6 toxic gases (Figure 8). Fire of ICEV₂ is the most hazardous, followed by EV₁, EV₂ and ICEV₁. The reason for this is greater toxicity of all the gases for ICEV₂ fire except HF. HF is the most critical criterion in the case of EVs (Figure 9).

CONCLUSION

Firefighting procedures for EV fires extinguishing are analysed in this paper. The assessment of professional risk for firefighters is based on experimental results from vehicle fire tests. BWM and PROMETHEE are used for ranking of EVs and ICEVs fire hazard based on emissions of toxic gases during vehicle fire testing and on the exposure limits for these gases.

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CALCULATION AND ANALYSIS OF ELECTROMAGNETIC RADIATION FROM FIFTH-GENERATION (5G) MOBILE SYSTEMS

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Abstract: The fifth generation of mobile communication systems (5G) represents a significant technological transformation of modern wireless networks through the implementation of heterogeneous network structures, Massive MIMO antenna systems, and adaptive beamforming. This concept alters the spatial and temporal distribution of electromagnetic fields in the environment and raises new questions regarding the assessment of public exposure to radiofrequency electromagnetic radiation.

This paper presents a theoretical and engineering analysis of the electromagnetic field levels generated by 5G systems under conservative "worst-case" operating conditions. The analysis encompasses macro, micro, and small cells across characteristic 5G frequency bands, with particular emphasis on beamforming scenarios involving maximum beam direction towards the point of observation. Calculations were performed using EIRP models, coherent field summation, and propagation loss models through obstacles. Furthermore, exposure in the near-field zone of modern 5G mobile devices was specifically analysed.

The results demonstrate that actual exposure levels at locations accessible to the general public remain within the limits defined by the national regulatory framework, aligned with the ICNIRP 2020 guidelines, although high instantaneous field values may occur locally within the directed beams. The analysis also indicates that mobile devices, due to their immediate proximity to the user's body, can constitute the dominant source of local exposure compared to distant base stations.

Keywords: 5G networks, electromagnetic fields (EMF), Massive MIMO, beamforming, radiofrequency radiation, non-ionising radiation, exposure assessment, SAR, electromagnetic safety.

INTRODUCTION

Modern fifth-generation mobile networks are based on the deployment of heterogeneous cellular structures, Massive MIMO antenna systems, and adaptive beamforming, which significantly alters the propagation and distribution of electromagnetic fields compared to previous generations of telecommunication systems. Instead of relatively uniform sectoral radiation, 5G systems utilise dynamically steered beams that track the position and requirements of active users, thereby increasing spectral efficiency and network capacity.

The implementation of such systems is achieved through macro, micro, and small cells operating across various frequency bands, with the 3.4–3.8 GHz range, dedicated to high-capacity 5G services, being of particular importance. In this frequency range, Massive MIMO systems with a large number of antenna elements and high effective gain of directed beams are applied, resulting in electromagnetic fields that are highly variable in both space and time. Due to this operational approach, the analysis of electromagnetic radiation in 5G networks necessitates a distinct methodology compared to previous mobile systems. Rather than assessing average and spatially uniform field levels, it is necessary to consider conservative "worst-case" scenarios involving maximum system load, peak beam steering, and electromagnetic wave propagation through obstacles and indoor environments.

The objective of this paper is to conduct a theoretical and engineering analysis of the maximum electromagnetic field levels generated by 5G base stations and mobile devices across characteristic operating scenarios, while comparing the obtained results with current regulatory limits.

TECHNICAL CHARACTERISTICS OF 5G TELECOMMUNICATION SYSTEMS

Unlike previous systems, where the primary focus was on increasing data transfer rates, 5G introduces the concept of an adaptive network capable of simultaneously supporting multiple types of services. Thus, in addition to Enhanced Mobile Broadband (eMBB)—characterised by ultra-high speeds in the Gbps range, high-resolution video, and VR/AR—new scenarios are introduced featuring ultra-low latency (≈ 1 ms) and high reliability (URLLC - Ultra-Reliable Low Latency Communications).

These enable high-level industrial automation and the use of autonomous vehicles, as well as Massive Machine-Type Communications (mMTC) involving a vast number of low-power devices, such as sensors and controllers for everyday household appliances and public city services. This diversity is made possible by a fundamentally different approach to 5G network design. One of the key characteristics of 5G technology is the use of a wider frequency spectrum than ever before.

Modern 5G architecture relies on the concept of Heterogeneous Networks (HetNet). This approach combines various base station layers to ensure simultaneous wide-area signal coverage and immense data transmission capacity within a limited area. This telecommunication system delivers services through the spatial organisation of cells, namely via macrocells, microcells, and small cells (picocells) that overlap one another.

Macrocells represent the fundamental infrastructure or the "backbone" of the mobile network. They are used for general coverage in residential and rural areas, as well as for ensuring signal continuity along transport routes. The typical Total Radiated Power (TRP) ranges from 120 W to 200 W. They are mounted on high towers or building rooftops, usually at heights of 25 m to 30 m. Macrocells primarily operate in low-frequency bands (e.g. 700 MHz) for wide coverage and mid-bands (3.5 GHz) with a coverage range of several kilometres (typically 2 km – 30 km).

Microcells serve to enhance network capacity within macrocell areas to support a high number of concurrent users. They operate with medium transmit power, ranging from 20 W to 60 W, and are situated on lower structures or dedicated poles at heights of 10 m to 15 m. Their coverage radius is between 200 m and 2 km, most commonly utilising frequency bands from 2.1 GHz to 3.5 GHz. They are ideal for city squares, busy streets, and densely populated urban centres.

Small cells are compact devices utilised for extremely dense urban environments and indoor settings.

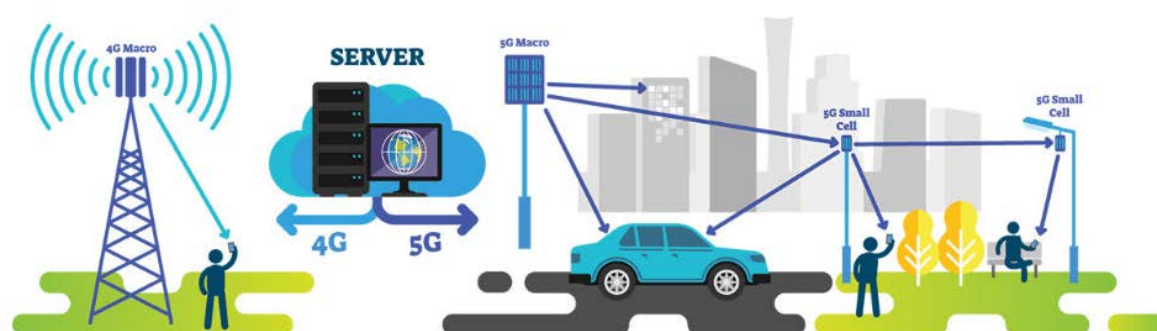
They have very low radiated power, typically from 0.25 W to 10 W. These are installed on street lighting, building facades, or indoors at heights of 3 m to 6 m, consequently covering very small zones from 10 m to 200 m. Operation at high frequencies (3.5 GHz) and millimetre waves (mmWave) (above 24 GHz/26 GHz) provides significant data bandwidth; however, it results in low penetration power, as data transmission is effectively obstructed by two to three obstacles (walls).

Table 1 . Comparative overview of 5G system cells,

Cell Type	Average Radius (Range)	Frequency Bands	Primary Purpose
Macro	2 km – 30 km	Low (<1 GHz) and Mid (1.8 – 2.6 GHz)	Wide-area coverage, rural and suburban areas
Micro	200 m – 2 km	Mid (2.1– 3.5 GHz)	Urban environments, squares, major streets
Small Cells	10 m – 200 m	High (3.5 GHz) and mmWave (24+ GHz)	Dense urban centres, stadiums, indoor environments

Whilst previous generations were primarily limited to low and mid-frequency bands, 5G encompasses three distinct frequency ranges: low frequencies that facilitate extensive territorial coverage; mid-frequencies, which offer a compromise between range and capacity; and high frequencies that enable exceptionally high speeds over short distances. This multi-layered structure allows operators to dynamically optimise the network based on requirements — providing signal availability over long distances while ensuring high capacity in urban environments.

The fundamental technological innovation of 5G systems is reflected in the manner in which the base station communicates with users. Rather than broadcasting the signal uniformly across a wide area, as was largely the case with previous generations, 5G introduces advanced antenna systems with a vast number of elements, known as Massive MIMO. These systems enable the formation of directed beams of electromagnetic radiation that dynamically adapt to the user's position. This technique, known as "beamforming", allows for more efficient use of energy and spectrum, as the signal is directed precisely where it is required, instead of being dissipated in all directions.



Figures 1. Illustration of 5G cellular coverage

Such an approach has multifaceted implications; on one hand, it enables a significant increase in network capacity and a reduction in inter-user interference, while on the other, it alters the very nature of the electromagnetic fields generated by base stations. Whilst radiation in previous systems was relatively uniform and constantly present in space, in 5G systems it becomes spatially and temporally variable. Peak electromagnetic field values occur within narrow beams — where instantaneous

maximum values may exceed average or limit thresholds — and only during periods of data transmission to a specific user, whereas radiation levels in the remainder of the space and time are considerably lower. This allows for greater flexibility, as network resources can be dynamically allocated to various services through a concept known as "network slicing". In this manner, a single physical infrastructure can simultaneously support diverse communication types with entirely different requirements regarding speed, reliability, and latency. 5G can be perceived not merely as an evolution of mobile communications, but as a transformation in the way wireless networks are designed and utilised, with direct implications for both system performance and the analysis of electromagnetic radiation and its environmental impact.

REGULATORY FRAMEWORK FOR TELECOMMUNICATION SYSTEMS IN THE REPUBLIC OF SERBIA

Every state necessitates the regulation of electromagnetic spectrum emissions and the telecommunication services market. A model in which a single regulatory body simultaneously manages the radio-frequency spectrum and supervises its use represents standard practice in most developed countries. Such an approach enables the efficient and coordinated management of the radio-frequency spectrum as a finite resource. This model, where the "manager" (planning and allocating spectrum) and the "controller" (supervising operators and compliance) reside within the same authority, is not without risk; for such a principle to function effectively, robust mechanisms of independence and oversight are essential. A key principle of the EU is that the Regulator must be: independent (legally separate and not under government control, as well as financially autonomous), transparent (in its decisions, public auctions, and public documentation), and must adhere to the principle of accountability (judicial review of decisions and audits).

RATEL is the independent regulatory body of the Republic of Serbia responsible for electronic communications and radio-frequency spectrum management. Its primary competencies include the planning and allocation of frequency bands, the issuance of licences to operators, the supervision of network operations, and the monitoring of compliance with technical and safety standards. RATEL also monitors electromagnetic radiation levels and ensures their alignment with international guidelines. In the context of 5G network development, RATEL plays a pivotal role in organising spectrum auctions, defining conditions for operators, and supervising infrastructure implementation.

In the Republic of Serbia, according to the plans and auctions conducted by the regulatory body RATEL, the key frequency bands for 5G technology implementation encompass:

- the 700 MHz band (low-band) for wide-area coverage;
- the 3.4–3.8 GHz band (mid-band), which serves as the primary 5G band for the deployment of Massive MIMO and beamforming technologies;
- the 900, 1800, 2100, and 2600 MHz bands, utilised through the refarming of existing networks;
- the 26 GHz band, designated for future mmWave implementations.

In 5G systems featuring Massive MIMO technology, multiple antenna elements do not function as a set of independent transmitters on different frequencies, but rather as a coherent antenna array. All elements operate within the same frequency band and participate synchronously in the formation of the electromagnetic field. In beamforming mode, the antennas emit an identical signal with varying

phase shifts, thereby achieving energy steering towards the user. In spatial multiplexing mode, it is possible to transmit multiple data streams simultaneously; however, even then, they share the same frequency resource and are distinguished by their spatial distribution rather than by frequency.

ANALYSIS AND CALCULATION OF THE WORST-CASE RADIATION SCENARIO FOR 5G BASE STATIONS

The technical characteristics of 5G telecommunication systems possess distinct specificities in the context of electromagnetic radiation. The introduction of directed beams and a vast number of antenna elements leads to an increase in the maximum possible gain in specific directions, whilst simultaneously reducing average spatial exposure. Consequently, analyzing the environmental impact of 5G systems necessitates a different approach compared to previous generations — rather than considering constant radiation, it is essential to analyse dynamic scenarios and so-called "worst-case" conditions, where all resources are directed towards a single point in space. The peak level of electromagnetic radiation occurs in a scenario where all antenna elements operate coherently, forming a directed beam towards the point of observation. Therefore, it is necessary to assess and calculate the maximum electric field strength for a 5G system in the direction of the main beam for the scenario of maximum data throughput requirements, achieved by directing all micro-antennas towards a single user. This represents an assessment of the case where the maximum electric field is expected at the user's location, assuming free-space propagation without obstacles that would attenuate the emitted wave from the antenna to the user. The calculation of the maximum electric field strength, E_{max} , in 5G Massive MIMO systems at the main beam point is based on the principle of coherent summation of signals from all individual antenna elements. When all elements are phase-aligned to radiate towards the same point (along the direction of the main beam), their fields sum linearly, leading to a significant increase in field intensity.

Calculation for Maximum Field in Free Space

The basic formula for the electric field E in the far-field zone for a single isotropic source is calculated via the Equivalent Isotropically Radiated Power (EIRP): $E = \frac{\sqrt{30 \cdot EIRP}}{r}$, where: E - is the electric field strength [V/m] and r is the distance from the antenna.

In an antenna array with N identical antenna elements, the maximum field is obtained when the contributions of each element coincide in phase. If E_{el} is the electric field strength generated by a single element, the total maximum is $E_{max} = N \cdot E_{el}$. Given that the power density S is proportional to the square of the electric field ($S \propto E^2$), the power density in the main beam increases with the square of the number of elements: $S_{max} \propto N^2$. To calculate the value of E_{max} , the total EIRP of the entire array is first determined. The total power of the array, $P_{total} = N \cdot P_0$, where P_0 is the power of each individual antenna element in the array. In the ideal case, the array gain is $G_{array} = N \cdot G_0$, where G_0 is the gain of an individual element. The total EIRP is: $EIRP_{total} = P_{total} \cdot G_{array} = (N \cdot P_0) \cdot (N \cdot G_0) = N^2 \cdot EIRP_0$. By substituting $EIRP_{total}$ into the basic field

formula, we obtain:
$$E_{max} = \frac{\sqrt{30 \cdot N^2 \cdot P_0 \cdot G_0}}{r} = \frac{N \cdot \sqrt{30 \cdot P_0 \cdot G_0}}{r}$$

In practical systems, it is necessary to account for feeder losses and imperfections in phase alignment (beamforming efficiency), which slightly reduce the theoretical maximum. Duty Cycle: In 5G TDD (Time Division Duplex) systems, the antenna does not transmit 100% of the time. For the assessment of public exposure to radiation, the time-averaged power value is frequently utilised. Configuration: For a typical 5G panel with a 64T64R (64-element) configuration, the field at the focal point will theoretically be 64 times greater than that of a single element with the same power.

Table 2 . Adopted typical cell values for field calculations

Cell Type	Height (H)	Average Tilt (α)	Distance of Maximum (d_{max})
Macro	30 m	5°	~ 340 m
Micro	12 m	10°	~ 68 m
Small Cell	5 m	25°	~ 10 m

The assumptions for the calculation are based on typical effective transmitter power values, taking approximately 160 W for macrocells, around 40 W for microcells, and approximately 5 W for small cells. These are coupled with corresponding antenna gains characteristic of 4G systems with sectoral beams: 4G (beam) – 5G (Beamforming maximum). This represents a situation where Massive MIMO has formed a maximum directed beam towards the point of observation – the receiving device.

Table 3 . Theoretical maximum in the main beam (worst-case scenario) and the ratio relative to the permissible limit in accordance with the National Regulation [12]

r [m]	4G Macro E [V/m]	% of Limit	5G Macro E [V/m]	% of Limit	5G Micro E [V/m]	% of Limit	5G Small E [V/m]	% of Limit
1	438,2	1203,8	870,8	1428	244,9	402	30,7	50,3
3	146,1	401,4	290,3	476	81,6	134	10,2	16,7
5	87,6	240,7	174,2	286	49,0	80	6,1	10,0
10	43,8	120,3	87,1	143	24,5	40,2	3,1	5,1
50	8,76	24,1	17,42	28,6	4,90	8,0	0,61	1,0
100	4,38	12,0	8,71	14,3	2,45	4,0	0,31	0,5
150	2,92	8,0	5,81	9,5	1,63	2,7	0,20	0,3
200	2,19	6,0	4,35	7,1	1,22	2,0	0,15	0,2

Calculation of the Maximum Field in Environments with Obstacles (Walls)

In practical scenarios, the user is typically located within an enclosed environment, where signal attenuation occurs during wave propagation through structural barriers. This phenomenon is significant both for safety assessments and for the evaluation of signal quality within indoor spaces. When an electromagnetic wave passes through an obstacle, its field strength is reduced by the obstacle

attenuation factor L_{wall} . Field Strength Behind an Obstacle (Indoors) $E_{in} = E_{out} \cdot 10^{\frac{L_{wall}(dB)}{20}}$

Table 4 . Attenuation table for 3.5 GHz (Typical 5G):

Obstacle Material	Attenuation, L_{wall} [dB]	E Attenuation Factor, $\frac{E_{out}}{E_{in}}$
Standard glass	3 -- 5	$\approx 1,6$
Brick wall (20 cm brick)	10 - 15	$\approx 3-5,6$
Thermal insulation glass (Low-E)	20 - 40	$\approx 10-100$
Reinforced concrete	25 - 35	$\approx 18-56$

We shall take the example of a 5G multi-band macro station that utilises both bands for different purposes (700 MHz and 3.5 GHz) under maximum load, specifically focusing on the 3.5 GHz component as it emits the strongest field at greater distances (worst-case).

Table 5 . Calculation results for the maximum E from a BS in the area behind an obstacle

Distance r [m]	Field at the facade E [V/m]	Behind a brick wall E_{in} [V/m]	Behind reinforced concrete E_{in} [V/m]
10 m	87,1	21,77	2,75
50 m	17,42	4,35	0,55
100 m	8,71	2,17	0,27
200 m	4,35	1,08	0,13

Maximum data requirements behind an obstacle (wall) lead to both devices in the system "ramping up" their operation to maintain the connection. This occurs because:

- When the mobile phone reports to the base station that the signal is attenuated due to the wall, while the user requests maximum throughput, the base station's antenna system (MIMO) activates Maximum Beamforming Gain. The antenna utilises the most precise beam possible to direct all energy exactly towards the receiver's location with the highest possible gain. It raises its transmitted power to its software or regulatory limit for that specific beam (Adaptive Power Control - APC). Additionally, the antenna will occupy a higher percentage of time transmitting data to the receiver to compensate for packet losses caused by the wall (Increase in Duty Cycle).
- The mobile phone (Uplink) also increases all parameters to establish communication with the base station. To download data at maximum speed, the phone must constantly send acknowledgements (ACK/NACK packets) and requests to the base station. This is achieved by the phone dramatically increasing its transmitted power (Uplink Power Control). For the user in close proximity to the device, this represents a potential health concern, as exposed tissues absorb radiation energy which can lead to biological effects. While the base station antenna is located dozens of metres away, the phone is held in your hand or against your head. When a phone raises its power to the maximum (typically around 200–250mW), the electric field strength it generates in your immediate vicinity can be significantly higher than the field arriving from a distant base station.

At the point where the user is located (behind a wall), the total electric field strength is the sum of two contributions: the field from the base station and the field from the user's phone. If maximum throughput is requested behind a wall, the antenna will emit its maximum towards the user, but the wall will block most of it; thus, the user's local exposure will actually increase the most due to the intensified operation of the user's phone, which must transmit more powerfully so that the antenna receives a satisfactory signal for the requested throughput. In an engineering sense, this is the "worst-case scenario" for user exposure: a weak received signal requires high transmit power from both sides to maintain the complex modulation necessary for high speeds.

For modern 5G phones, a 4x4 MIMO (Multiple Input Multiple Output) antenna system is standard. Such a phone utilises Uplink Beamforming (coherent summation of signals from multiple antennas towards the base station). Calculation of the electric field strength near the head: although the antennas in the phone are small, their synchronised operation achieves a higher directional gain. With 4 antennas working together, the theoretical gain increases, and the real array gain is approximately 6 dBi (which is factor 4). The total power remains limited by regulations to 200 mW (23 dBm for Power Class 3).

To account for the real-world situation with 4x4 MIMO antennas in the near-field zone, we must apply a model that considers the coherent summation of fields from four different sources (antennas) within the phone itself. In this zone (5–15 cm), the phone antennas are not point sources, but rather an array of elements creating a complex interference pattern. The input parameters for a real 5G phone used in the calculation are: total phone power $P_{total} = 200 \text{ mW} = 0,2 \text{ W}$, number of antennas **4** (each radiating $P_i = 0,05 \text{ W}$), directivity factor in the near-field $G_{nf} \approx 2$ (instead of the full far-field gain, we use a real focus factor near the body), Duty Cycle $DC = 0,2(20\%)$ of transmission time at maximum throughput, and in the near-field, the $E \text{ i } H$ ratio is not constant (377Ω), so an empirical formula for the near-field of a dipole is used.

The formula used to determine the field in the near-field zone (MIMO system) represents an engineering approximation, whereas the actual assessment of exposure in the near-field is performed using the SAR parameter defined by standards (IEC/IEEE).

The field strength of a single antenna in the near-field zone is estimated as: $E_i \approx \frac{\sqrt{60 \cdot P_i \cdot G_{nf} \cdot DC}}{r}$

For a 4x4 MIMO system, where the antennas operate together (beamforming), the fields are summed linearly. However, due to the physical spacing of the antennas within the phone casing, they do not sum perfectly at a single point. The real coherence factor is approximately 2,5 instead of the theoretical 4.

$$E_{total} \approx 2,5 \cdot \frac{\sqrt{60 \cdot 0,2 \cdot 2 \cdot 0,2}}{r} = E_{total} \approx \frac{5,477}{r}$$

These formulas represent a conservative engineering approach with built-in reflection and safety factors. Based on this, field values in the vicinity of the phone are obtained under these emission conditions.

Table 6 . Calculation results for the maximum field from a mobile phone in the near vicinity

Distance (r)	E (V/m)	% of Limit [2]
5 cm	109,5	469,3
10 cm	54,8	234,8
20 cm	27,4	117,4
50 cm	10,9	46,5
1 m	5,5	23,55

An exposure paradox can be observed here: the user is exposed to a significantly stronger field from their own phone at 5 cm (109.5 V/m) than from a base station at a distance of 50 m (17.42 V/m). This confirms that for the general population, the personal device is the primary source of exposure. Using the reflection constant and an external safety factor yields values that are approximately 2.5 times higher than those from standard physical models. Such an approach is justified in academic literature for defining "absolute safety". The exceedance of limits at 5 cm for the phone indicates the inappropriate application of far-field formulas in the near-field zone, where SAR values should be utilised for a realistic safety assessment.

With the introduction of the Regulation [12], the Republic of Serbia has increased the reference levels (e.g., from 24.4 V/m to 61.0 V/m for 3.5 GHz), thereby enabling the full implementation of 5G networks.

CONCLUSION

The analysis of electromagnetic radiation from modern 5G telecommunication systems demonstrates that, despite increased complexity and the application of advanced technologies such as Massive MIMO and beamforming, actual public exposure levels remain within the prescribed limits defined by the current regulatory framework.

Theoretical calculations of maximum values indicate a significant increase in field strength within directed beams; however, such conditions represent extreme and short-term scenarios that do not reflect the actual spatial-temporal distribution of radiation.

It is particularly important to highlight that, under everyday conditions, the dominant source of exposure is often found in the immediate vicinity of the user—namely, within the mobile devices themselves—whereas the contribution from base stations is significantly lower due to distance and the spatial distribution of radiation.

The simplest way to reduce exposure from a mobile device by 60–70% is to avoid holding the phone against your head during large data downloads, but rather to hold it in front of you.

From a health protection perspective, existing standards are based on clearly established biological mechanisms and provide a high level of safety. However, modern technological developments and continuous public concern point to the need for further research, particularly in the field of long-term and non-thermal effects.

In this sense, future work should be directed towards improving measurement and exposure modelling methods, as well as strengthening communication between the scientific community, regulatory

bodies, and the public, to ensure an understanding of actual risks and enable the sustainable development of telecommunication technologies.

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COMPARATIVE ANALYSIS OF CRANE INSPECTION REGULATIONS IN THE EUROPEAN CONSTRUCTION INDUSTRY

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Abstract: The safety and reliability of cranes mostly depend on adequate inspection and verification procedures. This paper presents a comparative analysis of national and international regulations in the scope of crane inspection, including the legal framework of the Republic of Serbia, the International Labour Organization (ILO), the European Union (EU), and the United Kingdom (UK). This research aims to identify key differences in the level of methodological structure and regulatory approaches to highlight the need for a standardized, comprehensive examination scheme that would improve consistency and enhance safety in crane operations. The analysis showed that international and national frameworks define basic inspection procedures but lack a fully developed, unified inspection methodology, leading to increased variability in inspection practices. Given the number of crane accidents in the construction industry and the fact that inadequate inspection can increase them, future research should focus on developing a universal, unified rulebook for crane inspection.

Keywords: *cranes, construction, crane inspection, regulations, comparative analysis.*

INTRODUCTION

Numerous studies have analyzed the causes of crane collapses and accidents (Raviv et al., 2017; Swuste, 2013), conducted crane identification and risk assessments (Yilmaz & Ozcan, 2019; Raviv et al., 2017), and shown that most failures originate from mechanical or structural damage, incomplete or inadequate crane inspections, and a lack of maintenance (Alverius et al., 2023; Amilia, 2023). The consequences of the above-mentioned failures include material damage, serious injuries, and fatal accidents (Health & Safety Executive, 2010). For this reason, it is important to analyze real accident cases to understand the deficiencies in existing inspection systems and safety management procedures. For example, Figure 1 shows three notable crane accidents worldwide to highlight the importance of regular crane inspections (Blic, 2014; Global News, 2020; BBC News, 2024).

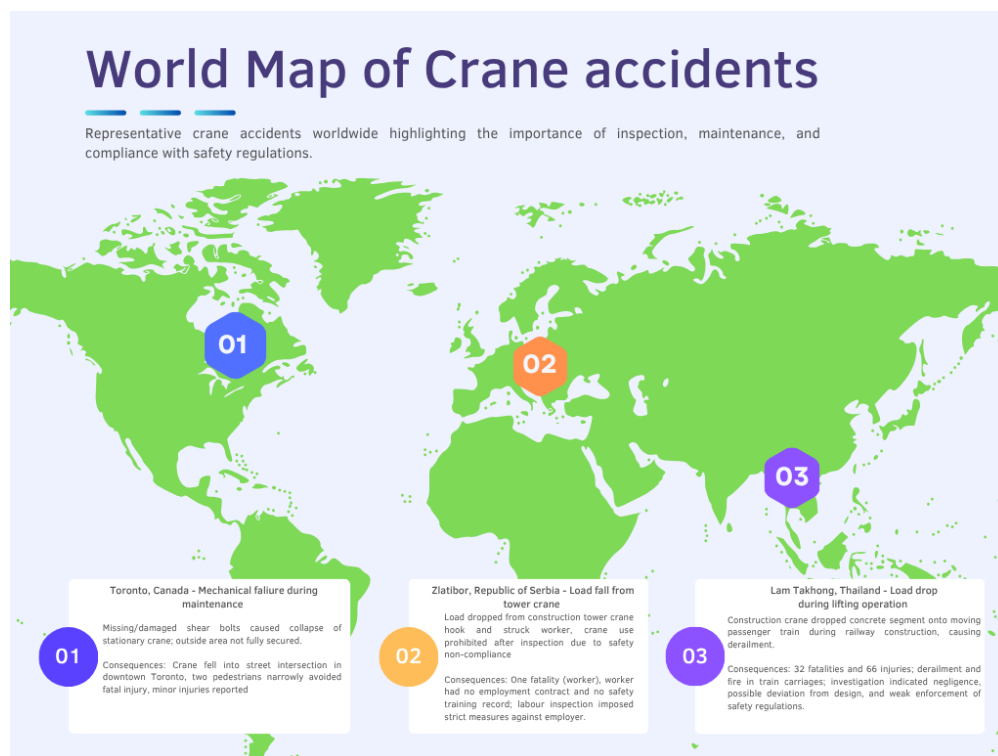


Figure 1. World Map of Crane Accidents

Preventive and periodic inspections of cranes shall check and determine whether safety and health at work measures established by regulations in the field of safety and health at work, technical regulations, standards, and manufacturer's instructions have been applied to the work equipment prescribed by Rulebook on the Procedure for Inspection and Verification of Work Equipment and Inspection and Testing of Electrical and Lightning Installations and Testing of Working Environment Conditions (Ministry of Labour, Employment, Veteran and Social Affairs of the Republic of Serbia, 2024). All crane components and accessories should be carefully examined to identify defects that may pose a safety risk. Efficient control will not only ensure a crane meets legal requirements but also reduce costs, improve quality and security, and deliver compelling improvements in the performance and safety of the equipment (Irhirane et al., 2019). Therefore, preventive and periodic inspections should cover all elements and accessories that are subject to damage and wear. Both technical and legal requirements define the inspection and verification of cranes. Therefore, this paper presents a comparative analysis of national and international regulations governing crane inspection in the European construction industry, including the legal frameworks of the Republic of Serbia, the International Labour Organization (ILO), the European Union (EU), and the United Kingdom (UK). This research aims to identify key differences in the level of methodological structure and regulatory approaches to highlight the need for a standardized, comprehensive examination scheme that would improve consistency and enhance safety in crane operations.

Understanding the legal framework contributes a base for outlining inspection methods and developing an examination scheme.

REVIEW OF REGULATORY FRAMEWORK

Defined by diverse legislation, the crane inspection procedure will be analysed on the national and international levels, thereby providing a comprehensive comparison between national and international legislation.

National regulatory framework of the Republic of Serbia

Providing proper work equipment on which preventive measures for safe and healthy work are an obligation of every employer. Also, equipment should be routinely maintained and inspected in accordance with legal requirements, such as standards (Yow et al., 2000). In the Republic of Serbia, when talking about the inspection of cranes, two main legal acts regulate the topic:

- Rulebook on the procedure for inspecting and checking work equipment and inspecting and testing electrical and lightning protection installations, and testing working environment conditions (Ministry of Labour, Employment, Veteran and Social Affairs of the Republic of Serbia, 2024), and
- Professional instructions for the development of methodologies for inspection and verification of work equipment and testing of working environment conditions (Ministry of Labour, Employment, Veteran and Social Affairs of the Republic of Serbia, 2019).

The main difference between these bylaws lies in their scope. The Rulebook establishes the competence of the inspection personnel, the legal framework, the time frame for execution of inspections, the report and its content, as well as the defect sticker. According to the Rulebook, cranes and lifting equipment, regardless of capacity or operating principle, are categorized as work equipment subject to the given inspections. It is important to distinguish the meaning of preventive and periodic inspections. Preventive inspections are carried out before use, after overhaul/reconstruction/breakdown, after relocation, following accidents, upon detection of defects, or upon request by the labour inspectorate. Periodic inspections are carried out at intervals defined by legal acts or manufacturer instructions, but not more than 3 years, while temporary electrical installations are inspected every 6 months. In contrast, the Professional instructions for the development of methodologies for inspection and verification of work equipment and testing of working environment conditions provide technical guidance by defining the mandatory elements of the methodology, and by providing instructions for preparing expert findings on the inspected work equipment.

Upon reviewing the extensive literature, a significant gap in the bylaws of the Republic of Serbia's national framework has been identified. Although the adoption of the Rulebook on Machine Safety ("Official Gazette of the RS", Nos. 58/2016 & 21/2020) and contemporary

standards are available and widely applied, the repeal of the 1991 Regulation on technical norms for cranes left a significant gap. Namely, the old regulation had several advantages over the current regulatory framework: it defined in detail the technical requirements that cranes must meet and clearly defined the inspection elements, ensuring uniformity and comprehensiveness. Also, the rulebook prescribed specific technical criteria, and the inspection requirements were directly related to the crane's design and construction characteristics, enabling consistent control throughout its life. The most important segment and, at the same time, the most important characteristic of the old rulebook was reflected in the reduced subjectivity and individual approach of the persons who perform the examination when evaluating the condition of the equipment, thanks to clearly defined criteria and rules. With the cancellation of this rulebook, a detailed, unambiguous technical framework was lost, leading to confusion in interpretation and increased subjectivity in the crane inspection procedure, especially for older crane types.

International regulatory framework

International Labour Organization (ILO)

The International Labour Organization (ILO, 2022) defines general provisions and requirements for cranes, without prescribing detailed inspection procedures. According to general requirements, the employer is responsible for designing and implementing an adequate program to ensure that all cranes are selected, installed, inspected, tested, maintained, used, and dismantled, to ensure safe crane operation, accident prevention, and compliance with legal and technical requirements.

ILO highlights that cranes should be properly designed and constructed, supplied with the necessary instructions and technical documentation, and that the entire testing procedure for cranes should be in compliance with national legislation. According to ILO provisions, crane inspection by competent personnel shall be performed: before first use; after installation on site; subsequently, at intervals prescribed by national laws and regulations; after any significant changes or repairs; and after any exceptional circumstance that may affect the safety of the equipment. Reviewing the literature showed that general safety requirements for crane inspection are defined by these provisions, leaving room for national and regional regulations to set detailed criteria for crane inspection.

European Union (EU)

Inspection of cranes within the European Union (EU) is regulated by Directive 2009/104/EC, which requires regular inspections to ensure cranes are in proper operational condition. In addition, the standard EN ISO 9927-1:2013 defines detailed crane inspection procedures conducted by competent personnel. Foremost, the standard defines the crane inspection schedule, as shown in Figure 2. Inspections are also carried out after technical and structural modifications. Furthermore, when cranes approach the limits of their designed load to

determine the safe period of operation, condition reviews are undertaken in accordance with ISO 12482-1.

The standard also defines the crucial inspection methods for cranes – visual inspection, functional tests, operational tests, and non-destructive tests - as well as the method for issuing inspection results after inspection. However, the standard EN ISO 9927 provides only a general list of crane elements that require inspection, without detailed specifications, and is used only as a basic guideline for crane inspection, rather than as a fully comprehensive inspection methodology.

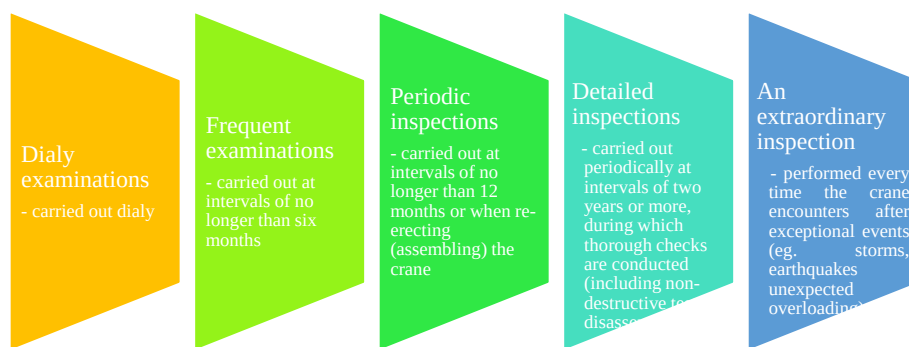


Figure 2. Crane inspection schedule according to EN ISO 9927-1

United Kingdom (UK)

The United Kingdom has specific Health and Safety legislation and is considered a role model in Health and Safety engineering. According to UK legislation, employers are required to conduct a risk assessment for both the specific crane and the work activities performed with it. The legislation of Great Britain regarding the safety of working with cranes is reflected in the utilization of three regulations: Provision and Use of Work Equipment Regulations (PUWER), Lifting Operations and Lifting Equipment Regulations (LOLER), and Occupational Health and Safety Management Regulations (The Stationery Office / Her Majesty's Stationery Office, 1999).

Since LOLER is directly linked to cranes and lifting operations, while PUWER applies generally to work equipment, it is important to note that LOLER requires all risks associated with crane operations to be controlled and assessed. Regulations 9, 10, and 11 of LOLER outline the detailed examination and inspection requirements for cranes, the obligations of inspection personnel, and the requirements for reports. Similar to ILO and EU legislation, LOLER also defines types of crane testing: first test after installation, regular testing (every 6-12 months), and emergency testing (in extraordinary circumstances). The frequency and scope of crane inspection depend on the level of risk and may include visual and functional tests, as necessary, followed by the issuance of an examination report. A key element of Regulation 9 on safe work with cranes is the examination scheme. An examination scheme is a

specification, typically in writing, of what must be tested and when the test will be conducted, and an examination report follows it. This key element underscores that the UK regulatory framework for crane inspection provides a structured, well-defined basis for comparison with other regulatory frameworks (Health & Safety Executive, 1998).

FINDINGS FROM THE ANALYSIS OF THE REGULATORY FRAMEWORK

When examining the regulatory landscape governing crane inspection across multiple jurisdictions, a consistent pattern emerges — none of the existing frameworks provides a truly comprehensive and unified inspection methodology. The ILO, despite its authority as the leading international body, confines itself to broad, general provisions, effectively delegating the methodological specifics to national and regional legislators. The EU moves somewhat further by referencing concrete standards and partial inspection methods through EN ISO 9927-1, yet stops well short of prescribing a coherent, end-to-end procedural framework. Among the jurisdictions examined, the UK's LOLER represents the most methodologically grounded approach, particularly through Regulation 9, which introduces the examination scheme as a mandatory procedural element. Serbia presents a particularly telling case — while inspector competence and reporting obligations are clearly defined, the inspection methodology itself remains underdeveloped. This gap is compounded by the fact that Serbia previously possessed a detailed technical framework, the 1991 regulation on technical norms for cranes, which was repealed without a substantive replacement, leaving a regulatory void that has measurably increased subjectivity in practice (Zelić et al., 2019). Taken together, these findings suggest that the existing international and national frameworks, while not without merit, fall short of the standardization that a safety-critical domain such as crane inspection demands.

Table 1. Comparative overview of crane inspection regulatory frameworks

Criteria	SERBIA	ILO	EU (EN ISO 9927-1)	UK(LOLER)
Legal framework	Rulebook (2024), Professional guidelines	International code of practice	Directive 2009/104/EC + EN ISO 9927-1	PUWER+LOLER+OHSM
Inspector competence	Precisely defined by Rulebook	Competent person	Competent person	Competent person
Types of inspection	Preventive and periodic	Before first use, after modifications, periodic	Periodic, after modifications, condition review	Initial, periodic (6-12 months), extraordinary
Inspection methodology	Not precisely defined	Not precisely defined	Partial (visual, functional, NDT)	Partial (visual, functional)
Examination scheme	Not required	Not defined	Not precisely defined	Mandatory

List of elements to inspect	Not defined	Not defined	Partial (general list only)	Partial
Technical criteria for condition assessment	Repealed with the 1991 Regulation	Not defined	Not defined	Not defined
Inspection report	Mandatory, defined by the rulebook	Not specified	Defined by a standard	Mandatory, defined by the LOLER
Level of inspector subjectivity	High	High	Medium	Medium

CONCLUSION

Considering the high number of crane accidents and the fact that incomplete crane inspections lead to unfortunate consequences, the conducted analysis additionally highlights that, despite general alignment with international standards, significant differences exist in the level of detail and methodological approach across the legislation set by the ILO, EU, UK, and the Republic of Serbia. The comparative analysis concluded that inspection procedures are defined but lack a fully developed, unified inspection methodology, whereas the UK makes examination scheme compliance an obligation in the crane inspection procedure.

The conclusion is, in fact, that it is necessary to adopt a universal, internationally available, unified rulebook for inspection of cranes. In this way, the rulebook will prescribe not only the legal framework and general and individual requirements that cranes must fulfil, but also the complete methodology and the list of crane elements to be inspected.

ACKNOWLEDGEMENT

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THE NEW REGULATION ON MACHINERY AND THE READINESS OF THE BZNR SYSTEM TO IMPROVE BUSINESS AND COMPETITIVENESS

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Abstrakt: Effective management of machine safety, as a subject in work processes, requires the need to learn from the past in order to develop the ability to predict the future. Investigations into machine accidents have been dominated by the search for causes, either as fundamental or human errors, a "reactive approach". That is why it is important that ZNR experts replace their traditional model of a reactive approach to security measures with a direction towards a proactive, holistic approach that addresses the "whole personality of a person" by integrating physical security, psychological and mental health, as well as environmental factors.

Turning challenges into opportunities requires an active approach, a change of perspective, anticipation and acceptance of change. Key opportunities are often found in problem solving, organization, learning new skills and adapting to new situations. Directive 2006/42/EC, known as the "machinery directive", ensures the harmonization of technical regulations for the design of machines in the European area, in order to ensure the health and safety of their users and to enable their free movement between countries.

Regulation 2023/1230 of the European Parliament and Council of 14 June 2023 clarifies the scope and certain definitions (machine, autonomous mobile machine, manufacturer, importer, distributor, etc.). The purpose of the regulation is to integrate new risks generated by digital and new technologies (collaborative robots, artificial intelligence, cyber security, etc.) while adapting requirements with regard to traditional risks and technologies (hazardous substances, vibrations of portable machines, overhead transmission lines, etc.).

Keywords: Machine safety; Process safety; Safety at work; Risk;

INTRODUCTION

A machine as a product and as an element of a process by definition is an assembly that is connected or intended to be connected to a drive system that does not directly use human or animal power, which consists of connected parts or components, at least one of which is movable and which are connected to each other for a special application. From the safety aspect, the machine as a product goes through three most important logical "life" phases: production, placement on the market and exploitation. The last stage requires the process owner to maintain the safety of the used product - the machine with risk-based management

tools. The meaning of proper maintenance is to achieve safety values in the process of creating a product, which will be sustainable throughout its lifetime.

At the end of the last century, the global approach to treating the problems left by machines in the exploitation phase changed. Protective devices, additional protection systems were not reliable enough, and the number of accidents, although significantly lower, was not acceptable for the community, as well as for employers. The concept of machine protection is replaced by the concept of safe machine. Namely, the provision of protective devices on already produced machines did not satisfy the producers and users, and especially left negative consequences for the operators. The technological development required a new approach to the code, which resulted in the form of the "Machinery Directive 2006/42/EC of the European Parliament and Council of May 17, 2006.

The main reasons for passing the Machinery Directive is to protect the health and safety of users:

- The directive set minimum requirements for machinery safety, in order to reduce the number of injuries and accidents at work.
- The focus was on physical risks (mechanical injuries, vibrations, noise), but also on new challenges such as software errors and automation.

As a "*guiding*" document for machinery manufacturers, the European Machinery Directive sets minimum safety requirements. The last amendment to the directive was on December 29, 2009, when 2006/42/EC was introduced.

In Europe, during the 1990s, the machinery directive marked the beginning of significant progress in cross-border cooperation by introducing European standards for the safety of machinery and equipment. Experience from different European countries has led to a wide range of safety standards and this has greatly facilitated the work on product safety. With the integration of Europe, it is now only sufficient for a security company to obtain one approval for its components for the whole of Europe instead of one per member state. Products bearing the CE mark - "Communaute Europeenne" can be imported and sold regardless of national regulations. That is why the "CE" mark is often referred to as a "*quasi passport for the European market*" in communication..

Today, machine safety has become a complex discipline that includes technical, legal and ergonomic aspects. There are international standards such as ISO 12100 and ISO 13849 that provide guidelines for risk assessment, the design of safe machinery and the implementation of appropriate protective measures. In addition, there are national regulations that apply in each country to ensure safety at work.

In the future, machine protection will continue to evolve to adapt to new technological innovations and industry demands. Advances in artificial intelligence, robotics and automation are expected to enable the development of more advanced protection systems on machines. Continuing education and training of workers to properly use and maintain the

safety features of the machines will also be important. In 2020, as part of the Commission's work program "Europe for the Digital Age", the Machinery Directive (2006/42/EC, is replaced by the EU Regulation 2023/1230 - which enters into force on 20 January 2027) in order to ensure uniform rules on machine safety at EU level and remove differences in national legislations and respond to new risks associated with digitization and advanced technologies.

Harmonization of national legislation with EU technical legislation, i.e. adoption of technical regulations in the field of machine safety is the responsibility of the Ministry of Economy. On the basis of the Law on Technical Requirements for Products and Conformity Assessment, the Minister of Economy issued the Rulebook on Machine Safety "Official Gazette of RS", No. 58/16, which is fully compliant with all principles and essential requirements from Directive 2006/42/EC on machines and its amendments from Directive 2009/127/EC.

The new regulation establishes for the first time specific essential requirements for the protection of health and safety related to the protection of the environment and which apply to pesticide application machines. These essential requirements are contained in section 2.4. Annex 1 of the Rulebook. Apart from the harmonization with the EU regulations in the part related to machines for applying pesticides, the new rulebook abolished the obligation to obtain certificates of conformity for certain types of machines. The Rulebook is accompanied by a list of *Serbian standards in the field of machine safety*, which is updated in accordance with the list of European harmonized standards published in the Official Journal of the EU. In the official gazette of the RS, no. 22/17 of March 12, 2017, a new list of Serbian standards in the field of machinery was published. At the same time, the Department for Quality and Product Safety of the Ministry of Economy has prepared it with the aim of helping all business entities (manufacturers, importers, distributors of machines), competent inspectors within the framework of market surveillance, competent authorities for occupational safety and health, but also other interested parties to whom it applies, that is, who apply this rulebook, such as designated bodies for conformity assessment, standardization, consumer associations, etc. Which of these practices has been implemented in the sphere of the Occupational Safety and Health system? Literally NOTHING. If we add to this the standard SRPS ISO 4501 *Occupational Health & Safety Management Systems*, the only conclusion is that our system of Safety and Health at Work is orthodox pathological.

The question is how to proceed? Directive 2006/42/EC on machinery and Directive 2009/127/EC on amendments have been replaced by Regulation 2023/1230 of the European

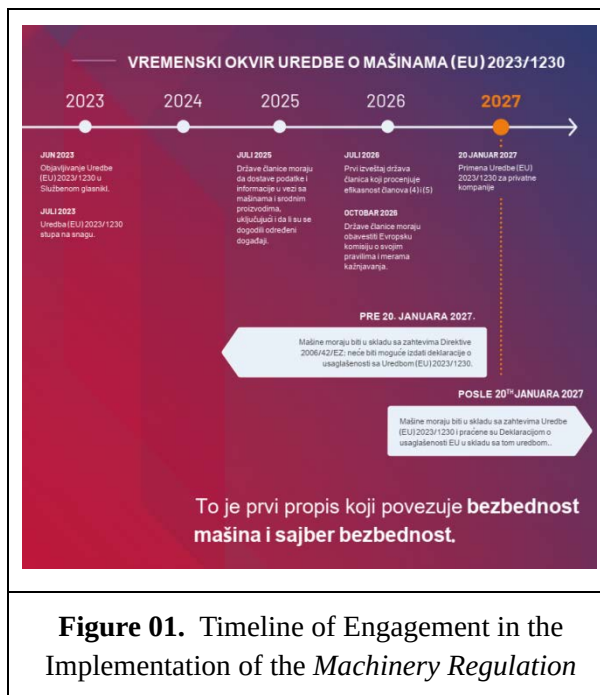


Figure 01. Timeline of Engagement in the Implementation of the *Machinery Regulation*

Parliament. Will the head of the System remain in the sand or will the system finally be organized into a respectable institution that will resemble such European institutions.

WHY CHANGES ARE NECESSARY

It is a fact that even during the eighties of the last century, industrial robots moved into production facilities and became more and more integral parts of the production processes day by day. This meant that the workers were outside the hazardous areas during production, but at certain time intervals they had to enter the hazardous area in order to adjust the device, inspect the components, diagnose the condition, eliminate defects and program the work process. With that fact new risks were introduced and new security methods were needed.

Today, there are significant opportunities for workplace advancement and productivity growth with the integration of *artificial intelligence* (AI) applications and tools in the workplace. However, there are also important OSH (*Occupational safety and health*) issues that arise as AI is integrated into the workplace. It has already been shown that stress, discrimination, increased insecurity, musculoskeletal disorders and the possibility of work intensification and job loss represent psychosocial risks, including physical violence in digitized workplaces. These risks are exacerbated when AI complements existing technology tools or is newly introduced for workplace management and design. Indeed, AI multiplies OSH risks in digitized workplaces, as it can enable increased tracking and monitoring and thus lead to micro-management, which is a major cause of stress and anxiety. AI emphasizes the imperative of giving greater credibility and potential authority to predictive machines, robotics and algorithmic processes at work (A.Bardri et al, 2022). But it is worth emphasizing that technology in isolation does not create benefits for occupational safety risks. *Collaborative robots*, often abbreviated "*cobots*", which are designed for safe interaction and work together with humans in shared workspaces, make a special mark in the new age or 4K industry. Unlike traditional industrial robots that work autonomously behind a cage, cobots are built with advanced sensors, artificial intelligence and control algorithms that allow them to work near humans. The concept of collaborative robots emerged in the late 1990s from research labs investigating how robots could work alongside humans on assembly lines or other tasks.

The outlook for collaborative robots remains very promising with cobot sales projected to grow by over 20% annually through 2030, reaching global annual shipments of between 600,000 to 900,000 units, and worldwide operational inventory exceeding 12 million cobots. Driving this growth is the expanding range of lightweight, simple cobots from pioneering companies such as Universal Robots and Techman Robot, which are affordable to most small manufacturers. Ultimately, collaborative automation will become indispensable in many more industries as cobots mature from new technologies to flexible main manufacturing partners integrated into the fabric of nearly all manufacturing and service operations that require optimized human-robot collaboration. (Phoebe V. Moore 2019).

In 2022, 2.97 million non-fatal accidents resulting in at least four calendar days of absence from work and 3286 fatal accidents were recorded in the EU in 2022. This is a ratio of approximately 905 non-fatal accidents for every fatal accident. Three out of ten (29.9%) non-fatal occupational accidents in the EU in 2022 occurred in industrial locations. More than a quarter (27.4%) of fatal accidents at work during 2022 in the EU are the result of loss of control over a machine, tool or transport/handling equipment. The most common types of accidents at work without fatal consequences in the EU are the result of physical or psychological stress (22.4%) or collision with an immovable object (21.6%).

Advanced sensor technologies and control methods are necessary to enable robots and humans to work together in shared spaces. Today's cobots use a combination of proximity sensors, vision systems, force sensors and artificial intelligence to continuously monitor their surroundings and precisely control movements. Common security features found in collaborative robots include:

- **Force Sensing:** Cobots can detect forces in multiple axes and respond by stopping motion to prevent collision injuries.
- **Speed and separation monitoring:** On-board sensors monitor speed, proximity to people and separation distance to avoid contact by automatically slowing down or stopping.
- **Lightweight design:** Cobots typically have payloads under 35kg and use rounded casings and padded materials to limit damage in the event of any accidental contact.
- **Emergency stop:** Manual e-stop buttons or automatic safety triggers can immediately stop cobot movements when triggered by sensors.
- **Proven safety methods:** Reputable cobot manufacturers send their robots for testing and certification by standardized bodies to confirm their adherence to global safety standards.

By leveraging these safety features, cobots can eliminate the need for physical barriers between robots and workers that have previously limited collaborative applications in industrial settings. Challenges with the implementation of collaborative robots offer enormous advantages, however, realistically, there are still some challenges around the adoption of *cobots*:

Perceived risks: There is lingering uncertainty on the part of workers and management about whether cobots can be fully trusted to work safely as co-workers without unintentionally harming humans, possible mechanical failures or control errors.

Inadequate sensor capabilities: Even the advanced sensor packages on today's cobots can still respond inadequately to rapid movements or complex sequences of movements that require more careful monitoring.

Custom applications: Although easier than traditional automation, some highly customized tasks or workflows are still complex endeavors to program collaborative robots to perform well at acceptable speed and safety.

Overcoming these challenges is a continuous challenge for robotics manufacturers, system integrators and companies to work closely with end users. Extensive operator training, adopting a phased deployment approach, and continuous sensor improvement are examples of current strategies that allow businesses to take full advantage of the promise of human-robot collaboration.

KEY CONTENTS OF THE NEW REGULATION

In an attempt to clarify the essence of the need to implement the new Machinery Regulation (EU 2023/1230) in business practice and the national area of the "Safety and Health at Work" system, it is best to emphasize three key dimensions: safety, competitiveness and legal compliance.

1. Safety and protection of workers

- The regulation introduces expanded essential health and safety requirements (EESS - *Essential Health and Safety Requirements*), including digital risks (Artificial Intelligence, cyber security, collaborative robots).
- Through implementation, companies will ensure a higher level of employee protection, reducing the number of injuries and accidents.
- This directly reduces the costs of sick leave, compensation and lost productivity.

Annex III. It has been reorganized in relation to the Directive, and it refers to basic health and safety requirements (EHSRs - Essential health and safety requirements). This annex to the Regulation has been significantly amended, including:

Ergonomics (Article 1.1.6), which considers the way operators interact with machines or related products that have fully or partially self-developing behavior.

Autonomous mobile machines (clause 3.6.3.3) receive additional requirements, which are included in Annex III and additional essential health and safety requirements to mitigate risks due to the mobility of machines or related products.

Protection against corruption (clause 1.1.9) introduces cyber security requirements related to OT (operational technology) and has been added to cover the increase of industrial networks for security systems, as well as data generation to support the growth of connected business solutions. It covers both hardware and software requirements.

Machines must ensure that the other device is connected - either locally or remotely - in a way that does not lead to a dangerous situation. In addition, any hardware component that transmits signals or data and has access to software that is critical to the machine's compliance with relevant health and safety requirements must be protected from accidental or intentional damage and will collect evidence of legitimate or illegal intervention.

Finally, to protect against corruption, software and data that are critical to the compliance of machines or related products with relevant health and safety requirements must be identified

as such and must be adequately protected against accidental or intentional corruption. The machine or related product must identify the software installed on it that is necessary for its safe operation; and must be able to leak information at all times in an easily accessible form.

The machine or related product must collect evidence of legitimate or illegitimate intervention in the software or modification of the software installed on the machine or related product or its configuration.

2. Competitiveness and market access

- Only machines that meet the requirements of the regulation can carry the CE mark and move freely on the EU market.
- The implementation enables domestic producers and users to remain competitive and to place products on the European market without obstacles.
- Compliance with the regulation becomes a prerequisite for international tenders and infrastructure projects.

3. Legal certainty and responsibility

- The regulation clearly defines the obligations of producers, importers, distributors and employers.
- Any significant modification of the machine is treated as a new production, so responsibility for safety is clearly established. (how to carry out "*examination - verification and examination*" - authorization)?
- Implementation prevents legal disputes and fines, because it shows that the company acted in accordance with EU regulations.

The new Regulation (EU) 2023/1230 on machinery brings significant changes in its content compared to the previous Directive 2006/42/EC: because it introduces mandatory rules for the entire life cycle of the machine, expands definitions and includes new risks associated with digital technologies, artificial intelligence and cyber security.

What is new in the Regulation? Essentially, many of the requirements of the Machinery Regulation are only described in more detail and clarity than the content of the Directive. However, there are also some changes in content compared to the 2006 Directive. These are requirements that particularly relate to the area covered by the BZNR system, and they refer to requirements for functional security extended to software. In addition, there are aspects of cyber security and artificial intelligence. Added security requirements for autonomous (*mobile*) machines. The obligations of economic operators (manufacturers, authorized representatives, importers and distributors) are described in Chapter II of the regulation. They are very clearly presented for individual commercial operators in separate articles.

All other machinery and related products	Machinery or related products listed in Annex I		
	Category Annex I, part B (e.g. Presses, Woodworking, Injection Molding, ...)		Category Annex I, part A (6 Categories including e.g. Vehicle lifts, Safety-Systems containing self-evolving behavior, ...)
	Full compliance to harmonized standards	No only partly compliance to harmonized standards	
	a) Module B (Annex VII) EC Type Examination AND Module C (Annex VIII) Conformity to Type Based on Internal Production Control b) Module H (Annex IX) Full Quality Assurance c) Module G (Annex X) Unit Verification		
Module A (Annex VI) Internal Production Control Voluntary testing by TÜV Rheinland and Certificate of Conformity possible	Involvement of a Notified Body mandatory (e.g. TÜV Rheinland LGA Products GmbH) CE with Number of Notified Body (e.g. CE 0197 TÜV Rheinland LGA Products GmbH or CE 1008 TÜV Rheinland Intercert (Hungary))		

Figure 02. Flow diagram showing possible conformity assessment procedures for different categories of machinery.

Annex I - Regulation lists machines for which a special conformity assessment procedure is prescribed, Figure 02. This list is now divided into two parts:

- **Part A** (provides mandatory participation of the certified body) i
- **Part B** (provides a procedure as for machines 2006/42/EC, Annex IV).

The key news is Regulation (EU) 2023/1230 on machinery:

- Directive replacement: Directive 2006/42/EC and 73/361/EEC are repealed; the new regulation is directly applicable in all EU member states without the need for national transposition.
- Life cycle of a machine: The Regulation covers all stages – design, production, procurement, operation, modification, maintenance, resale, rental, recycling and disposal.
- New definitions: Terms like "autonomous mobile machine", "manufacturer", "importer", "distributor" are clearly defined.
- Digital risks: Collaborative robots, AI systems, cyber security, as well as traditional risks (vibration, hazardous substances, power lines) are included.
- Obligations in the supply chain: Manufacturers, importers and distributors have clearly defined responsibilities.
- Machine modifications: Any natural or legal person who makes a significant modification becomes a "manufacturer" and assumes all obligations in accordance with Art. 10 of the decree.

Table 01. Comparison of obligations declared by the Old Directive and the New Regulation

Element	Directive 2006/42/EC	Regulation (EU) 2023/1230
Legal form	Directive (requires transposition)	Regulation (directly applicable)

Element	Directive 2006/42/EC	Regulation (EU) 2023/1230
Entry into force	2006	14. January 2027.
Fokus	User health and safety	Security + Digital Risks (AI, Cyber)
Liability for modifications	Not clearly defined	Any major overhaul is a new manufacturer
Definitions	Basic	Extended (autonomous machines, AI systems)
Supply chain	Less precise	Clearly delineated obligations of producers, importers, distributors

The consequences produced by the application of the new Regulation are:

- *Harmonization of legislation:* As a candidate country for the EU, Serbia will have to adapt its regulations to this regulation.
- *Industry and employers:* Businesses that use or modify machinery will need to ensure compliance with the new rules, particularly with regard to digital technologies.
- *Safety of workers:* A higher level of protection is expected through mandatory risk assessment and integration of cyber security measures.

Table 02 presents a matrix of obligations, which clearly shows the obligations of different actors according to the new Regulation (EU) 2023/1230 on machinery. You can use it as a technical attachment in project documentation or presentations. The practical role of the matrix gains importance in:

- **Manufacturers:** use the matrix as a checklist for design and certification.
- **Importers and distributors:** they ensure that machines entering the market meet all requirements.

Employers/users: have clearly defined obligations regarding safety, training and responsibility for modifications.

Table 02. Matrix of obligations by subjects - participants in the implementation of the Regulation

Actor / Obligation	Manufacturer	Importer	Distributor	Employer / User
Design and production	Must ensure compliance with essential health and safety requirements, including digital risks (AI, cyber security).	Not applicable	Not applicable	Not applicable
Risk assessment	Mandatory risk assessment for all stages of the	Checks whether the manufacturer has	Checks whether the machine has "CE" marking and	Mandatory internal risk assessment during

Actor Obligation	Manufacturer	Importer	Distributor	Employer / User
	machine's life cycle.	documentation.	documentation.	use and modification.
Technical documentation	Compulsory compilation and storage of technical documentation.	Must ensure documentation exists and is available.	It must ensure the availability of documentation to the user.	Keeps documentation and uses it in training and maintenance.
"CE" marking and declaration	Mandatory placement of the "CE" mark and issuance of the EU declaration of conformity.	Checks that the "CE" mark is correct.	Must not distribute the machine without the "CE" mark.	Use only "CE" - marked machines.
Digital security	Integration of cyber security measures and protection against software manipulation.	Checks whether the measures are implemented.	May not distribute machines that do not meet digital requirements.	Mandatory software maintenance and updates for security.
Machine modifications	If he makes a significant modification, he becomes a new manufacturer.	If he makes a modification, he assumes the manufacturer's obligations.	If he makes a modification, he assumes the manufacturer's obligations.	If he makes a modification, he becomes the manufacturer and bears full responsibility.
Training and worker safety	Not applicable	Not applicable	Not applicable	Mandatory training of workers and application of occupational safety measures.
Recycling and disposal	Must provide end-of-life instructions.	Checks for instructions.	It must pass instructions to the user.	Responsible for proper disposal and recycling.

CONCLUSION

Management systems must be designed and constructed in a way that prevents dangerous situations from occurring. They should also withstand, where appropriate under the circumstances, risks, anticipated operational stresses and anticipated and unintended external influences, including reasonably foreseeable malicious attempts by third parties leading to a

dangerous situation. If it is about equipment that is an element of the process, and which is marked with the "CE" mark, i.e. harmonized means that it has satisfied the principle of prevention in everything, then it is left to engineering practice that the equipment taken over from the manufacturer, which carries a certain level of residual risk, retains functional and safety attributes. The employer has the obligation to implement procedures that ensure the supervision of the condition of the equipment.

That fact is enough for the notion of risk and the specific engineering knowledge used to manage risk to place the elements of process safety in the highest level of the proactive management model. As a function of such interests, a series of risk-based tools corresponding to the proactive management concept is developed in the management process model.

Only risk-based maintenance management can serve as a basis for conceiving occupational safety management, which, with the support of engineering diagnostic methods, will turn the concept of risk into a powerful management tool and define the responsibility of each element in the exploitation process, such as product conformity regulated by the manufacturer's obligations.

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DESIGNING GREEN ENGINEERING LEARNING MATERIALS FOR SUSTAINABLE AND DIGITAL TRANSFORMATION

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Abstract: The growing importance of green and digital transition processes has increased the demand for new knowledge, skills, and educational approaches within engineering education. This paper presents the GreenTech Horizons Ecosystem as a theoretical model for the development of sustainability-oriented engineering learning resources in higher education. The proposed model integrates European educational and sustainability frameworks with learning approaches and educational outcomes relevant to green engineering education. The discussion draws upon GreenComp, DigComp, Industry 5.0, the European Green Deal, the Digital Education Action Plan, Education for Sustainable Development, and Competency-Based Education. The analysed frameworks reflect increasing integration of sustainability-related concepts, digital technologies, and applied learning within higher engineering education. Attention is devoted to AI-supported learning materials, simulations, virtual laboratories, project-based learning, and interdisciplinary educational activities. The study highlights systems thinking, environmental awareness, digital skills, lifelong learning, and problem-solving as important educational outcomes associated with green engineering education. The proposed model provides a basis for the development of sustainability-related educational resources aligned with green and digital transition processes within higher education.

Keywords: *Competency-based education; Sustainability capabilities; Digital learning; Green learning ecosystems.*

INTRODUCTION

Sustainable and digital transition processes increasingly influence competence requirements within engineering education and professional practice. The European initiatives such as the European Green Deal, Industry 5.0, and the Digital Education Action Plan emphasize the importance of integrating sustainability, digital technologies, and human-centered innovation within education and industrial development (European Commission, 2019; European Commission, 2020; European Commission, 2021). The concept of the “twin transition” increasingly connects green transition objectives with digital transformation processes, particularly in sectors characterized by technological and environmental change.

Higher education institutions are increasingly expected to modernize engineering curricula and introduce digitally supported and practice-oriented educational approaches relevant to green engineering fields. Climate challenges, technological development, and industrial digitalization continue to influence the organization of higher education systems and engineering education (Bulut and Haçat, 2026). Recent studies emphasize the importance of curriculum modernization, practice-oriented learning, and digitally supported educational approaches in engineering education, particularly in relation to emerging green engineering profiles and industrial requirements (da Costa et al., 2025). At the same time, higher education institutions continue to face challenges related to integrating sustainability-related knowledge and skills within existing engineering curricula (Safee and Kosnan, 2024).

In the field of green engineering education, learning materials are increasingly designed to support systems thinking and environmental awareness, practical problem-solving, and digital competences. GreenComp emphasizes sustainability values, systems thinking, futures literacy, and collective responsibility, while DigComp focuses on digital literacy, communication, collaboration, and responsible use of digital technologies (European Commission, 2022; Vuorikari et al., 2022). Competency-Based Education (CBE) promotes learner-centered and practice-oriented learning relevant to engineering education and professional preparation (Mulder, 2017; Wiek et al., 2011). Education for Sustainable Development (ESD) additionally supports the integration of sustainability principles, ethical responsibility, and environmental awareness within educational systems (UNESCO, 2020). Together, these educational approaches provide a basis for the development of Green Engineering Learning Materials that integrate environmental and sustainability principles, digital technologies, and applied learning within engineering education.

Digital educational technologies increasingly influence engineering learning environments and practical educational activities (Zawacki-Richter et al., 2019; UNESCO, 2023).

The aim of this paper is to develop the GreenTech Horizons Ecosystem as a theoretical framework for the design of Green Engineering Learning Materials in higher education (GreenTech Horizons Project, 2025). The proposed framework integrates sustainability competences, digital literacy, and Industry 5.0 principles with interdisciplinary and practice-oriented educational approaches. These include interdisciplinary curricula, AI-supported learning materials, virtual laboratories, simulations, and collaborative learning environments. The paper further discusses the potential contribution of the proposed framework to the modernization of engineering education in the context of sustainable and digital transformation.

METHODOLOGY

This study proposes a theoretical model for the design of Green Engineering Learning Materials within higher engineering education. The model was developed through comparative analysis of educational frameworks, sustainability-related concepts, and digital

learning approaches relevant to green engineering education. It combines digital learning methods, interdisciplinary educational practices, and applied learning activities associated with green and digital transition processes. Figure 1 illustrates the relationship between educational priorities, digital learning approaches, and expected educational outcomes within the conceptual structure of the model.

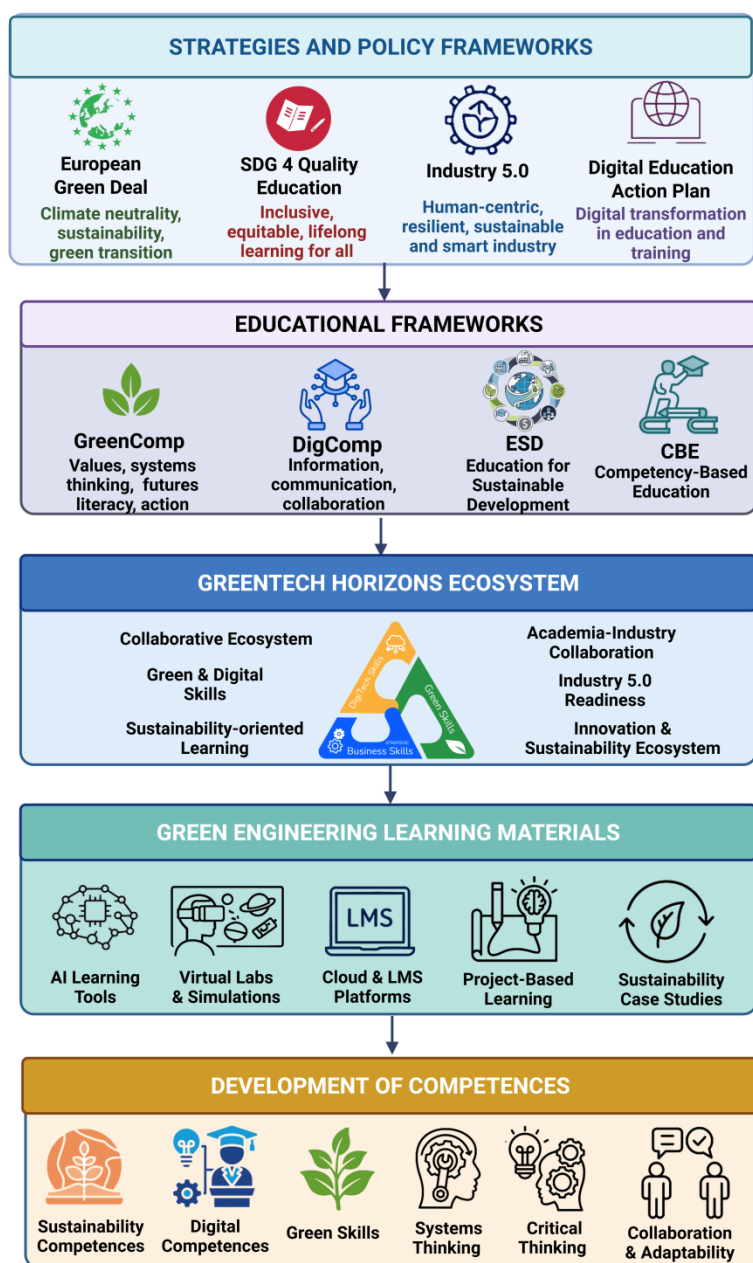


Figure 1. Conceptual framework for designing Green Engineering Learning Materials for sustainable and digital transformation

The analysis included educational frameworks and policy initiatives related to sustainability, digital education, and skills-oriented learning, including GreenComp, DigComp, Education for Sustainable Development (ESD), and Competency-Based Education (CBE).

The framework additionally integrates digital technologies, interdisciplinary learning environments, and practice-oriented educational activities within the GreenTech Horizons Ecosystem. AI-supported learning materials, virtual laboratories, simulations, and project-based learning activities are included as important components of Green Engineering Learning Materials.

These educational activities are associated with systems thinking, environmental awareness, digital skills, and applied engineering knowledge relevant to green and digital transition processes. The conceptual model therefore provides a basis for the development of sustainability-related engineering learning resources and applied educational practices within higher engineering education.

RESULTS AND DISCUSSION

The proposed model was developed through the mapping of European educational and sustainability frameworks with Green Engineering Learning Materials, learning approaches, and expected educational outcomes (Table 1). The analysed frameworks reflect closer integration of sustainability-related concepts, digital technologies, and applied learning within higher engineering education. Systems thinking, digital skills, interdisciplinary learning, and applied learning activities appear consistently across the analysed frameworks.

Recent studies highlight the growing use of digital technologies within engineering education, particularly through virtual laboratories, simulations, AI-supported learning environments, and eLearning platforms (Zawacki-Richter et al., 2019; UNESCO, 2023). Such tools may improve practical understanding of environmental and technological challenges related to sustainability.

The analysed approaches connect environmental knowledge with applied and workplace-oriented learning. Competency-Based Education and Industry 5.0 concepts place stronger emphasis on collaborative learning, practical problem-solving, and human-centered technological development (Mulder, 2017; European Commission, 2021). Project-based learning, simulations, and interdisciplinary activities are therefore increasingly incorporated into engineering education related to green and digital transition processes.

The GreenTech Horizons model integrates green engineering educational content with digital learning tools and collaborative educational activities. AI-supported learning materials, simulations, virtual laboratories, and interdisciplinary activities represent important elements of the proposed educational model. These approaches may support systems thinking, digital skills, environmental awareness, and practical engineering knowledge relevant to

contemporary industrial and environmental challenges (Wiek et al., 2011; da Costa et al., 2025).

Table 1. Mapping of European Frameworks and Green Engineering Learning Materials within the GreenTech Horizons Framework

Framework / Policy	Green engineering learning materials	Learning approaches	Expected outcomes
GreenComp	Green engineering educational materials	Case studies, interdisciplinary learning	Systems thinking, environmental awareness
DigComp	Digital and AI-supported educational materials	Simulations, virtual labs, e-learning	Digital literacy, digital collaboration skills
ESD	Environmental learning resources	Reflective and student-centered learning	Environmental awareness, lifelong learning
CBE	Applied and skills-oriented learning materials	Project-based learning, authentic assessment	Workplace preparedness, applied skills
Industry 5.0	Industry-related engineering resources	Practical activities, virtual simulations	Problem-solving skills, human-centered technological understanding
European Green Deal	Educational content related to green transition	Integration of sustainability topics within courses	Awareness of green transition principles
Digital Education Action Plan	AI-supported digital learning resources	AI-supported teaching, digital collaboration	Digital collaboration and AI-related skills

The analysed frameworks reflect increasing integration of sustainability-related concepts, digital learning, and applied engineering education. Although the frameworks differ in their educational focus, they collectively support practical learning, digital skills, interdisciplinary education, and environmental and sustainability knowledge within higher engineering education.

CONCLUSION

This paper discussed the development of Green Engineering Learning Materials in the context of sustainable and digital transformation within higher education. The proposed GreenTech Horizons model integrates European sustainability initiatives, digital education strategies, and applied educational approaches relevant to contemporary engineering education.

The discussion highlights strong connections between sustainability goals, digital technologies, and engineering learning environments. Educational approaches based on simulations, virtual laboratories, AI-supported learning materials, and project-based activities may support interactive and applied learning within green engineering education.

The analysed educational frameworks identify systems thinking, lifelong learning, digital skills, interdisciplinary learning, and problem-solving as important educational outcomes related to green and digital transition processes. Such approaches may support practical engineering education aligned with environmental and technological transition processes.

The proposed model therefore provides a basis for the development of development of sustainability-related engineering learning resources aligned with green and digital transition processes within higher education.

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DETERMINATION OF CRITICAL CONTROL POINTS FROM A FIRE PROTECTION PERSPECTIVE IN SURFACE MINING AND COPPER PRODUCTION

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Abstract: This paper presents a comprehensive analysis of the technological process of surface copper ore exploitation and its subsequent processing, from the excavation stage to the production of high-purity refined copper. The main objective of the study is the identification of critical control points (CCPs) from a fire protection perspective across all stages of the process, including mining, ore transportation, comminution, flotation, pyrometallurgical processing, electrolytic refining, and waste management. Special emphasis is placed on the assessment of fire and explosion risks associated with flammable dust, elevated temperatures, combustible chemicals, mechanical sparks, and electrostatic discharge. Based on a systematic risk analysis, key points and mechanisms of fire initiation and propagation within the process were identified. Furthermore, appropriate preventive measures are proposed, including technical solutions, monitoring systems, organizational procedures, as well as advanced fire detection and suppression systems. The results highlight the importance of an integrated approach to risk management in complex mining and metallurgical systems, with the aim of enhancing occupational safety, fire protection, and environmental performance.

Keywords: *copper production, surface mining, critical control points (CCPs), fire protection.*

INTRODUCTION

In the modern mining and metallurgical industry, copper production is mainly based on the exploitation of sulphide ores, among which chalcopyrite (CuFeS_2), chalcocite (Cu_2S) and bornite (Cu_5FeS_4) dominate, where the copper content in the primary ore usually does not exceed 1%. Much less often, oxide ores such as malachite ($\text{CuCO}_3 \cdot \text{Cu(OH)}_2$), azurite ($2\text{CuCO}_3 \cdot \text{Cu(OH)}_2$) and cuprite (Cu_2O) are exploited, which have a limited importance in overall copper production (Schlesinger, 2021). The low concentration of the valuable component in the ore necessitates the application of complex technological processes aimed at its beneficiation and the production of high-purity copper (Mitovski, 2015).

The copper production process comprises several interconnected stages:

- surface exploitation and transport of ore,
- crushing of ore (crushing and grinding),

- flotation,
- pyrometallurgical and hydrometallurgical processing,
- electrolytic refining,
- disposal of mining waste.

Each of these stages is characterized by specific technological conditions and operations that may represent potential sources of fire and explosion hazards (Tjernlund, 1999). In this context, the identification of critical control points (CCPs) is a key element of risk management, as it enables the recognition of process locations and operations with an increased likelihood of fire occurrence, as well as the definition of appropriate preventive and protective measures. A systematic approach to risk analysis, combined with the implementation of effective control mechanisms, is essential for improving occupational safety and health, ensuring process reliability, and enhancing environmental protection (Andjelković, 2002).

EXPLOITATION AND TRANSPORT OF COPPER ORE

Copper ore is extracted in open-pit mines, which represent a significantly simpler and safer method compared to underground mining. This method, commonly referred to as surface mining or open-pit mining, is applied to mineral deposits located at or near the surface. Deposits situated close to the surface are typically covered by overburden, consisting of humus soil or other rock material, often of sedimentary origin or derived from the weathering of primary rock. Prior to ore extraction, this unproductive material must be removed in a process known as stripping, after which the exploitation of the mineral resource can commence (Milić, 2005). The removed overburden is deposited in designated areas on the surface, commonly referred to as waste dumps or disposal sites. Excavation in open-pit mines is performed on working levels, usually horizontal, known as benches.

During the exploitation phase, a wide range of heavy machinery is employed, including drilling rigs, excavators, loaders, and haul trucks. The operation of such equipment introduces potential fire hazards, primarily due to engine overheating, mechanical failures, and faulty electrical installations. Additional risks arise from fuel, oil, and lubricant leaks, which may serve as ignition sources under certain conditions. Furthermore, storage facilities for fuel, lubricants, and explosives are often located in proximity to mining operations, which may further increase the overall fire risk.

Measures aimed at reducing fire risk during the exploitation phase include the regular maintenance and inspection of equipment, as well as the installation of automatic fire protection systems. In addition to these systems, all vehicles must be equipped with portable fire extinguishers for initial fire response. Fuel, oil, and lubricant storage facilities, as well as explosives storage areas, should be equipped with automatic fire detection systems, including flame detectors due to the potential risk of explosions. In addition to detection systems, adequate fire protection infrastructure must be provided, including portable fire extinguishers

and both internal and external hydrant networks. If an explosives storage facility is located within or in close proximity to the mining complex, the applicable legislation of the Republic of Serbia requires the establishment of a properly equipped and trained industrial fire brigade.



Figure 1. Surface exploitation of copper ore

The extracted ore is transported by haul trucks to the primary crushing plant. From there, the crushed ore is conveyed via belt conveyors to the secondary and tertiary crushing stages. In this phase, conveyor systems represent critical control points, as friction between rollers and the belt structure may lead to overheating and ignition. Additionally, the accumulation of fine dust beneath and alongside conveyor belts poses a significant fire hazard. Transfer points between conveyor belts are particularly critical due to increased dust generation and dispersion.

From a fire safety perspective, mineral dust-especially from sulphide ores-can ignite under certain conditions, particularly during improperly managed hot work activities such as cutting, soldering, and welding. Furthermore, sulphide ores are prone to oxidation processes that release heat, which may result in self-heating, smouldering, and eventually fire. Mechanical sparks generated by metal-to-rock contact or during equipment operation can also act as ignition sources.

Preventive measures include the installation of automatic temperature monitoring and flame detection systems on conveyor belts, as well as fixed fire suppression systems. Regular maintenance of transport systems and systematic removal of accumulated dust are essential. During hot work operations, all prescribed fire protection measures must be strictly implemented. Personnel performing such tasks must be adequately trained, qualified, and fully aware of associated risks and mitigation measures. Work areas must be equipped with appropriate portable fire extinguishers, and the implementation of a formal hot work permit system is mandatory.

COPPER ORE CRUSHING

Crushing of ores aims to bring the ores to the required granulation, by the action of external forces, while at the same time creating the possibility of classification. Ore crushing devices are divided into crushers (jaw, cone, roller, impact centrifugal and disintegrator) and mills (roller, mill, rotary with balls or rods, vibration, disintegrator and current mills).



Figure 2. Copper ore crushing

During the operation of the crushing and grinding line, dust is generated at all stages, particularly at material transfer points. The risk of fire and dust explosions arises not only from the presence of explosive dust concentrations and ignition sources, but also from the high reactivity of the processed material, temperature increase, electrostatic charge accumulation, and the prolonged residence of finely dispersed particles in mills and associated equipment.

Mills generally exhibit relatively low energy efficiency, with a significant portion of the input energy dissipated as heat, resulting in the heating of both the mill components and the processed material. The operating temperature within mill chambers depends on several factors, including mill type and size, degree of comminution, mode of operation (continuous or batch), and cooling capacity. In ball mills, operating temperatures may reach up to 100 °C, creating conditions conducive to self-heating and potential self-ignition. In contrast, fluid energy (jet) mills transfer particle kinetic energy to the working fluid (air), maintaining particle temperatures typically below 15-20 °C and significantly reducing the likelihood of self-ignition. In other mill types, however, conditions may favor material heating, particularly in cases of material stagnation, which can lead to self-heating and eventual ignition (Krstić, 2018).

During dry grinding of dielectric or semi-conductive materials, dust particles may become electrostatically charged. This can lead to particle repulsion from mill surfaces, reduced grinding efficiency, and the accumulation and adhesion of dust on equipment surfaces, prolonging its residence time. Electrostatic discharge may occur under such conditions, potentially igniting flammable aerosols and initiating explosions. However, practical experience indicates that proper grounding of rotary, vibration, and impact centrifugal mills effectively mitigates electrostatic hazards. In contrast, significant risks remain in systems involving mills and associated equipment such as cyclones and filters, where electrostatic sparks may ignite combustible aerosols.

Statistical data indicate that one of the most frequent causes of material ignition in mills is the presence of foreign objects (e.g., stones or metal fragments). During impact or friction between hard materials and steel components of mills (e.g., rotor or stator in impact centrifugal mills), highly heated particles-known as friction or impact sparks-are generated. These sparks result from the conversion of kinetic energy into heat, as well as from exothermic oxidation reactions. Their energy may be sufficient to ignite flammable mixtures of gases, vapors, or dust in air. The ignition potential of such sparks depends on both the sparking conditions and the physicochemical properties of the combustible material. A suspension of air and dust originating from sulphide ores can lead to explosions. The lower explosive limit (LEL) for most sulphide ores ranges from 250 g/m³ to 500 g/m³, with the most destructive explosions occurring at concentrations from 800 g/m³ to 1000 g/m³. In concentrations over 2000 g/m³, there is no explosion due to lack of O₂.

Factors affecting the hazard level are sulphur content and particle size. The higher the percentage of sulphur in the ore, the easier the dust is to burn and the greater the strength of the explosion. Ores with more than 25-30% sulphide are considered high risk. On the other hand, the finer the dust, the greater the total surface area of the particles exposed to oxygen - particles smaller than 0.075 mm are the most dangerous.

COPPER ORE FLOTATION

Due to the low copper content in the ore, it is necessary to apply a flotation process. This process results in the production of a concentrate containing approximately 25% sulphur, around 25% iron, and over 20% copper. Flotation is a physicochemical separation process based on differences in the surface properties of minerals. It utilizes the ability of certain minerals, when suspended in water, to attach to air bubbles and rise to the surface, forming a froth layer. In contrast, minerals that do not exhibit this property remain in the pulp and settle at the bottom, enabling their separation. By separating valuable minerals from gangue (tailings), the valuable components are concentrated; therefore, the resulting product is referred to as a concentrate. Since not all minerals exhibit the same wettability characteristics, various flotation reagents are added to modify their surface properties. These reagents include collectors, frothers, activators, depressants, and pH regulators.

Within a single flotation processing line, several sequential operations are performed. These include the dosing of ore, water, and flotation reagents into grinding mills for primary comminution, followed by material classification using spiral or rake classifiers. Subsequent stages involve secondary and tertiary grinding with classification, conditioning of the pulp to maintain proper dispersion, and processing in flotation cells. The generated froth, containing the concentrate, is removed and directed to thickeners and filtration units (e.g., rotary filters) for solid–liquid separation. The remaining material (tailings) collected at the bottom of the flotation cells is transported to thickeners and subsequently disposed of in tailings storage facilities.



Figure 3. Copper ore flotation

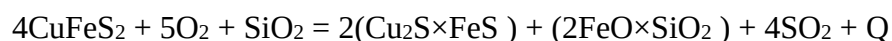
In all processing stages, including flotation cells, flotation reagents are continuously dosed. The majority of these reagents are classified as hazardous and toxic substances. They include mercaptans, dithiocarbamates, amines, various types of alcohols, potassium cyanide and other toxic salts, as well as strong acids and alkalis.

As flotation is predominantly a wet processing technology (excluding the initial mineral preparation stages), the inherent risk of fire and explosion is relatively low. However, considering the chemical composition of the reagents, the presence of flammable substances—such as various alcohols—cannot be neglected. In addition, numerous auxiliary materials used during maintenance activities (e.g., paints and varnishes) are also flammable. Furthermore, maintenance operations such as welding and grinding are frequently performed, which may introduce additional ignition sources and consequently increase fire risk.

PYROMETALLURGICAL AND HYDROMETALLURGICAL PROCESSING OF COPPER

Copper can be produced by pyrometallurgical or hydrometallurgical process. Most of the copper in the earth's crust is present in sulphide form, so **pyrometallurgical production** is far

more extensive. About 90% of copper is obtained by pyrometallurgical process (Biswas, 1994). At the moment, the application of the hydrometallurgical process of obtaining copper is limited to copper oxide ores. Today, in the exploitation of sulphide copper ores, they contain from 0.5% (surface exploitation) to 1-2% Cu in some mines and more (underground exploitation). In these deposits, most of the copper is present in the form of sulphide minerals such as chalcopyrite (CuFeS_2), bornite (Cu_5FeS_4), chalcosine (Cu_2S). Complex sulphide ores also contain other metal sulphides (ZnS , PbS , AsS , etc.) and represent significant copper reserves. Usually, the first stage of pyrometallurgical copper production is smelting. In order to remove impurities, sometimes some concentrates are pre-fried or go directly to melting. During the smelting process, the copper concentrate is melted and part of the sulphur and iron is removed by oxidation. The batch in the smelting furnaces is composed of copper concentrate, flux (SiO_2), air or oxygen-enriched air, return dust and waste. In order to balance the heat balance of the process, it is sometimes necessary to add fuel and/or inert materials. Modern smelting takes place in furnaces at temperatures of around 1200°C under an oxidizing atmosphere. The overall smelting reaction for chalcopyrite concentrate can be expressed as:



Usually, the operation of the furnace is semi-continuous (there are openings and vessels for the transfer of melting products) or completely continuous. The smelting products are: copper (45-77% Cu), slag and exhaust gas rich in sulphur dioxide.

The copper is transported in containers to the converter. The slag is discarded directly if its copper content is low (typically $< 1\%$ Cu) or processed by flotation or pyrometallurgical methods for copper and precious metals recovery and then discarded. The exhaust gas, which is rich in sulphur dioxide, is "washed" to remove dust before it is processed into sulphuric acid or liquid sulphur dioxide. When environmental regulations permit, the exhaust gas and sulphur dioxide are emitted directly into the atmosphere. In most developed countries, this practice is no longer allowed by law.

Critical points in this process occur in furnaces that develop high temperatures. Gas installations, burners, oxygen supply systems can also be risky. Manipulation of molten metal is also a risky work operation.

Hydrometallurgical processes are used to obtain metals or compounds in which an aqueous solution of acids, bases or salts is used as a means of separation. The basic processes that take place during the hydrometallurgical processing of raw materials are: leaching of raw materials (transferring metals into solution directly from minerals), concentrating and purifying metals from solutions and extracting metal compounds or metals themselves from solutions. Metal compounds are separated by precipitation, hydrolysis, crystallization, ion flotation, and metals by electrolysis, chemical reduction or cementation.



Figure 4. Coope leaching

Certain leaching reactions, particularly those involving sulphide-rich materials, may be highly exothermic. When combined with inadequate waste management practices, this can lead to self-heating and, in extreme cases, spontaneous combustion. The risk of fire may be further exacerbated under conditions of elevated ambient temperatures, such as during extreme heat waves. Other metallurgical processes and operations are also associated with increased fire and explosion hazards due to the use of flammable chemicals, the generation of flammable and explosive vapors, and the presence of outdated or improperly maintained electrical installations and equipment. These factors, individually or in combination, can significantly increase the likelihood of ignition.

Appropriate control measures include the implementation of continuous temperature monitoring systems, automatic flame detection systems, and integrated fire suppression and inerting systems. In addition, regular inspection and maintenance of electrical installations and process equipment are essential to ensure safe operation and to minimize the risk of fire and explosion.

ELECTROLYTIC COPPER REFINING

The objective of electrolytic refining is to produce high-purity copper and anode sludge enriched with valuable elements such as precious metals, selenium, and tellurium. This is achieved through the anodic dissolution of impure copper under the influence of direct current in an electrolyte solution, accompanied by the simultaneous deposition of pure copper onto the cathode. During copper electrolysis, direct current passes from the anode (impure copper) through an electrolyte composed of copper sulfate (CuSO_4) and diluted sulfuric acid (H_2SO_4), and is discharged at the cathode, where pure copper is deposited. Conventionally, electric current is considered to flow from the positive (+) to the negative (–) pole. The electrochemical system can be represented as:

Cu with impurities - (CuSO_4 ; H_2SO_4 ; H_2O) - pure Cu.

Critical points in this phase can occur when the electrolyte comes into contact with electrical equipment and installations. Vapors and gases are present to a great extent.

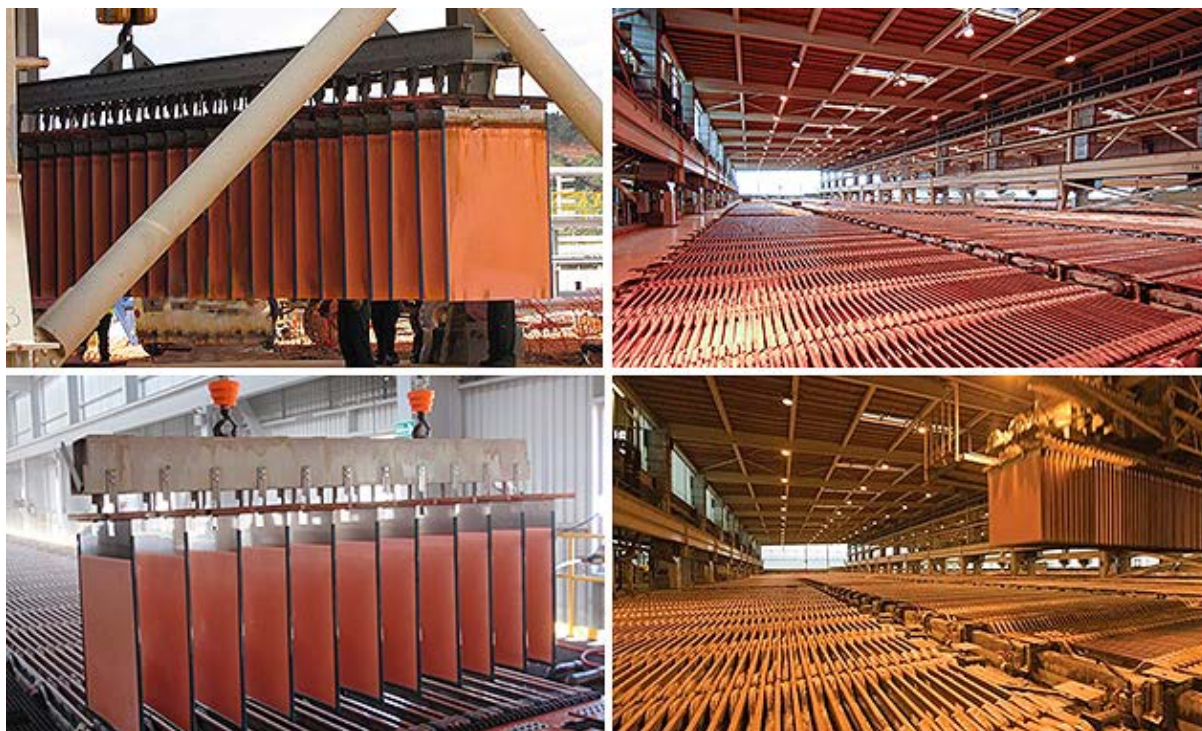


Figure 5. Electrolytic copper refining

The control measures are primarily focused on regular inspection and maintenance of installations, ensuring adequate electrical insulation, and continuous monitoring and detection of hazardous gases. The mining–pyrometallurgical extraction of metals comprises several sequential stages, including ore extraction, comminution (crushing and grinding), concentration of valuable components to produce mineral concentrates, and, finally, further metallurgical processing and refining to obtain purified metals.

MINING WASTE DISPOSAL

Waste is generated at all stages of metal extraction. It may consist of natural materials that have only undergone physical fragmentation (e.g., waste rock and low-grade mineralized material), or of materials that have been subjected to various degrees of processing during concentration and metallurgical treatment, and which may contain chemical, inorganic, and organic additives (Management of Mining, 2001). Ore extraction and concentration processes produce large quantities of non-marketable materials (mineral waste), most of which are typically disposed of as waste rock (coarse fractions) and tailings (fine-grained materials) (Chan, 2008). Mining waste disposal often occupies extensive land areas and, if not properly managed, can lead to significant adverse impacts on soil, water, and air quality. Mining activities expose large volumes of sulphide-bearing materials to atmospheric oxygen and

water, leading to oxidation processes that generate sulfuric acid. This, in turn, promotes the dissolution of metals, resulting in contamination of both surface and groundwater and the formation of acid mine drainage (AMD) or acid rock drainage (ARD) (Maluckov, 2014).

Residual sulphide minerals are frequently present in mining waste deposits. These materials are susceptible to oxidation and, under certain conditions, may lead to self-heating and spontaneous combustion. Therefore, continuous monitoring of parameters such as moisture content and temperature is essential. Upon closure, waste disposal sites should be covered with a suitable layer of topsoil (e.g., humus) and subjected to land recultivation measures. In order to prevent or minimize environmental impacts, it is necessary to implement integrated waste management practices at all stages of mining and pyrometallurgical operations. The reuse or reprocessing of mining waste, which may still contain significant amounts of copper, can reduce the demand for primary ore extraction and decrease the overall volume of waste requiring disposal.

CONCLUSION

The analysis of the technological processes involved in surface mining and copper production has demonstrated that specific fire and explosion risks are present throughout all operational phases. These risks are primarily driven by the characteristics of the working environment, the nature of process equipment, the presence of flammable substances, and elevated operating temperatures. The identification of critical control points has enabled a systematic assessment of locations and activities with an increased likelihood of fire occurrence. The results indicate that the most significant risk sources are associated with material transport systems, crushing operations, pyrometallurgical processing, and mining waste disposal. In these stages, hazards arise from the presence of combustible dust, generation of mechanical sparks, self-heating of materials, and exposure to high temperatures. Furthermore, inadequate equipment maintenance, the accumulation of static electricity, and the execution of hot work activities without appropriate safety measures have been identified as additional factors that significantly increase the probability of incident events. The application of an integrated risk management approach, based on the identification and control of critical points, represents an effective strategy for reducing fire risk. The proposed measures encompass technical, organizational, and preventive actions, including the implementation of continuous monitoring systems, improvement of maintenance practices, strict control of ignition sources, and the adoption of advanced fire detection and suppression systems.

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DIGITAL TWINS AS A MODERN SOLUTION FOR IMPROVING OCCUPATIONAL SAFETY AND HEALTH

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Abstract: Digital twins represent one of the key technologies of Industry 4.0, enabling the integration of physical and virtual systems through continuous real-time data exchange. In the field of occupational safety and health (OSH), this technology provides new opportunities for risk identification, simulation of hazardous scenarios, and improvement of decision-making processes.

This paper aims to analyze the application of digital twins in OSH through a review of relevant literature, identify key enabling technologies, and examine their advantages and limitations. The results indicate that digital twins enable proactive risk management, the reduction of workplace accidents, and the improvement of working conditions. However, their implementation requires significant technical and organizational resources.

Keywords: *Digital Twin, Occupational Safety and Health, Industry 4.0, Risk Management*

INTRODUCTION

Occupational safety and health remain one of the major challenges in modern industrial systems. Despite continuous improvements in regulations and standards, workplace injuries and occupational diseases still represent a significant global issue (ILO, 2023). Traditional approaches to risk assessment are often based on static analyses and expert judgment, which may limit their effectiveness, particularly in dynamic and complex environments (Kritzinger, 2018).

The development of Industry 4.0 has enabled the adoption of advanced digital technologies, among which digital twins stand out as a key innovation (Tao, 2023). A digital twin represents a virtual replica of a physical system that is continuously updated using real-time data

(Rasheed, 2023). This technology enables simulation, prediction, and optimization of processes, significantly improving safety management.

The application of digital twins in OSH is based on the integration of technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics (Lu, 2020). Through continuous monitoring and data processing, it becomes possible to identify potential risks at an early stage, before they lead to accidents (Leng, 2021).

Additionally, digital twins enable simulation of hazardous scenarios in a controlled virtual environment, without exposing workers to real danger. This capability is particularly important for safety training and evaluation of preventive measures (Javaid, 2023).

However, despite their advantages, digital twins face challenges related to high implementation costs, technical complexity, and data security concerns (Radanliev, 2023). Furthermore, the lack of standardization and interoperability limits their broader adoption [9]. Reports from European institutions also emphasize the importance of digital systems in improving OSH practices (EU-OSHA, 2023).

THEORETICAL BACKGROUND OF DIGITAL TWINS

Digital twins represent a modern concept that enables the digital representation of physical systems within a virtual environment, with continuous data exchange between the real and digital worlds. This concept is based on the idea that the behavior of a physical system can be modeled, monitored, and analyzed through its virtual replica, which is dynamically updated using real-time data.

The foundation of digital twins lies in the integration of three interconnected elements: the physical system, the virtual model, and the communication layer. The physical system represents the real object, process, or environment being observed, while the virtual model serves as its digital representation, enabling simulation and analysis of various scenarios. The communication layer ensures data exchange between the physical and virtual components, allowing their synchronization.

The theoretical framework of digital twins is based on an interdisciplinary approach that includes elements of machine learning, simulation, system modeling, and data analytics. Key enabling technologies include the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and cloud computing, which support the collection, processing, and interpretation of large volumes of data in real time.

From a theoretical perspective, digital twins can be viewed as dynamic feedback systems, where data from the physical system is used to continuously improve the virtual model, while insights generated in the virtual environment are applied to optimize the physical system. This approach enables more accurate prediction of system behavior, more efficient process management, and reduced uncertainty in decision-making.

According to Tao et al. (Tao, 2023), digital twins represent one of the key technologies of Industry 4.0, with significant potential to enhance industrial processes through the integration of physical systems and advanced data analytics.

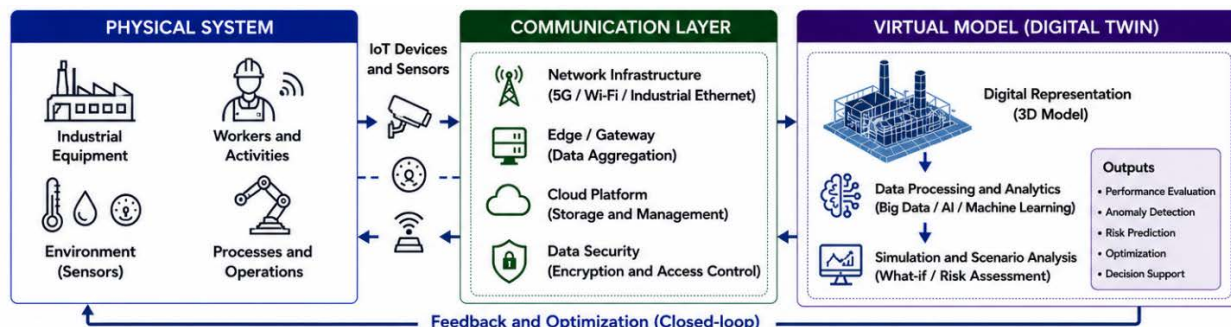


Figure 1. Horizontal architecture of a digital twin

A digital twin operates through a horizontal flow of data between the physical system, the communication layer, and the virtual model. As shown in Figure 1, the physical system generates data that is transmitted via IoT devices and network infrastructure to the virtual model. Within the virtual environment, the data are processed using analytics, artificial intelligence, and simulation techniques. The obtained results are then used to optimize the physical system, forming a closed feedback loop for continuous performance improvement.

APPLICATION OF DIGITAL TWINS IN OSH

The application of digital twins in the field of occupational safety and health (OSH) is based on the concept of cyber-physical systems, which enable continuous interaction between the physical environment and its digital counterpart. In the literature, this approach is most commonly described through a layered architecture consisting of three main levels: data acquisition, data analytics, and operational decision support (Lu, 2020; Leng, 2021).

Based on this architecture, the application of digital twins in OSH can be analyzed through several key functional areas, including risk identification and assessment, simulation of hazardous scenarios, employee training, predictive maintenance, and monitoring of working conditions. These areas form the foundation for improving traditional safety management approaches by enabling a transition toward predictive and proactive models based on real-time data (Javaid, 2023; EU-OSHA, 2023).

Identification and risk assessment

Digital twins enable continuous monitoring of the work environment and real-time identification of potential hazards. Unlike traditional risk assessment methods, which are primarily based on static analyses and periodic inspections, digital twins allow for dynamic risk assessment based on continuously updated data from the physical system (Leng, 2021).

Simulation of hazardous scenarios

One of the key advantages of digital twins is the ability to simulate various hazardous scenarios, such as fires, explosions, or equipment failures, without exposing workers to actual risk. These simulations enable detailed analysis of potential consequences and support improvements to preventive measures, thereby contributing to better planning of safety procedures and reducing the likelihood of accidents.

In the construction industry, digital twins are increasingly used for predicting safety risks during complex operations, such as lifting and assembling structures, where even minor deviations can lead to serious consequences (ILO, 2023).

Employee Training

Digital twins enable the development of virtual training environments in which real working conditions and potentially hazardous situations can be simulated. In this way, workers gain practical experience without being exposed to actual risks. Research shows that this approach significantly improves training effectiveness and contributes to better adoption of safety procedures (Tao, 2023).

Predictive Maintenance

The application of digital twins enables predictive maintenance of equipment through the analysis of real-time data. Based on identified patterns and deviations in system operation, it becomes possible to anticipate potential failures before they occur. This reduces the risk of accidents caused by technical malfunctions and increases the reliability of operational systems (Leng, 2021).

Monitoring of Working Conditions

Digital twins enable continuous monitoring of workplace environmental factors such as temperature, noise levels, vibrations, and air quality. These data enable timely responses and adjustments to working conditions, thereby directly contributing to improved employee safety and health (EU-OSHA, 2023).

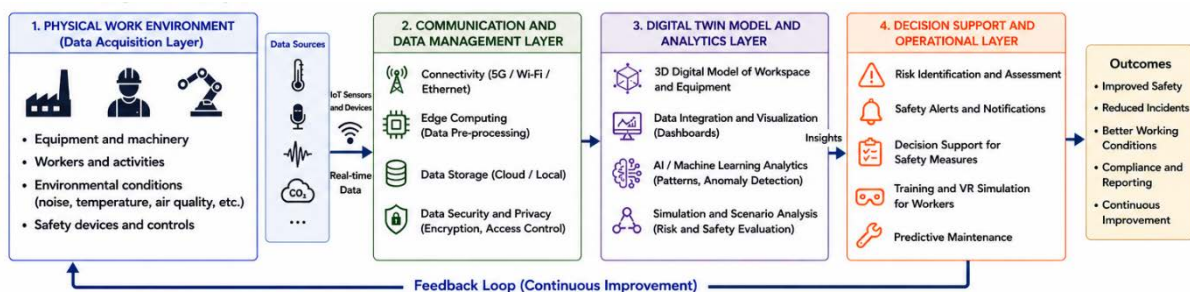


Figure 2. Layered architecture of digital twin applications in occupational safety and health

Figure 2 illustrates the layered architecture of digital twins in the field of occupational safety and health (OSH), which connects the physical work environment with its digital counterpart. Data are collected from the physical system through sensors and IoT devices, and are continuously transmitted to the digital model, where they are processed using analytical and simulation methods. The resulting outputs are used to support decision-making processes and to enhance safety measures at work. The system operates as a closed feedback loop, enabling continuous monitoring, evaluation, and ongoing improvement of occupational safety and health conditions.

DISCUSSION

The application of digital twins in the field of occupational safety and health brings significant advantages compared to traditional risk management approaches. The most important benefits include proactive risk management, a reduction in the number of workplace accidents, and the improvement of decision-making processes. By integrating various data sources and processing them in real time, digital twins enable a more accurate understanding of the work environment and timely responses to potential hazards (ILO, 2023).

This approach represents a significant advancement compared to conventional methods, which are often based on periodic inspections and static risk assessments, as it enables continuous monitoring and dynamic evaluation of safety conditions.

However, despite numerous advantages, the implementation of digital twins in practice faces certain challenges. One of the main challenges relates to high implementation costs, as well as the need for advanced technical and analytical expertise. In addition, the processing and storage of large volumes of data raise concerns regarding privacy protection and information security (Tao, 2023).

An additional limitation is the lack of standardization and interoperability between different systems and platforms, which complicates their broader adoption and integration into existing industrial frameworks. These factors indicate that, although digital twins have significant potential to enhance occupational safety and health, their effective implementation requires further technological development and harmonization of standards.

CONCLUSION

Digital twins represent one of the key technologies of Industry 4.0 with significant potential for improving occupational safety and health. Their ability to integrate physical and digital systems enables continuous monitoring of work processes, timely identification of risks, and decision-making based on real-time data.

The results of the analysis show that the application of digital twins contributes to proactive risk management, a reduction in the number of workplace accidents, and the improvement of working conditions. Of particular importance is the ability to simulate hazardous scenarios,

enable predictive maintenance, and continuously monitor environmental parameters, which represents a significant advancement compared to traditional safety management methods.

However, despite numerous advantages, the implementation of this technology faces challenges such as high costs, the need for advanced technical infrastructure, data protection concerns, and a lack of standardization and system interoperability. These factors indicate that further technological development and harmonization of industrial standards are necessary for the wider adoption of digital twins.

In the future, the integration of digital twins with artificial intelligence, the Internet of Things, and advanced data analytics is expected to further enhance their application in occupational safety and health, thereby contributing to the creation of safer and more efficient working environments.

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DIGITALIZATION OF OCCUPATIONAL SAFETY AND HEALTH ELECTRONIC TRACKING AND COMPLIANCE SOLUTION

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Abstract: In many occupational safety and health (OSH) systems, record-keeping is still predominantly based on manual or partially digital processes, resulting in fragmented, non-standardized, and analytically limited datasets. Such data structures significantly restrict the ability to perform detailed risk analysis, monitor compliance in real time, and implement truly proactive safety management. This paper addresses these limitations by proposing a comprehensive design of an electronic OSH record-keeping system aimed at transforming dispersed and static records into a structured, continuously updated digital dataset. The system is designed to integrate data on workplaces, employees, risk assessments, training, medical examinations, and protective measures into a unified information model. The proposed architecture is intended to enable automated tracking of legal obligations, real-time monitoring of compliance, and generation of key performance indicators, including incident frequency and compliance rates. In addition, the system establishes a foundation for advanced analytics, including trend analysis, risk prediction, and decision support. The main contribution of this paper is the formalization of system requirements and data structures necessary for overcoming the limitations of traditional record-keeping and enabling a transition toward data-driven, proactive OSH management. The proposed approach represents a necessary step toward the digital transformation of occupational safety systems.

Keywords: *Occupational Safety and Health; Electronic Records*

INTRODUCTION

According to reports from the Ministry of Labour, Employment, Veteran and Social Affairs for the period 2019–2024, the number of workplace injuries shows an increasing trend, as clearly presented in **Table 1**. The highest number of injuries (Annual report, 2024) consistently occurs in the manufacturing industry, reflecting both the large workforce and high labor turnover in this sector. This underscores the need for systematic monitoring of training, periodic knowledge assessments, and digital oversight of compliance with safety obligations. Despite existing regulatory frameworks and mandatory documentation, current OSH record-keeping practices remain fragmented and insufficiently structured, limiting the ability to link incidents to specific workplaces, risk factors, and preventive measures, and thereby reducing the effectiveness of risk assessment processes.

Therefore, the key research question addressed in this paper is whether a systematically designed electronic record-keeping system can overcome these limitations and provide a foundation for data-driven and proactive occupational safety management.

Overview of previous research

International studies by (Akyıldız,2023) highlight the concept of OHS 4.0, where digital technologies contribute to improving safety, while (Trask, 2023) emphasize the importance of digital tools in the construction industry, as well as the need for empirical evaluation of their effects.

It is particularly important to note that digitalization cannot be considered separately from data protection. Hybrid cryptographic frameworks (Wang, 2024), blockchain approaches in healthcare systems (Shi, 2020), and lightweight cryptographic algorithms (Rasheed, 2025) for IoT environments have already demonstrated that security and efficiency can be successfully combined.

Table 1. Number of workplace injuries by injury severity (Annual report, 2024)

Injury severity	2024	2023	2022	2021	2020	2019
Fatal occupational injuries	21	14	11	12	11	14
Severe occupational injuries	1567	1308	1127	1289	1226	1233
Severe commuting injuries	825	612	596	487	435	597
Minor injuries	12070	11472	10958	9487	8623	11462
Total:	14483	13406	12692	11275	10295	13306

The graphical representation of fatal workplace injuries shows noticeable year-to-year fluctuations, with a general increasing tendency in the observed period. Although the absolute number of fatal injuries is significantly lower compared to other injury categories, their severity justifies separate analysis. Presenting fatal injuries independently improves visualization clarity and highlights critical safety issues that require immediate attention.

The high number of workplace injuries, particularly in the manufacturing sector, indicates that legal regulations and manual record-keeping alone are not sufficient. Digital systems, as demonstrated in international studies (Akyıldız,2023), enable timely monitoring of training activities, automated reminders, and improved transparency in fulfilling obligations.

On the other hand, data security and employee privacy represent critical challenges. This creates an opportunity for the application of advanced cryptographic methods (Rasheed, 2025), (Wang, 2024) and blockchain technologies (Shi, 2020), which ensure the authenticity and integrity of records (Živković, 2026).

This establishes a foundation for further research in the direction of evaluating and designing electronic OSH record-keeping systems that are aligned both with the legal framework of the Republic of Serbia and with international best practices.

EXPERIMENTAL EVALUATION

The evaluation of the proposed electronic Occupational Safety and Health (OSH) system is constrained by the limited availability of complete datasets, particularly those including the total number of employees required for calculating standardized safety indicators. Nevertheless, an initial analysis can be performed based on publicly available data on workplace injuries.

Data presented in Table 1 indicate a noticeable upward trend in the total number of workplace injuries over the observed period (2019–2024), with a particularly significant increase in severe injuries. Although fatal injuries fluctuate on a yearly basis, their overall trend also suggests a growing concern. For clarity of visualization, fatal injuries are presented separately in the corresponding Figure 1., as their significantly lower absolute values compared to other injury categories would otherwise reduce the interpretability of the graphical representation.

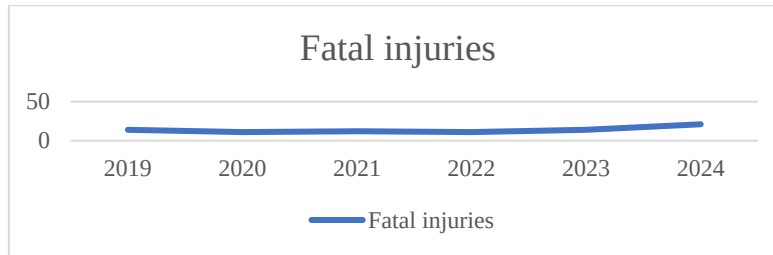


Figure 1. Trend of fatal workplace injuries (2019–2024) (Annual report, 2024)

To support future quantitative evaluation, standard OSH performance metrics can be introduced. One of the most commonly used indicators is the Incident Frequency Rate (IFR), defined as the number of recorded injuries per 1,000 employees(1):

$$IFR = \frac{N_{injuries}}{N_{employees}} \times 1000 \quad (1)$$

Although the required data for calculating IFR are not available in this study, the proposed system architecture is designed to enable systematic collection of such data, allowing for precise measurement of safety performance over time.

In addition to IFR, the system is intended to enable monitoring of operational performance indicators related to compliance and process execution. One of the key indicators is the compliance rate, defined as (2):

$$Compliance = \frac{N_{completed\ obligations}}{N_{total\ obligations}} \times 100\% \quad (2)$$

This metric reflects the degree to which legally prescribed obligations-such as employee training, medical examinations, and implementation of safety measures are fulfilled within the required timeframes. Unlike IFR, which measures outcomes, the compliance rate provides insight into preventive system performance and organizational discipline.

This limitation directly reflects the fundamental weakness of existing record-keeping practices, where essential parameters required for standardized safety indicators are not systematically collected.

The primary contribution of the proposed system is not only in digitalizing existing records, but in redefining the structure and usability of OSH data. By transforming fragmented and manually maintained records into a standardized and relational dataset, the system is intended to enable a level of analytical capability that is not achievable within traditional record-keeping approaches.

Future work will focus on implementing the system in real organizational environments and conducting longitudinal studies to compare key safety indicators-such as injury frequency, response time, and compliance rates-between organizations using traditional record-keeping methods and those adopting the proposed digital system.

System characteristics of electronic records

An electronic record-keeping system must enable data entry using modern devices such as mobile phones and tablets, in addition to personal computers and laptops. The system must be available 24/7 to all users regardless of location. Data entry and usage must be simple and intuitive, and the system should support multiple languages. Web architecture is intended to enable client-server data exchange, continuous availability (24/7), and secure data transmission via the HTTPS protocol. Data access is controlled through user roles and permissions, ensuring that each user can access only the data relevant to their authorization level. The system should enable integration with user email accounts for sending automatically generated notifications, as well as tracking deadlines and notifying users about upcoming obligations.

Data structure and key OSH records

Designing an application for digital OSH record-keeping requires a clearly defined data structure that is intended to enable reliable tracking of all obligations, deadlines, and legal requirements. Central to this model are **workplaces and employees**, around which all other entities and relationships are structured.

Workplace Data Model

A workplace is considered the primary entity in the system. For each workplace, the following data should be recorded: name and description, activity and sector, risk level (low, medium, high), number of employees and workforce dynamics, type of equipment used, types and

quantities of hazardous materials, including frequency of use, working environment conditions, injury statistics, including causes of incidents, working hours (in accordance with internal regulations, collective agreements, or employment contracts), age structure of employees (e.g., minors), specific workplace conditions (e.g., restrictions for minors, pregnant women, persons with disabilities, or gender-specific limitations), as well as required medical conditions for performing the job

Workplace-Related Relationships

Risk Assessment – Includes general and specific measures, as well as preventive activities. Similar digital risk modeling methodologies have been identified in the construction sector, where digital databases are used to map risks and mitigation measures. Risk assessment methodologies (e.g., Kinney method, 5×5 matrix, AUVA method for computer-based work) are standardized and fully suitable for digitalization.

Personal Protective Equipment (PPE) – The system must link each workplace with the prescribed list of PPE. This approach aligns with OHS 4.0 practices, where digital systems connect employee roles with appropriate protection measures.

Instructions and Notifications – Digitally archived instructions and mandatory notices must be available to employees, with version control and change tracking.

Employee Records

The second central entity in the system is the employee, who may be associated with one or more workplaces during their employment.

The employee record includes: basic personal data (name, surname, national ID, employment status), years of experience and training history, medical examination status, preferred language, email address

Employee-Related Relationships

OSH Training – The system maintains records of initial and periodic training, as well as knowledge assessment results. Such records are also used in digital healthcare systems, where training and certification represent a critical part of the safety chain.

Medical Examinations – Linked to legally prescribed deadlines with automatic reminders.

Personal Protective Equipment (PPE) – Records of assigned equipment, replacement deadlines, and usage status.

WORKPLACE RISK ASSESSMENT

The system should support identification of workplaces with similar characteristics and provide recommendations for risk assessment, as well as for implementing general and specific measures aimed at minimizing risks.

Legal compliance and document generation

Based on the entered data, the system should enable automatic generation of risk assessment documents for all workplaces. Additionally, by combining data on employee training, equipment, and implemented safety measures, the system can track performance indicators and propose improved OSH measures and activities. Thus, the application is not limited to record-keeping but also supports **legal compliance**. Similar approaches have demonstrated that digital systems significantly facilitate the generation of reports and compliance-related documentation.

Special focus on critical workplaces

Based on statistical data and practical experience, certain workplaces are classified as critical. Criteria include: frequency of injuries, high risk levels, high workforce turnover, inherent risks due to working conditions, hazardous materials, or equipment. For such workplaces, the system provides additional functionalities: emphasized reminders for training and medical examinations, mandatory archiving of all relevant documentation, automatic alerts and reports for management. Given that critical workplaces involve large amounts of sensitive data (injuries, medical records, personal data), the implementation of **cryptographic protection methods** is essential. Recommended approaches include hybrid encryption (e.g., AES + ECC) and lightweight cryptographic algorithms for IoT environments, particularly in mobile access scenarios.

Workplace inspection records and architecture

To ensure effective monitoring, the proposed system is designed to support structured records of workplace inspections and site visits. This includes a predefined set of control questions for each workplace, enabling systematic data collection during inspections, documentation of observed conditions, and identification of potential risk factors.

During inspections, users would be able to record observations, detected irregularities, and proposed corrective measures directly within the system. The collected data would be stored in a structured format, allowing for subsequent analysis and tracking of recurring issues.

The system is intended to support automated generation of inspection reports, which could be distributed to relevant stakeholders in order to facilitate timely response and implementation of corrective actions. Such functionality would contribute to improved transparency and accountability in the execution of OSH procedures.

All inspection-related functionalities are designed to be accessible across different devices, including mobile phones, tablets, and laptops, allowing data to be entered directly at the workplace location.

The overall system architecture is based on a web-oriented approach that is intended to provide centralized data management, secure access, and continuous availability, supporting efficient execution of OSH-related processes.

ADVANTAGES OF THE DIGITAL SYSTEM

The proposed electronic OSH record-keeping system offers several advantages compared to traditional approaches: automated tracking of deadlines, reduced administrative workload, improved risk analysis, centralized documentation, easier inspection and compliance control, reduced probability of workplace injuries.

Unlike traditional systems, which primarily serve administrative purposes, the proposed system is intended to enable continuous analytical processing of safety-related data, thereby directly supporting proactive risk management.

DISCUSSION AND POTENTIAL APPLICATIONS

The proposed system can be applied both in agencies specializing in OSH services and in organizations with internal OSH departments.

Labor inspectorates may be granted controlled access to the system, allowing them to review data without the ability to modify it. This is designed to provide better insight into implemented safety measures and procedures.

Future research should focus on system evaluation through comparison with international studies addressing digital transformation in OSH, as well as on the implementation of advanced data protection methods, including cryptography, blockchain technologies, and hybrid encryption approaches.

CONCLUSION

This paper presents the design of an electronic OSH record-keeping system as a response to the fundamental limitations of traditional, predominantly manual approaches to safety data management. It has been shown that existing record-keeping practices do not provide sufficient data structure or continuity to support advanced analysis, real-time monitoring, or predictive safety management.

The proposed system addresses these limitations by introducing a unified data model that integrates workplaces, employees, risk assessments, training, and compliance-related activities into a single digital framework. Such integration is intended to enable continuous monitoring, automated compliance tracking, and generation of performance indicators essential for effective safety management.

The results of this study indicate that digitalization of OSH records is not merely a technological upgrade, but a necessary condition for transitioning from reactive to proactive safety systems. Without structured and continuously updated digital data, the application of advanced analytical methods and systematic risk optimization remains significantly constrained.

Future work will focus on the practical implementation of the system and its evaluation in real organizational environments, with particular emphasis on measuring improvements in safety performance indicators and reduction of workplace injuries.

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BIOMETHANE IN SERBIA: ADVANCING THE CIRCULAR BIOECONOMY AND ENERGY SECURITY

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Abstract: This paper presents proposed national targets for biomethane production in Serbia and evaluates their contribution to circular bioeconomy development and energy security across short-, medium-, and long-term horizons. The study investigates the role of biomethane in valorizing agricultural by-products and organic waste streams. In the short term (2027), biomethane could replace approximately 3.5% of final natural gas consumption primarily using manure, sequential crops, harvest residues, and kitchen waste from the HORECA sector. In the medium term (2030), expanded infrastructure and regulatory support could increase this share to approximately 18%, while in the long term (2050) biomethane could exceed 28% of final natural gas consumption through the additional utilization of municipal biodegradable waste, slaughterhouse waste, and biogenic CO₂. The results indicate that biomethane could significantly improve organic waste management, resource efficiency, and resilience to imported fossil fuel dependency. Achieving the proposed targets will depend on regulatory support, feedstock mobilization, and technological progress. Overall, biomethane represents a strategic pathway for advancing climate neutrality, circular bioeconomy principles, and energy independence in Serbia.

Keywords: *Biomethane; Serbia; Circular Bioeconomy; Energy Security.*

INTRODUCTION

At the EU level, there is a clear commitment to the European Green Deal (EGD) and its goals. In particular, the EGD is supported by documents that directly affect the field of biogas and biomethane: the EU strategy for reducing methane emissions (EC, 2020a), REPowerEU (EC, 2022), integrated national energy and climate plans, but also indirectly through documents such as the Action Plan for the Circular Economy (EC, 2020b). In 2021, biomethane production in the EU was 3.54 billion m³. REPowerEU, a more ambitious addition to REDIII directive (EC, 2023), establishes a target of 35 billion m³ of biomethane by 2030. Each of the EU27 members, in accordance with their own potential, should contribute to the fulfillment of the target. The availability of raw materials, the development of agriculture, the advanced waste management systems, as well as the presence of other forms of renewable energy sources (RES) play a significant role in defining the potential of biomethane.

There is a clear tendency to replace NG with biomethane, primarily in the transport and energy sectors. In Europe, 29% of biomethane is used in the transport sector, 28% in households, 26% in industry, and about 17% in the service sector and other sectors (EBA,

2024). In countries like Italy, Finland, Estonia, it is exclusively used in transport, and in Belgium for industry. All sectors are represented in Germany. In the region, the number of biomethane plants is minimal, only two in Hungary, while the implementation of new plants is announced or under construction in Croatia and Slovenia.

The existence of an appropriate legal framework will be extremely important for the implementation of biomethane production facilities in Serbia. The existence of the biogas sector since 2012 can serve as a good example to further develop biomethane sector in Serbia. The development of the biogas sector was made possible by: a clearly defined national target; incentive measures (with a clear incentive mechanism); guides for the realization of investments for biogas projects; the effort of the biogas sector through the Association of Biogas Serbia to coordinate incentive measures in accordance with market trends.

The national target for biogas production was defined by the National Action Plan for the use of renewable energy sources of the RS, which amounted to 30 MW of installed electrical power and was to be realized by 2020. This clearly defined the role of the biogas plant as a renewable source of electricity. However, the document defines that the target refers to the production of biogas from "manure", which is not practical or techno-economically feasible, because agricultural plants use a mixture of raw materials (most often manure and energy plants, with the addition of organic waste).

The construction of biogas plants was further initiated in 2010 with the entry into force of the first Regulation on incentive measures for the production of electricity using renewable energy sources and the combined production of electricity and heat, which resulted in the commissioning of the first biogas plants in 2012. Then the financial incentive measure Feed-in tariff (FiT) was defined. The FiT value has been redefined several times, and the most favorable one was introduced in 2015, which clearly resulted in increased construction of new biogas plants (Figure 1). As an additional incentive, the relevant ministry, in cooperation with the Global Environmental Facility (GEF) and the United Nations Development Program (UNDP), awarded grants for 4 biogas plants.

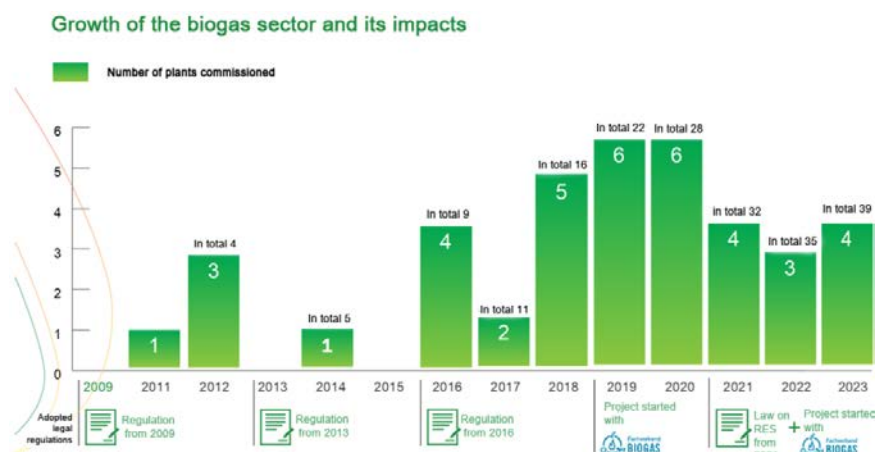


Figure 1. Development of the biogas sector in Serbia.

Specialized guides for investors also made a significant contribution (Lepotić Kovačević et al., 2010; Martinov and Djatkov, 2012), as well as public presentations organized by the Council for Biomass and the Provincial Secretariat for Energy and Mineral Resources of Autonomous Province of Vojvodina. There were also administrative measures (e.g. exemption from customs duties and taxes for importing equipment from the EU, exemption from balance responsibility).

Through the Integrated National Energy and Climate Plan– INECP (INEKP, 2024), initial steps were taken towards introducing biomethane sectors and defining targets for biomethane production in the RS. Through the regulations in force in Serbia, the Law on the Use of RES (ZKOIE, 2023) and numerous other documents laid good foundations for the integration of biomethane on the Serbian market. The main driver to produce biomethane is reducing climate change, namely decarbonization. Scope of this paper was to investigate effects of the proposed national targets for biomethane production in Serbia for advancing circular bioeconomy and energy security as indirect positive effects in Serbia.

SUGGESTED NATIONAL BIOMETHANE PRODUCTION TARGETS

The national biomethane production targets in Serbia were elaborated for the three defined time horizons: 2027 (short-term), 2030 (mid-term), and 2050 (long-term). These time horizons are in line with INECP decarbonization goals. Depending on the time horizon, to define appropriate targets for biomethane production considered were either conservative, expected or optimistic approaches of the biomethane potentials determined in Djatkov et al. (2025). For sooner time horizons, the focus has been on conservative potential utilization, as it is not anticipated that significant changes in the availability of certain types of raw materials will occur by 2027 or 2030. For the later time horizon, the focus has shifted to utilizing the potential derived from the expected and optimistic approaches, considering greater mobilization of raw materials and especially organic waste, as well as the application of innovative technologies (Djatkov et al., 2025).

Short-term target (2027)

This target is primarily based on the partial utilization of existing capacities for biogas production, which is currently used for electricity generation. Existing biogas plants may contribute in total 18.6 ktoe. The time horizon required to convert a biogas plant to a biomethane production facility is up to one and a half years. If plant owners make timely decisions and define necessary prerequisites, preparations can begin before the expiration of the status for subsidized electricity, significantly reducing lead time and enabling production capacity readiness by 2027. For new biomethane plants utilizing available raw material potentials in the short term, and considering technological limitations for harvest residues, a total of 13.3 ktoe can be achieved. These plants would use raw materials such as manure, energy crops, secondary crops, harvest residues, and kitchen waste (from the HORECA sector). By 2027, no targets are set for biomethane production from slaughterhouse waste,

sewage sludge, or municipal biodegradable waste. Organic waste from the food industry, which is of suitable quality and form, is already integrated into the value chain for biogas production in Serbia, and its use is foreseen through logistical chains for existing biogas plants being converted to biomethane production. Only biomethane produced from energy crops is classified as non-advanced biomethane. All other biomethane shares originate from raw materials listed in Annex IX, List A of the REDII Directive, representing advanced biomethane eligible for double counting (calculation with a multiplier) when used in the transport sector.

Table 1. Proposed national biomethane target for 2027 (new plants)

Raw material	Amount of DM, kt/year	Energy, ktoe	Energy share, %	Type, REDII
Manure	29.2	6.2	46.1	A
Energy crops	9.2	3.1	23.1	1G
Sequential crops	6.5	2.1	15.4	A
Harvest residues	3.4	1.0	7.7	A
Kitchen waste	3.8	1.0	7.7	A
Total	52.1	13.3	100.0	–

DM: Dry matter; REDII: Renewable Energy Directive (classification of biomethane according to the type of raw material used for production, Annex IX– lists A and B); toe: ton oil equivalent; 1G: first generation (nonadvanced biomethane).

Mid-term target (2030)

The mid-term target subsumes existing biogas plants that would be converted to biomethane production facilities and newly constructed biomethane production plants. The total potential is estimated at 186.5 ktoe. The composition and share of raw materials are similar to those planned for 2027 to ensure compliance with GHG (Greenhouse Gases) emission reduction criteria. It is estimated that manure mobilization could produce approximately 80 ktoe/year of biomethane out of the available conservative potential of 123 ktoe/year (Djatkov et al., 2025). This represents a maximized sub-target for manure, aiming to reduce overall GHG emissions in Serbia through its mobilization for biomethane production.

Table 2. Proposed national biomethane target for 2030

Raw material	Amount of DM, kt/year	Energy, ktoe	Energy share, %	Type, REDII
Manure	415	80	42.9	A
Energy crops	207	64	34.3	1G
Sequential crops	102	30	16.1	A
Harvest residues	36	10	5.4	A
Kitchen waste	10	2.5	1.3	A
Total	770	186.5	100.0	–

DM: Dry matter; REDII: Renewable Energy Directive (classification of biomethane according to the type of raw material used for production, Annex IX– lists A and B); toe: ton oil equivalent; 1G: first generation (nonadvanced biomethane).

Long-term target (2050)

The long-term target is based on a similar approach to the mid-term. It is estimated that sufficient manure could be mobilized to produce approximately 118 ktoe/year of biomethane out of the expected potential of 227 ktoe/year (Djatkov et al., 2025). Slaughterhouse waste and municipal biodegradable waste (MBW) are also included. The optimistic potential for biomethane production from slaughterhouse waste by 2050 is 7.3 ktoe, with a contribution of 4.1 ktoe/year to the target, as the remaining quantities will be processed through competitive methods. From municipal biodegradable waste, about 23.9 ktoe of biomethane could be produced, contributing 7.5 ktoe/year to the target. Additionally, biomethane produced from biologically sourced CO₂ (bioCO₂) is included. This CO₂ is obtained during the biogas purification process to biomethane. It is assumed that around one-quarter of the CO₂ remaining from biomethane production from all other raw materials will be utilized for additional biomethane production, while the rest will be allocated for other competitive uses.

Table 3. Proposed national biomethane target for 2050

Raw material	Amount of DM, kt/year	Energy, ktoe	Energy share, %	Type, REDII
Manure	612	118	32.3	A
Energy crops	306	94	25.9	1G
Sequential crops	149	44	12.1	A
Harvest residues	52	15	4.0	A
Kitchen waste	30	8	2.2	A
MBW	43	8	2.2	A
Slaughterhouse waste	108	4	1.1	B
bioCO ₂	-	73	20.0	e-fuel
Total	1,150	365	100.0	–

MBW: Municipal biodegradable waste; bioCO₂: biomethane produced from CO₂ of biological origin, obtained by purifying biogas to biomethane; DM: Dry matter; REDII: Renewable Energy Directive (classification of biomethane according to the type of raw material used for production, Annex IX– lists A and B); toe: ton oil equivalent; 1G: first generation or nonadvanced biomethane.

EFFECTS OF PROPOSED NATIONAL TARGETS

Replacement of natural gas

The effects of the proposed national targets for biomethane production in Serbia in the following table were analyzed in relation to the energy balance projections of the Republic of Serbia as defined in the adopted version of INECP (INEKP, 2024). Data for three time

horizons are used for scenarios S and S-N, which include the implementation of additional measures compared to the baseline scenario (WEM). The goal of both scenarios is to reduce emissions by increasing RES and energy efficiency. Scenario S-N additionally considers the introduction of nuclear power plants with a total capacity of up to 1,000 MW into the energy system. Furthermore, the Energy Sector Development Strategy of the Republic of Serbia up to 2040 with Projections up to 2050 (MRE, 2024) was used to define the natural gas energy in the gross domestic consumption, as well as natural gas imports.

Table 4. Effects of the proposed national biomethane production targets on energy security

Parameter	2027	2030	2050	
	INECP scenario			
	S/S-N	S/S-N	S	S-N
Replacement of NG total, %	1.1	6.1	12.8	13.7
Replacement of NG in FC, %	3.5	17.7	28.6	28.6
Replacement of imported NG, %	1.3	7.0	13.2	14.1
Replacement of NG in transport, %	95.4	100.0	100.0	100.0
Contribution of BM in transport ¹ , %	1.3	2.3	1.5	1.6
Contribution of BM in transport ² , %	2.3	3.8	2.7	2.7

NG: natural gas; FC: final energy consumption; BM: biomethane; 1&2: without and with double calculation of the amount of energy of advanced biomethane (multiplication).

Circular bioeconomy

The following Table 5 provides an overview of utilization rate of the foreseen feedstock potential intended to fulfil biomethane production targets in the considered time horizons. Presented and further will be discussed agricultural by-products (manure and harvest residues), as well as organic waste (kitchen, municipal, slaughterhouse), as feedstocks which utilization for biomethane production may advance the circular bioeconomy in Serbia.

Across all considered feedstocks, the target for the initial time horizon (2027) envisages a cautious and gradual introduction of the biomethane sector in Serbia, and consequently, a carefully managed mobilization of available feedstock resources. Except energy crops and sequential crops, the core feedstock base consists of manure that is selected primarily due to its potential to ensure compliance with GHG emission saving criteria, alongside harvest residues and kitchen waste from the HORECA sector. In this period, the utilization of crop residues is particularly constrained due to existing technical and technological limitations related to their use in anaerobic digestion. Kitchen waste from the HORECA sector was selected under the assumption that, with appropriate regulatory support, it could become the first significant organic waste stream to be effectively mobilized.

In the medium- and long-term time horizons (2030 and 2050), a more extensive utilization of manure is envisaged, under the assumption that the regulatory framework will contribute to a greater mobilization of this feedstock. In other words, it is expected that manure from smaller

farms will be appropriately disposed, while simultaneously alleviating the logistical challenges associated with the timely and efficient use of manure as an organic fertilizer in agricultural production. Regarding crop residues, both time horizons also foresee a substantial increase in the quantities mobilized for biomethane production, assuming that lignocellulosic biomass pretreatment technologies will reach technological readiness level for the market and thus become less expensive. This would enable the overcoming of current technical and technological barriers. Food waste from the HORECA sector has limited competing disposal pathways other than anaerobic treatment, thus a higher share of this waste stream is expected to be mobilized for biomethane production.

Although slaughterhouse waste is expected to enter the biomethane value chain before 2050, its quantity has not been defined as a target, as a precaution to the credible introduction of clear procedures and the establishment of an appropriate pretreatment system in accordance with the existing regulatory framework. Municipal biodegradable waste (MBW) is currently not primarily separated and in that form used. A quantity which refers to the collection of the two regional landfills could be used as a feedstock for biomethane production. This quantity is remaining after utilizing 340,000 tons which will be incinerated at the Vinča plant. An additional assumption is that a significant portion of this type of waste will already be redirected to composting. The target for biomethane production using biogenic CO₂ in the process of methanation is considered only for the long term. Thereby, the share of 30% of the total amount, *i.e.* using expected potentials, was intended for biomethane production.

Table 5. Feedstock potentials utilization rate for biomethane production targets in %

Raw material	Time horizon		
	2027	2030	2050
Manure	7.9	65.4	52.0
Harvest residues	0.5	6.2	6.6
Kitchen waste	8.8	23.2	70.8
MBW	nr	nr	31.5
Slaughterhouse waste	nr	nr	51.3
bioCO ₂	nr	nr	30.0

MBW: Municipal biodegradable waste; bioCO₂: biomethane produced from CO₂ of biological origin, obtained by purifying biogas to biomethane.

CONCLUSIONS

The proposed national biomethane production targets demonstrate that Serbia has significant potential to simultaneously advance decarbonization, strengthen energy security, and support the transition toward a circular bioeconomy. The proposed pathway is based on the gradual mobilization of agricultural by-products and organic waste streams, with manure identified as the key strategic feedstock due to its contribution to GHG emission savings and improved manure management practices. Harvest residues, kitchen waste from the HORECA sector,

municipal biodegradable waste, and slaughterhouse waste further contribute to feedstock diversification and the valorization of underutilized waste streams. The realization of these targets will depend on the establishment of an enabling regulatory and market framework, as well as further technological progress. Overall, biomethane represents a realistic and strategic opportunity for Serbia to support climate neutrality, improve waste management, and reduce dependence on imported fossil fuels.

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ECOLOGICAL RISK ASSESSMENT OF PESTICIDE USE REGARDING SOIL CONTAMINATION

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Abstract: Agricultural production worldwide has significantly increased in recent years, accompanied by greater pesticide use. The application of glyphosate, the most widely used herbicide globally, causes various changes in soil, affecting both soil quality and the quality of groundwater and/or surface water. Depending on the maximum amount of this chemical compound, it is possible to determine the volume of contaminated groundwater, with maximum and minimum values of 1.333333 and 0.041667 dm³. The maximum quantity of the substance (Q_{GW}), depending on the period of entry into groundwater flow, can range from 0 to 4 mg. The use of pesticides in agriculture leads to environmental impacts that can be classified as minimal, minor, moderate, severe and catastrophic. In assessing ecological risk caused by pesticide infiltration into groundwater, it is important to determine both the probability of release and the consequences of the released amount on environmental media. This paper analyzes the ecological risk arising from the infiltration of the pesticide glyphosate into soil, leading to groundwater contamination. A risk matrix with both quantitative and qualitative assessment is provided.

Keywords: *ecological risk; pesticides; agriculture; soil; groundwater.*

INTRODUCTION

Modern agricultural production uses various types of pesticides, which are most commonly applied to eliminate, control, and destroy plant and other pests in order to protect crops and maximize yields (Golubović, 2020; Vazquez, 2021). According to the United Nations Food and Agriculture Organization (FAOSTAT), pesticide production has increased by 40% annually over the past 20 years and has reached approximately 4.1 million tons since 2017 (Riedo, 2023). Globally, among all types of pesticides, the highest usage has been recorded for herbicides (40–50%), followed by insecticides (17%) and fungicides (10%) (Ashworth, 2013; El Jaouhari, 2023). It is estimated that these categories account for 95% of the total consumption of these chemical compounds in agriculture (Riedo, 2023). The application of pesticides in soil leads to chemical and physicochemical changes, as well as alterations in biological characteristics; it harms flora and fauna and affects soil fertility and microbial diversity (Zhou, 2025). The persistence and movement of pesticides in soil depend on numerous parameters, such as the soil adsorption constant, the octanol–water partition coefficient, and the half-life of degradation in soil (Aktar, 2009). According to research, only

0.1% of applied pesticides in soil is effective, while the remainder enters the environment and contributes to its degradation. Certain types of pesticides can easily reach surface and groundwater through runoff or leaching from soil, thereby contributing to their contamination. (Golubović, 2020) Globally, the herbicide glyphosate holds a leading position in agricultural production (El Jaouhari, 2023). Glyphosate, also used in the form of its isopropylamine salt, is a widely applied herbicide used in the production of numerous agricultural crops (Safety Data Sheet – Glifohem, 2021; Kanissery, 2019). The application of glyphosate in soil shows low toxicity and herbicidal activity for plants, primarily due to microbial degradation into non-phytotoxic products, which influences the cycling and decomposition of nutrients and organic matter in soil (El Jaouhari, 2023; Zhou, 2025; Morillo, 2000). Ecological risk assessment related to glyphosate use in agriculture refers to its application in soil and the exposure of microorganisms, groundwater, surface water, plant and animal species, and humans to its adverse effects. Determining threshold values of this herbicide in soil, as well as its quantities and chemical characteristics, is essential for proper ecological risk assessment in agricultural production. (Đorđević, 2024; Đorđević, 2020)

METHODS

The assessment of the consequences of substance release into soil is based on evaluating the volume or area that may be exposed to risk from a specific hazardous substance. Based on the maximum allowable quantity of a substance that can be released into soil (Q_{ws}) it is possible to calculate the volumes of contaminated surface or groundwater, as expressed by Equation 1. (Đorđević, 2020):

$$V = \frac{Q_{ws}}{LC_{50} \times P \times BCF} \quad (1)$$

where are: V – volume of contaminated water resulting from the release of a hazardous substance into soil [dm^3], Q_{ws} – maximum quantity of a substance that can reach the soil after release [mg], LC_{50} – median lethal concentration of the considered toxic substance [mg/dm^3], P – relative persistence factor [dimensionless quantity] whose values may be: 1 (short persistence in weeks), 0.75 (medium persistence in months) and 0.5 (long persistence in years), BCF – bioconcentration factor [dimensionless quantity] which has values: 0.5 for $\log(K_{ow}) > 3.5$, 0.75 for $2.5 < \log(K_{ow}) < 3.5$, and 1 for $\log(K_{ow}) < 2.5$, where K_{ow} is the octanol–water partition coefficient of the substance.

Since soil, as an environmental medium, has a certain permeability, it is possible to calculate the overall permeability of the lower soil layer, which is obtained as the product of the water flow sensitivity factor and the permeability coefficient of the lower soil layer with respect to the considered substance, according to Equation 2. (Đorđević, 2020):

$$TSP = WSF \times P \quad (2)$$

where are: TSP – overall permeability of the lower soil layer[m/s], WSF – water flow sensitivity factor, P – ground permeability coefficient[m/s].

Values of the water flow sensitivity factor (WSF) may have the following values: 1 (permeability similar to water - H), 0.5 (permeability lower than water - M) and 0 (permeability much lower than water - L) (Đorđević, 2020).

The time period for the arrival of a hazardous substance to groundwater flow is also used to determine the GWF factor, which is required for estimating the effective amount of the substance that can reach the groundwater flow. The calculation of the effective amount of the substance that can reach the groundwater flow is presented by the following equation (Đorđević, 2020):

$$Q_{GW} = Q_{WS} \times GWF \quad (3)$$

where are: Q_{GW} – maximum quantity of a hazardous substance that can be released into groundwater flow[mg], Q_{WS} – maximum quantity that can be released into soil[mg], GWF – auxiliary factor for groundwater. Depending on the arrival time period (TT), the auxiliary factor GWF has specific values: days are assigned a value of 1, weeks 0.75, months 0.5, while years have a value of 0. If the time period for a substance to reach groundwater is long (more than 1 year), the GWF factor value is 0, and such a substance does not contribute to groundwater contamination and is not considered in the ecological risk assessment. (Đorđević, 2020)

RESULTS AND DISCUSSION

Ecological risk assessment, according to the *Guidelines on the methodology for developing the content of risk assessments for disasters and protection and rescue plans*, includes, in addition to the environment, the categorization of risks to human lives, health and the economy. It should be noted that the maximum concentration of the glyphosate compound that can be found in soil is 2 mg per kilogram of soil. The LC_{50} value for the herbicide glyphosate is 12 mg/dm³ (Safety Data Sheet – Glifohem, 2021). The total volume of contaminated water resulting from the release of certain quantities of glyphosate into the soil, calculated using Equation 1, is given in Table 1. (Guidelines on the methodology for developing the content of risk assessments for disasters and protection and rescue plans, 2019; Silva, 2018)

Table 1. Presentation of volume values based on released quantities of substances, the bioconcentration factor and the relative persistence factor

Quantity of released hazardous substance Q_{ws} [mg]	Bioconcentration factor	Relative persistence factor	Volume [dm ³]
0.5	0.5	1	0.083333
		0.75	0.111111
		0.5	0.166667

1	0.75	1	0.055556
		0.75	0.074074
		0.5	0.111111
	1	1	0.041667
		0.75	0.055556
		0.5	0.083333
	0.5	1	0.166667
		0.75	0.222222
		0.5	0.333333
	0.75	1	0.111111
		0.75	0.148148
		0.5	0.222222
1.5	1	1	0.083333
		0.75	0.111111
		0.5	0.166667
	0.5	1	0.25
		0.75	0.333333
		0.5	0.5
	0.75	1	0.166667
		0.75	0.222222
		0.5	0.333333
	1	1	0.125
		0.75	0.166667
		0.5	0.25
2	0.5	1	0.333333
		0.75	0.444444
		0.5	0.666667
	0.75	1	0.222222
		0.75	0.296296
		0.5	0.444444
	1	1	0.166667
		0.75	0.222222
		0.5	0.333333
2.5	0.5	1	0.416667
		0.75	0.555556
		0.5	0.833333
	0.75	1	0.277778
		0.75	0.37037
		0.5	0.555556
	1	1	0.208333
		0.75	0.277778
		0.5	0.416667
3	0.5	1	0.5
		0.75	0.666667
		0.5	1
	0.75	1	0.333333
		0.75	0.444444
		0.5	0.666667
	1	1	0.25

		0.75	0.333333
		0.5	0.5
		1	0.583333
	0.5	0.75	0.777778
		0.5	1.166667
		1	0.388889
3.5	0.75	0.75	0.518519
		0.5	0.777778
		1	0.291667
	1	0.75	0.388889
		0.5	0.583333
		1	0.666667
	0.5	0.75	0.888889
		0.5	1.333333
		1	0.444444
4	0.75	0.75	0.592593
		0.5	0.888889
		1	0.333333
	1	0.75	0.444444
		0.5	0.666667

Based on the data presented in Table 1, it can be concluded that the highest and lowest volume values occur at bioconcentration factor and relative persistence factor values of 0.5 and 1, for concentrations of the hazardous substance that are below and above the limit concentration found in soil. The maximum volume of contaminated water was 1.333333 dm³ at bioconcentration and relative persistence factor values of 0.5, while the minimum volume was 0.041667 dm³ at bioconcentration and relative persistence factor values of 1.

The values of the overall permeability of the lower soil layer (TSP) under the most unfavorable conditions, at a terrain permeability coefficient value of 0.1 (clean gravel, fractured granite, and karst limestone), are 0.1, 0.05 and 0.

Depending on the time period (TT) for the arrival of a hazardous substance into groundwater flow, the maximum quantity of the substance (Q_{GW}) that can be released into the groundwater flow on a daily basis is: 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4. On a weekly basis, the Q_{GW} values are: 0.375, 0.75, 1.125, 1.5, 1.875, 2.25, 2.625, and 3. Monthly maximum substance quantities are: 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, and 2, while annual values are 0.

The assessment of ecological risk to human life is based on the consequences that pesticide application may have on people and human health, which can be classified as: minimal (<50), minor (50–200), moderate (201–500), severe (501–1500) and catastrophic (>1500). The consequences of pesticide use on the economy are determined according to the following criteria: minimal (exceeds 1% of the budget), minor (exceeds 3% of the budget), moderate (exceeds 5% of the budget), severe (exceeds 10% of the budget) and catastrophic (exceeds 15% of the budget). (Đorđević, 2024; Đorđević, 2020)

In ecological risk assessment, a so-called “risk matrix” is used. The risk matrix consists of probability columns and consequence rows. Each of the columns and rows is characterized by five values, where the risk can be low, moderate, high, and very high. Figure 1 shows the risk matrix used in ecological risk assessment. (Đorđević, 2024; Đorđević, 2020)

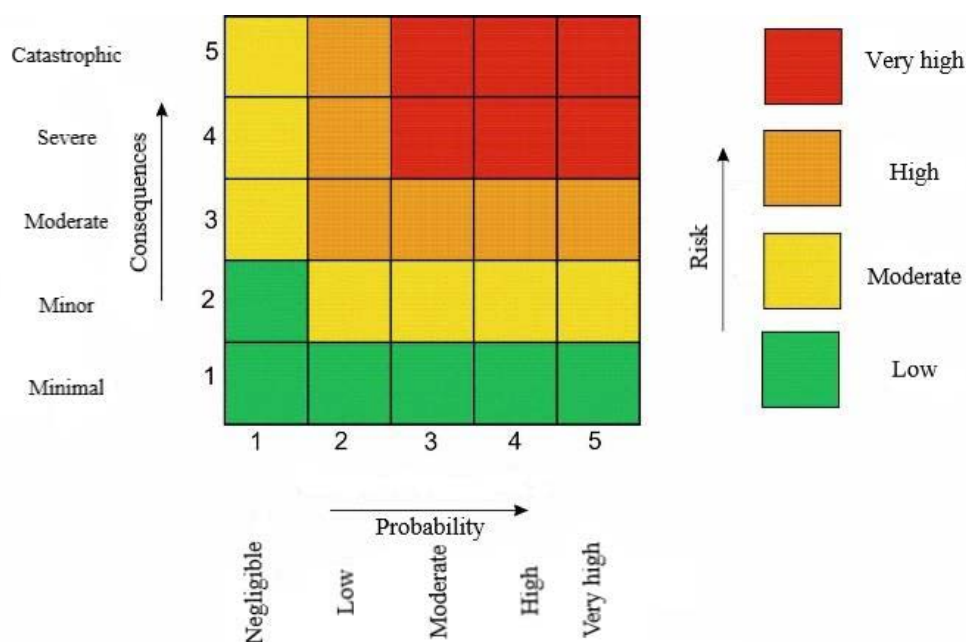


Figure 1. Presentation of the ecological risk matrix based on probability and consequence values (Đorđević, 2024; Đorđević, 2020)

The risk to groundwater flow is defined as the product of the probability of releasing certain amounts of pesticides into the soil and the damage, i.e., the consequences for the soil and the wider environment, and is expressed by Equation 4 (Đorđević, 2024; Đorđević, 2020):

$$R = P \times W \quad (4)$$

where are: R – ecological risk, P – probability of releasing certain quantities of pesticides into soil that leads to increased ecological risk and W – consequences for soil and the environment.

CONCLUSION

Worldwide, pesticides are widely used, with herbicide particularly glyphosate compounds being the most prevalent in crop production. Any application of pesticides above permitted threshold values carries a certain risk to soil, groundwater and surface water, the environment, human life and health, and a country's economy. The highest volume of contaminated water was 1.333333 dm³ at bioconcentration and relative persistence factor values of 0.5, while the lowest contaminated water volume was 0.041667 dm³ at a bioconcentration factor value of 1 and a relative persistence factor value of 1. The maximum quantity of a substance that can reach groundwater flow depends on the arrival time period (days, weeks, months, and years)

and ranges from 0 to 4 mg. The consequences of ecological risk assessment for human life and health range from minimal (<50) to catastrophic (>1500). Likewise, the consequences for a country's economy range from minimal, exceeding 1% of the budget, to catastrophic, exceeding 15% of the budget. In assessing ecological risk associated with pesticide use, it is important to determine the amount of substance applied in agriculture and the consequences it has on different environmental media (soil and surface/groundwater). In order to preserve the environment, it is necessary to find alternative methods or less toxic substances that can provide the same or similar effects in agricultural production without causing adverse environmental impacts.

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EXPOSURE TO ORGANIC SOLVENTS IN THE WORKPLACE

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Abstract: Organic solvents constitute a heterogeneous group of chemicals widely used across numerous industrial sectors, representing a persistent challenge in occupational health and safety. This review paper synthesizes current knowledge on the physicochemical properties, toxicokinetic and toxicodynamic behavior, and health effects associated with occupational exposure to organic solvents. Particular emphasis is placed on their high volatility and lipophilicity, which enable efficient absorption through inhalation and dermal routes, as well as systemic distribution and accumulation in lipid-rich tissues such as the central nervous system, liver, and adipose tissue.

The paper critically examines both acute and chronic health outcomes, including neurotoxicity, hepatotoxicity, nephrotoxicity, hematological disorders, and carcinogenic effects, with special attention to the role of oxidative stress and molecular mechanisms of toxicity. Occupational exposure scenarios are analyzed across key industrial sectors, highlighting the complexity of mixed exposures and the influence of working conditions on risk levels.

In addition, the review addresses contemporary approaches to exposure assessment, including environmental and biological monitoring, with a focus on biomarkers of exposure and effect. Preventive strategies based on the hierarchy of control measures—substitution, engineering controls, administrative measures, and personal protective equipment—are discussed in the context of their effectiveness and practical limitations.

The paper further explores emerging research directions, such as the application of modern technologies, real-time exposure monitoring systems, and the development of green solvents, which collectively contribute to a more predictive and individualized framework for occupational risk assessment.

The aim of this paper is to provide a comprehensive and integrative overview of occupational exposure to organic solvents, with a focus on health effects, risk assessment methodologies, and contemporary strategies for prevention and control.

Keywords: *Organic solvents, Occupational exposure, Protective measures, Contemporary research directions*

INTRODUCTION

Organic solvents are predominantly hydrocarbon-based compounds capable of dissolving lipophilic substances. Their extensive application in industrial processes results in substantial occupational exposure, particularly in sectors such as the chemical industry, paint and

coatings manufacturing, petrochemicals, and metal processing (Huang et al., 2024). Contemporary research indicates that the effects of organic solvents extend beyond classical acute intoxications and encompass complex chronic syndromes, including chronic toxic encephalopathy, reproductive health disorders, and carcinogenic outcomes (Joshi & Adhikari, 2019). Understanding these effects requires an integrative approach combining toxicology, molecular biology, and occupational medicine.

Organic solvents are commonly classified into aliphatic, aromatic, halogenated, and oxygenated derivatives. Their toxicological profiles are largely determined by key physicochemical properties, among which the octanol/water partition coefficient (K_{ow}) serves as an indicator of lipophilicity, influencing the compound's ability to penetrate biological membranes and accumulate in lipid-rich tissues. Vapor pressure is another critical parameter, as it governs volatility and, consequently, the potential for inhalation exposure. In addition, molecular weight and chemical structure play a significant role in determining metabolic pathways, biotransformation rates, and the potential for bioaccumulation within the organism. Lipophilic solvents (e.g., benzene, toluene) exhibit a pronounced ability to cross the blood–brain barrier, rendering them particularly hazardous to the central nervous system.

Inhalation represents the dominant route of exposure, with alveolar diffusion governed by partial pressure gradients and blood solubility. Dermal absorption, often underestimated, may be significant in the case of lipophilic solvents and prolonged contact (Williams et al., 2011). Distribution occurs according to tissue perfusion and compound lipophilicity, with notable accumulation in adipose tissue, brain and liver. This phenomenon contributes to prolonged elimination half-lives and cumulative effects.

Elimination of organic solvents occurs via the lungs as unchanged compounds, via the kidneys as metabolites, and via bile and feces as lipophilic derivatives. Many organic solvents induce the formation of reactive oxygen species (ROS), leading to lipid peroxidation, DNA damage, and protein denaturation. Oxidative stress represents a central mechanism of chronic toxicity.

Chronic exposure may result in cognitive impairment and syndromes resembling neurodegenerative diseases. Aromatic solvents, particularly benzene, induce chromosomal aberrations, mutations, and suppression of hematopoiesis, effects associated with leukemia and other malignancies (de Oliveira et al., 2017; Lim & Oh, 2023).

Acute exposure leads to central nervous system depression, respiratory insufficiency, and cardiac arrhythmias, whereas chronic exposure is associated with liver diseases (steatosis, hepatitis), kidney disorders (nephropathy), and hematological conditions (anemia, leukemia) (Albin et al., 2024).

Contemporary approaches to assessing worker exposure to organic solvents include biological monitoring through biomarkers of exposure. For example, urinary phenol is indicative of benzene exposure, while hippuric acid reflects toluene exposure. Exposure to methylene

chloride (dichloromethane) leads to the formation of carboxyhemoglobin (COHb) in the blood, as this solvent is metabolized into carbon monoxide in vivo. This represents a critical toxic mechanism, as carbon monoxide reduces the oxygen-carrying capacity of blood.

Occupational Exposure to Organic Solvents

Occupational exposure to organic solvents represents a major concern in occupational safety and health, given their widespread use in modern industrial processes. Organic solvents such as benzene, toluene, xylene, and halogenated compounds like trichloroethylene are characterized by high volatility and lipophilicity, facilitating their entry into the body via inhalation, dermal absorption, and, less frequently, ingestion. Chronic exposure may result in neurotoxicity, hepatotoxicity, nephrotoxicity, and hematological disorders, with aplastic anemia classically associated with prolonged benzene exposure.

Among the most exposed occupational groups are workers in the chemical and petrochemical industries, where solvents are used as raw materials, intermediates, or cleaning agents. In paint and coating production, workers are continuously exposed to mixtures containing aromatic and aliphatic hydrocarbons. Operators in poorly ventilated enclosed systems are particularly at risk, as concentrations of volatile organic compounds may exceed permissible exposure limits (Wang et al., 2023).

A similar exposure profile is observed in the printing industry, where solvents are used in inks and cleaning agents. Maintenance workers often come into direct contact with solvents, increasing the relevance of dermal absorption. In this sector, exposure to mixtures of ketones, esters, and alcohols complicates toxicological assessment due to potential synergistic effects (Aydemir & Özsoy, 2021).

The construction industry also represents a significant source of exposure. Painters, varnishers, and parquet installers regularly use solvent-rich products. In field conditions, ventilation is often inadequate, leading to solvent vapor accumulation in confined spaces. Prolonged exposure may result in chronic toxic encephalopathy, characterized by cognitive deficits, attention disorders, and mood disturbances (Lee et al., 2019).

Healthcare workers, particularly in laboratories and pathology departments, are also exposed to solvents such as formaldehyde and xylene used in tissue fixation and processing. Although exposure levels are typically lower than in industrial settings, long-term exposure and cumulative effects remain a concern, especially under inadequate protective measures (de Aquino et al., 2016).

The footwear and textile industries provide additional examples of high-risk sectors. Solvent-based adhesives containing toluene and hexane are widely used, leading to significant exposure in poorly ventilated workshops. The neurotoxic effects of n-hexane, including peripheral neuropathy, are well documented (Abedsoltan, 2023).

A distinct category includes workers involved in vehicle maintenance and servicing, where solvents are used for degreasing and cleaning metal parts. Combined exposure to solvents and other chemical agents complicates risk assessment and necessitates a multidisciplinary approach.

Modern risk management approaches rely on the hierarchy of control measures, including substitution with less toxic alternatives, engineering controls such as local exhaust ventilation, administrative measures, and the use of personal protective equipment. Biological monitoring, including the determination of solvent metabolites in blood and urine, is a key tool in assessing individual exposure and early detection of adverse effects.

Protective Measures Against Organic Solvent Exposure

Protective measures against organic solvent exposure constitute a complex, hierarchically structured system integrating engineering, organizational, and personal strategies, alongside continuous exposure and health monitoring.

The primary level of protection involves elimination or substitution of hazardous substances, representing the most effective control measure. Replacing highly toxic solvents such as benzene with less hazardous alternatives (e.g., water-based systems or solvents with higher boiling points and lower volatility) significantly reduces exposure potential. However, such substitutions require thorough toxicological and technological evaluation to avoid replacing one hazardous substance with another of uncertain risk (Weerasinghe et al., 2024).

Engineering controls form the cornerstone of prevention. The implementation of closed systems, process automation, and local exhaust ventilation (LEV) significantly reduces airborne solvent concentrations. Ventilation systems must be designed based on fluid dynamics and mass transfer principles, optimizing airflow velocity, intake positioning, and filtration efficiency. Real-time sensors for solvent vapor detection enable dynamic ventilation control and timely response to exposure limit exceedances (Beduk et al., 2025).

Organizational measures include optimizing work procedures and reducing exposure duration through job rotation and task planning. Standard operating procedures and mandatory training are essential in minimizing occupational risk. Education must encompass toxicokinetics, toxicodynamics, proper use of protective equipment, and emergency response procedures.

Personal protective equipment (PPE) represents the last line of defense. Respiratory protection, including masks with appropriate organic vapor filters, must be selected according to solvent type and concentration. Dermal protection involves chemically resistant gloves, protective clothing, and barrier creams, with careful consideration of material permeability. Inadequate PPE selection may create a false sense of security and increase risk.

Exposure monitoring is a key component of modern protection systems. Environmental monitoring quantifies solvent concentrations in workplace air, while biological monitoring assesses internal dose through biomarkers. Integration of monitoring data with

epidemiological studies enables more precise risk assessment and targeted preventive strategies.

Medical surveillance, as part of occupational health systems, includes periodic examinations aimed at early detection of subclinical effects. Neurological assessments, liver and kidney function tests, and hematological parameters are standard components, depending on solvent type. Identification of vulnerable worker populations, including individuals with genetic polymorphisms affecting metabolism, is of particular importance.

Regulatory frameworks and occupational exposure limits (OELs) are based on toxicological and epidemiological evidence. However, emerging research highlights the need for revising these limits in light of low-dose effects and chemical mixtures. Assessing combined exposures remains a major challenge due to potential additive, synergistic, or antagonistic interactions.

In transitional economies, including Serbia, implementation of protective measures is often constrained by economic and organizational factors. Small and medium-sized enterprises frequently lack resources for advanced technical solutions, underscoring the importance of institutional support, regulatory enforcement, and continuous education. Harmonization with European regulations and strengthening implementation capacity are essential steps toward improving occupational safety.

Contemporary Research Directions in Occupational Safety and Health

In materials science and engineering, research focuses on the development of advanced adsorbents and filtration systems for removing organic vapors from air. Nanomaterials, including functionalized carbon nanostructures and metal–organic frameworks (MOFs), demonstrate exceptional efficiency in adsorbing volatile organic compounds. These materials enable the design of high-performance filters for personal protective equipment and industrial ventilation systems, with reduced energy consumption and enhanced selectivity (Dolez, 2015).

The development of sensor technologies and the digitalization of work environments represent another important research direction. Wearable devices equipped with miniaturized gas sensors allow continuous real-time monitoring of solvent concentrations in workers' breathing zones (Sekhar et al., 2024). Integration with artificial intelligence systems enables identification of exposure patterns and prediction of high-risk situations before threshold exceedance, forming the basis of “smart” workplaces.

A significant research focus is also directed toward the development of “green” solvents within the framework of green chemistry. The goal is to identify and implement alternatives with reduced toxicity, lower volatility, and improved environmental profiles. However, comprehensive evaluation of their long-term effects remains essential.

A major challenge lies in studying the effects of combined exposure to multiple chemical agents, where traditional single-substance approaches are insufficient. Emerging concepts

such as the exposome integrate total lifetime exposure, including occupational, environmental, and lifestyle factors. This holistic approach requires advanced analytical and statistical methodologies for large-scale data analysis.

At the regulatory level, contemporary research aims to redefine exposure limits based on the latest scientific evidence, with particular emphasis on low-dose and long-term exposure effects, as well as vulnerable populations. Interdisciplinary collaboration among academia, industry, and regulatory bodies is crucial for effective implementation.

At last, contemporary research in protection against organic solvent exposure is characterized by a high degree of interdisciplinarity, the application of advanced technologies, and a focus on individualized risk assessment. The integration of molecular, engineering, and digital approaches forms the foundation for developing more effective protective strategies, ultimately aiming to minimize health risks and enhance workplace safety in modern industrial environments.

CONCLUSION

Occupational exposure to organic solvents remains a significant and multifaceted challenge in modern industrial environments, driven by the physicochemical properties of these compounds and their widespread use across diverse sectors. Their high volatility and lipophilicity facilitate efficient absorption and distribution within the human body, leading to a broad spectrum of toxic effects that extend beyond acute intoxication to include chronic, systemic, and potentially irreversible health outcomes. A comprehensive understanding of toxicokinetic and toxicodynamic mechanisms, including the role of oxidative stress and molecular alterations, is essential for accurate risk assessment and effective prevention. The integration of biomonitoring, advanced analytical techniques, and epidemiological data has substantially improved the ability to detect early biological effects and to evaluate individual susceptibility.

Despite significant advancements in regulatory frameworks and workplace safety practices, substantial challenges persist, particularly in the context of mixed exposures, low-dose chronic effects, and variability in implementation across industrial settings. The hierarchy of control measures—ranging from substitution and engineering controls to organizational strategies and personal protective equipment—remains the cornerstone of effective risk management, yet its success depends on consistent application and continuous improvement.

Emerging research directions, including the application of modern technologies, physiologically based pharmacokinetic modeling, smart sensor systems, and the development of green solvents, are reshaping the field toward a more predictive, personalized, and sustainable paradigm of occupational health protection. These innovations offer the potential to move beyond traditional reactive approaches toward proactive risk mitigation.

Finally, ensuring the protection of workers from the adverse effects of organic solvents requires an integrated, interdisciplinary approach that combines scientific innovation, regulatory enforcement, and practical implementation. Continued research, technological advancement, and international harmonization of standards are essential to minimizing health risks and improving occupational safety in the evolving landscape of industrial production.

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SAFETY AND ETHICAL CHALLENGES OF ARTIFICIAL INTELLIGENCE APPLICATION IN WASTE MANAGEMENT

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Abstract: Artificial intelligence (AI) is increasingly applied in waste management systems to enhance efficiency, optimize resource utilization, and support sustainable urban development. At the same time, the transition toward AI-driven waste management introduces new forms of vulnerability, as operational reliability, cybersecurity exposure, and ethical accountability become increasingly dependent on data quality, digital infrastructure, and automated decision-making. This paper aims to identify, systematize, and critically interpret key safety and ethical risks associated with the implementation of AI in waste management systems. The study is based on a qualitative research approach that combines literature review and conceptual analysis. Identified challenges are classified into two main categories: safety challenges, including technical, cybersecurity, and operational risks, and ethical challenges, encompassing privacy, fairness, transparency, and accountability. A socio-technical perspective is adopted to examine the interactions between technological components, human factors, and organizational structures. The results indicate that AI-based waste management systems operate as complex cyber-physical environments in which risks are interconnected and may propagate across system layers. A key contribution of the study is the development of an integrated classification framework that links safety and ethical challenges within a unified analytical structure. Furthermore, the paper introduces the concept of risk transformation, demonstrating how the implementation of AI shifts risks from traditional operational domains toward digital, systemic, and governance-related dimensions. The findings suggest that effective risk management in AI-driven waste management systems requires a multidimensional approach that integrates technical solutions, regulatory frameworks, and organizational strategies. This research contributes to a better understanding of safety and ethical challenges in AI-based waste management and provides a conceptual basis for developing resilient and trustworthy smart urban systems.

Keywords: *Artificial intelligence; Waste management; Safety risks; Ethical challenges;; Risk transformation; Socio-technical systems.*

INTRODUCTION

In recent years, the application of artificial intelligence (AI) has become increasingly prominent in waste management systems, aiming to improve efficiency, optimize resource use, and reduce environmental impact. Advanced AI-based approaches enable route optimization, waste generation prediction, and automated waste sorting using computer vision

techniques (Longhi et al., 2012; Xiao et al., 2022). Furthermore, the integration of AI with Internet of Things (IoT) technologies has facilitated the development of smart waste management systems capable of real-time monitoring and adaptive decision-making (Anagnostopoulos et al., 2017). However, the growing dependence of municipal waste management on automated and data-intensive systems transforms traditional operational challenges into interconnected technological, cybersecurity, and governance-related vulnerabilities (Leso et al., 2018; Stahl and Wright, 2018). Despite these advantages, the implementation of AI introduces safety and ethical challenges that are particularly relevant in waste management systems. The reliability of AI-driven waste management depends on the quality and availability of data (Kumar and Samadder, 2017). Increasing digitalization exposes waste management infrastructures to cybersecurity risks, particularly within interconnected IoT environments, where cyberattacks, unauthorized access, or data manipulation may compromise not only information integrity but also the continuity of essential municipal services (Sicari et al., 2015).

Ethical considerations further complicate the application of AI technologies in waste management, particularly because these systems directly affect public services and urban resource management. Issues such as data privacy, algorithmic transparency, and accountability for automated decisions therefore represent not only technical and legal concerns but also questions of public trust and fairness in municipal service provision. The use of black-box models limits interpretability, while extensive data collection raises concerns regarding misuse, unequal treatment, and reduced transparency in automated decision-making (Floridi et al., 2018; Jobin et al., 2019).

In the context of the Republic of Serbia, these challenges are further intensified by limited digital infrastructure, insufficient technical capacity, and the absence of clearly defined regulatory frameworks for AI implementation in municipal systems. Weaker infrastructural support may increase system instability and make AI-based solutions more vulnerable to technical and cybersecurity failures (OECD, 2021; European Commission, 2020). At the same time, insufficient regulatory clarity may create uncertainty regarding accountability, decision-making authority, and risk management when automated systems generate inaccurate predictions or harmful operational outcomes (Floridi et al., 2018; Jobin et al., 2019). The Serbian context represents an important environment for examining the institutional, technical, and governance-related conditions that may limit its effective and responsible implementation.

This paper aims to identify, systematize, and critically interpret key safety and ethical challenges associated with the application of artificial intelligence in waste management systems. Its scientific contribution lies in the development of an integrated classification framework that connects safety-related and ethical challenges within a unified analytical structure. The framework is considered integrated because it examines technical, cybersecurity, operational, privacy-related, fairness-related, and governance-related issues as

mutually interconnected dimensions of AI-driven waste management systems. The paper introduces the concept of risk transformation, describing the shift from operational toward digital and governance-related risks. The study therefore provides a conceptual basis for understanding how AI adoption transforms risk structures within smart municipal systems.

METHODOLOGY

This study is based on a qualitative research approach that combines literature review and conceptual analysis. The analysis included peer-reviewed scientific literature, policy documents, and professional reports addressing AI applications in waste management, IoT-enabled municipal systems, cybersecurity risks, and ethical aspects of artificial intelligence. Sources were selected according to their relevance to the research topic, with particular emphasis on studies focusing on AI-supported operational processes, digital infrastructure, and governance-related implications in public service environments. The analysis focused on identifying recurring categories of risks and challenges within AI-driven waste management systems. The research was structured to support a conceptual understanding of the main safety and ethical issues associated with AI-driven municipal systems.

A classification approach was used to systematize the identified challenges into two primary categories: safety challenges and ethical challenges. This classification was developed through analytical grouping of recurring issues identified in the reviewed sources. Within this structure, safety-related challenges were grouped into technical, cybersecurity, and operational risks, while ethical challenges were organized through the dimensions of privacy, fairness, transparency, and accountability. Accordingly, the proposed classification represents a conceptual synthesis derived from the reviewed literature.

In addition, a comparative perspective was employed to distinguish between traditional and AI-driven waste management systems. The comparison focused on changes in risks, the role of data in decision-making, the degree of automation, and the distribution of responsibility within the system. Attention was given to the emergence of new categories of risk associated with digitalization, especially those that are not typically present in conventional waste management systems. The analysis was guided by a socio-technical framework used to examine the interactions between technological components, human actors, and organizational structures in the emergence, amplification, and management of risks.

SAFETY CHALLENGES OF AI APPLICATION IN WASTE MANAGEMENT

The analysis of relevant literature indicates that the application of artificial intelligence in waste management systems brings notable improvements in efficiency and decision-making, while simultaneously introducing a set of interconnected safety challenges that may affect system reliability, stability, and operational performance. These challenges emerge through the interaction between data quality, system architecture, digital infrastructure, and increasing reliance on automated processes within AI-driven municipal systems.

Among the identified categories, issues related to the reliability and accuracy of AI models appear particularly significant. AI performance is highly dependent on the quality of input data, while incomplete, inaccurate, or biased datasets may result in incorrect predictions, inefficient route optimization, and increased operational costs (Kumar and Samadder, 2017; Xiao et al., 2022). AI systems often demonstrate limited adaptability to dynamic operational conditions, while their algorithmic complexity complicates validation, transparency, and error detection processes (Anagnostopoulos et al., 2017).

The integration of AI with IoT technologies additionally expands exposure to cybersecurity risks, particularly within interconnected cyber-physical infrastructures (Longhi et al., 2012; Sicari et al., 2015). Cybersecurity risks extend beyond technical vulnerabilities, since their consequences may include operational disruptions, infrastructure instability, and reduced reliability of public services. Threats such as unauthorized access, data manipulation, and data poisoning represent systemic risks affecting both digital and physical dimensions of waste management systems.

Operational risks represent another major category of identified challenges. Increasing dependence on automated decision-making processes amplifies system vulnerability in cases of technical failures, operational disruptions, or communication breakdowns. Failures in algorithms, communication systems, or supporting infrastructure may interrupt waste collection and processing activities, while excessive dependence on automation without sufficient human oversight further intensifies these vulnerabilities (Leso et al., 2018).

ETHICAL CHALLENGES OF AI APPLICATION IN WASTE MANAGEMENT

The analyzed literature points to ethical challenges that directly influence public trust, system acceptance, and the long-term sustainability of AI-based waste management systems. Within the proposed classification, these challenges are organized through the dimensions of privacy, fairness, transparency, and accountability (Floridi et al., 2018; Jobin et al., 2019).

A central issue relates to privacy and data protection. AI-based systems rely on extensive data collection, including information on user behavior and waste generation patterns. While such data are essential for system optimization, they may also expose sensitive personal information and raise concerns regarding misuse (Stahl & Wright, 2018). Systems such as Pay-as-you-throw (PAYT) can generate detailed user profiles, making anonymization, encryption, and regulatory compliance essential.

Algorithmic bias represents another important concern (Jobin et al., 2019). Models trained on unrepresentative datasets may produce biased outcomes, leading to unequal service distribution across regions or user groups. In waste management systems, such outcomes may reinforce existing social and infrastructural inequalities and undermine the fairness of municipal service provision. Addressing this issue requires bias mitigation strategies and continuous monitoring.

Transparency and explainability represent additional critical ethical dimensions. AI systems based on complex black-box models often limit the interpretability of automated decisions (Floridi et al., 2018). In public-service systems such as waste management, limited transparency may reduce trust in automated processes and complicate error identification.

Finally, accountability and governance remain key concerns. The use of automated decision-making systems raises questions regarding responsibility in cases of system failure or incorrect outcomes. The absence of clearly defined regulatory frameworks may create legal uncertainty and complicate the distribution of responsibility between developers, operators, and public institutions (European Commission, 2020). Accountability should therefore be understood not only as a legal issue, but also as a governance challenge relevant to the responsible implementation of AI in municipal systems.

DISCUSSION

The findings of this study suggest that AI-based waste management systems should be understood as complex socio-technical systems in which risks emerge from interactions between technological, human, and organizational components. Rather than appearing as isolated technical failures or ethical dilemmas, the identified challenges are interconnected and may propagate across system layers. This interpretation is consistent with the analytical approach of the study, in which safety and ethical challenges were examined as interconnected dimensions of AI-driven municipal systems. This interdependence becomes particularly visible when specific challenges are considered together rather than separately. In this sense, safety and ethical challenges do not merely coexist, but often reinforce one another through shared system dependencies.

A key insight of this study is that artificial intelligence does not eliminate risks but rather redistributes and transforms them. Traditional physical and operational risks are increasingly complemented or replaced by digital, systemic, and governance-related vulnerabilities.

The concept of risk transformation is used to describe this shift from visible and localized risks toward more distributed, less immediately observable, but often more complex forms of risk (Figure 1).

Figure 1 highlights how the introduction of AI changes the focus of risk management from predominantly physical and operational concerns toward digital, ethical, and governance-related dimensions, reinforcing the need for integrated approaches. The figure also illustrates why conventional approaches are no longer sufficient in AI-driven systems.

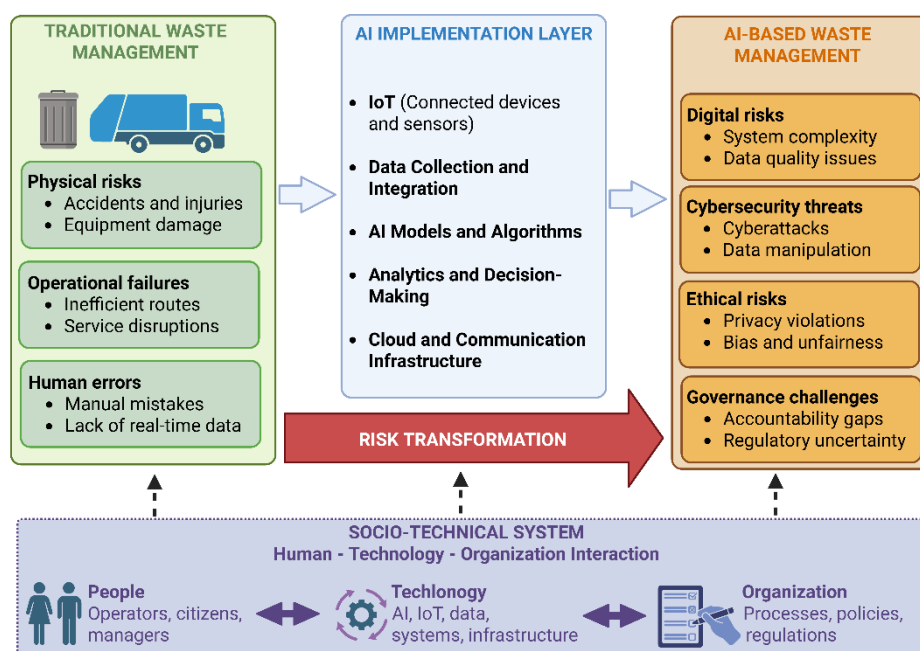


Figure 2. Conceptual representation of risk transformation in AI-based waste management systems

This transformation becomes particularly evident in contexts characterized by limited infrastructural and institutional capacity. In developing countries such as Serbia, implementation is further constrained by infrastructural limitations, insufficient technical capacity, and the absence of clearly defined regulatory frameworks. Such conditions may intensify both safety and ethical risks by reducing system robustness and increasing vulnerability to operational and cybersecurity failures. From an occupational health and safety perspective, the introduction of AI also creates new forms of risk related to human-machine interaction, reduced situational awareness, and increased cognitive workload. In AI-supported waste management systems, workers may increasingly operate in environments where critical decisions are shaped by automated recommendations, sensor-based monitoring, and real-time system feedback.

The results suggest that decision-makers should adopt a multidimensional perspective that includes safety, ethical responsibility, and human factors, rather than focusing solely on efficiency. The proposed framework should be understood not only as a classification tool, but also as a conceptual basis for interpreting interconnected risks in AI-driven waste management systems.

To further systematize the identified challenges, the results are summarized in Table 1, which provides a structured overview of key safety and ethical risks. The impact levels presented in Table 1 are based on the interpretative assessment conducted in this study. The classification demonstrates that safety-related and ethical challenges are closely interconnected, while the most critical risks arise at the intersection of technological and societal dimensions. The table

also highlights the need for multidimensional mitigation strategies that combine technical, regulatory, and organizational approaches.

Table 7. Classification of safety and ethical challenges in AI-based waste management

Category	Challenge	Potential consequences	Recommended measures	Impact level
Safety	Inaccurate data and model uncertainty	Suboptimal route optimization, increased operational costs, reduced system efficiency	Data validation, continuous monitoring, and quality assurance mechanisms	High
	Cybersecurity threats (e.g., cyberattacks, data breaches)	System disruption, unauthorized access, data manipulation, potential physical consequences in CPS environments	Strengthening cybersecurity protocols, network protection, and intrusion detection systems	Critical
	Operational system failures	Service interruptions, delays in waste collection, reduced reliability of municipal services	Implementation of backup systems, redundancy mechanisms, and human-in-the-loop supervision	High
Ethical	Privacy violations and data misuse	Loss of public trust, potential misuse of sensitive personal data	Data anonymization, encryption, and compliance with data protection regulations (e.g., GDPR)	Critical
	Algorithmic bias and fairness issues	Unequal service distribution, discrimination across regions or user groups	Use of representative datasets, bias mitigation strategies, and regular auditing of AI models	High
	Lack of transparency and explainability	Limited understanding of AI decisions, reduced trust and accountability	Implementation of explainable AI (XAI) approaches and transparent decision-making processes	High
	Accountability gaps and unclear responsibility	Legal uncertainty, challenges in assigning responsibility for system failures	Development of regulatory frameworks and clear governance structures for AI systems	Critical

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

This study is based on qualitative analysis and conceptual interpretation, which limits the generalizability of the findings. The proposed framework has not been validated in operational waste management systems, while the relationships between identified categories of challenges remain conceptually interpreted rather than quantitatively examined. The impact levels presented in Table 1 should be understood as interpretative assessments derived from the reviewed literature and expected system consequences.

Future research should focus on validating the proposed framework through real-world case studies and comparative analyses of AI-supported municipal systems. Attention should be directed toward examining the mechanisms through which risk transformation occurs, testing the practical applicability of the identified categories, and refining the assessment of interdependencies between safety and ethical challenges.

CONCLUSION

Artificial intelligence presents significant potential to enhance the efficiency, adaptability, and sustainability of waste management systems; however, its implementation simultaneously introduces complex safety and ethical challenges. The findings indicate that AI implementation represents not only a technological advancement, but also a transformation of risk structures and governance requirements within municipal systems.

The proposed classification framework contributes to a more comprehensive understanding of these challenges by integrating safety and ethical perspectives within a unified socio-technical context. The framework supports the identification and interpretation of interconnected risk categories and highlights the importance of considering technological, organizational, and governance-related dimensions simultaneously.

The results emphasize the need for multidimensional strategies aimed at ensuring system reliability, protecting user rights, and strengthening public trust. In this regard, the proposed framework may support local authorities, municipal service operators, and regulators in the planning, implementation, and oversight of AI-supported waste management systems.

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SCENARIO-BASED ASSESSMENT OF ALTERNATIVE FUELS FOR TRANSPORT DECARBONIZATION IN SERBIA

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Abstract: The transport sector in Serbia accounts for a significant share of total final energy consumption and greenhouse gas (GHG) emissions, yet systematic national-level assessments of alternative fuel potential remain limited. This paper presents a methodology for quantifying the potential of alternative fuels and energy sources for transport decarbonization in Serbia for the 2030 horizon, with a focus on the S/SN macro-energy decarbonization scenario defined in the Integrated National Energy and Climate Plan of Republic of Serbia (INECP). Feedstock potentials were assessed across five categories: agriculture, food industry, municipal waste, forestry, and renewable electricity. A linear programming (LP) simplex model with seven objective functions was applied, yielding eight scenarios per approach under the S/SN scenario, evaluated under conservative and optimistic feedstock availability approaches. Objective function f1 (minimum GHG emissions) produced seven equally optimal solutions with negative net GHG emissions (-3,057 to -4,266 tCO_{2eq}) due to the dominant role of manure-based biomethane, which generates emission savings through avoided uncontrolled storage. Objective function f2 (minimum production cost) produced one solution with positive GHG emissions (54,935 tCO_{2eq}), illustrating the fundamental trade-off between cost and climate objectives. Scenario S2, derived from f1, achieves the minimum GHG emissions combined with the lowest production cost within the f1 group, making it the preferred pathway for transport decarbonization in Serbia.

Keywords: *Alternative fuels; Transport decarbonization; Linear programming; GHG emissions.*

INTRODUCTION

The transport sector is one of the primary contributors to greenhouse gas (GHG) emissions both globally and in Serbia. Under the Integrated National Energy and Climate Plan (INECP) and Energy Sector Development Strategy of Republic of Serbia, the planned share of renewable energy in transport reaches 3.2% by 2030 under the S/SN decarbonization scenario, rising sharply to 44.8–48.6% by 2050 (MMERS, 2024a; 2024b). Fulfilling these targets requires the systematic deployment of alternative fuels, including biomethane, bioethanol, hydrotreated vegetable oil (HVO), Fischer-Tropsch (FT) synthetic fuels, and renewable electricity.

Serbia possesses substantial untapped biomass and waste resources suitable for alternative fuel production. Agricultural residues, manure, organic waste streams, used cooking oil (UCO), and forest biomass represent a diverse feedstock base that can support multiple conversion pathways. However, the optimal allocation of these feedstocks to fuel types,

subject to regulatory, technical, and resource constraints, requires a structured optimization approach. Previous studies have assessed biogas potentials for Serbia (Martinov et al., 2020) and crop residue availability (Scarlat et al., 2010), but a comprehensive national-level scenario-based assessment integrating all relevant feedstocks and technologies under a unified linear programming (LP) framework has not been performed.

To address this gap, the paper develops an LP optimization model that generates alternative fuel scenarios for Serbia's transport sector in 2030 based on two contrasting objective functions, compares their GHG performance, and identifies the pathway best suited for transport decarbonization.

MATERIALS AND METHODS

Feedstock potential assessment

Feedstock potentials were assessed using a hierarchical framework distinguishing theoretical, technical, sustainable, and alternative fuel potential. Five categories were considered: (1) agriculture, comprising manure, crop residues, corn silage, cover crops (rye, triticale), and first-generation feedstocks (corn, cereals, sugar beet for bioethanol); (2) food industry, including UCO, slaughterhouse waste, and organic industrial waste; (3) municipal sector, comprising organic fraction of municipal solid waste (OFMSW), kitchen waste (HORECA), landfill gas, green waste, and sewage sludge; (4) forestry, with forest biomass allocated for FT synthesis; and (5) renewable electricity from solar PV, wind, and hydropower.

Data sources include the different databases (SORS, 2023; SEPA, 2023), national documents (MMERS, 2024b; MEPRS, 2022; MAFWMRS, 2021), and relevant literature (Viskovic et al., 2022; Martinov et al., 2020; Djurisc-Mladenovic et al., 2018; Scarlat et al., 2010). Conservative and optimistic approaches were applied to reflect uncertainty in mobilization rates of feedstock. In the S/SN macro-energy scenario for 2030, the total energy potential of alternative fuels is estimated at approximately 452 ktoe (conservative) and 653 ktoe (optimistic). These figures exceed the INECP planned biofuel contribution of 49.2 ktoe by a factor of nine to thirteen.

GHG emissions assessment

GHG emissions for each feedstock-technology pathway were calculated using the methodology and default values defined in RED II (Renewable Energy Directive) (EC, 2018), supplemented by the JEC Well-to-Tank report (Prussi et al., 2020). The fossil fuel comparator was set at 94 gCO_{2eq}/MJ in accordance with RED II. The minimum GHG saving threshold for transport biofuels is 65% for plants operational from 1 January 2021 onwards (EC, 2018).

Production cost assessment

Production costs for each feedstock-technology pathway were expressed in k€/TJ. For biomethane pathways, production costs were calculated using the BiogasPro tools developed for economic assessment of biomass energy projects under Serbian market conditions

(Martinov et al., 2012). For pathways not yet commercially deployed in Serbia, such as Fischer-Tropsch synthetic fuels and advanced bioethanol production costs were sourced from peer-reviewed literature and institutional reports (Brown et al., 2020; Cazzola et al., 2023; Soler et al., 2022). Costs for renewable electricity were sourced from IEA energy technology databases (IEA, 2026).

Linear programming simplex model

LP model was developed to define optimal alternative fuel mixes. The general form of the LP problem is:

$$\min c^T x \quad (1)$$

subject to

$$Ax \leq b \quad (2)$$

$$Cx = d \quad (3)$$

$$x \geq 0 \quad (4)$$

where $x \in \mathbb{R}^n$ is the decision vector representing the annual energy quantities of alternative fuels (in ktoe) by fuel type and feedstock; $c \in \mathbb{R}^n$ is the vector of objective function coefficients (varying across scenarios); $A \in \mathbb{R}^{m \times n}$ and $b \in \mathbb{R}^m$ represent the inequality constraint matrix and vector, respectively; while $C \in \mathbb{R}^{p \times n}$ and $d \in \mathbb{R}^p$ define the equality constraints.

Nine constraint categories were applied: (1) feedstock availability per feedstock type; (2) total energy level of alternative fuels fixed to macro-energy scenario values; (3) total renewable electricity level fixed per scenario; (4) 1G biofuels capped at 2% of final transport energy (RED II); (5) UCO and slaughterhouse waste capped at 1.7% (RED II); (6) crop residues in biometan substrate limited to $\leq 15\%$ dry matter; (7) manure share in biometan substrate between 10–50% dry matter; (8) bioethanol blend limited to E10 (EN 228); and (9) cover crop mass limited to $\leq 70\%$ of corn silage mass.

Two objective functions were applied per macro-energy variant, generating multiple scenarios. The LP problem may yield one, multiple, or infinitely many optimal solutions of equal objective function value. In this study, objective function f1 (minimum total GHG emissions) produced seven equally optimal solutions per analysis case, differing only in production cost. Objective function f2 (minimum total production cost) produced a single optimal solution. No objective function was infeasible. The S/SN macro-energy scenario was selected as the primary decarbonization pathway in line with INECP commitments, and all results are presented for this scenario under both conservative (CA) and optimistic (OA) feedstock availability approaches, yielding eight scenarios per approach.

RESULTS AND DISCUSSION

Figure 1 presents the relationship between total GHG emissions and total production cost for all eight scenarios under the S/SN macro-energy scenario for 2030, for both conservative and

optimistic approaches. The x-axis shows total GHG emissions (ktCO_{2eq}), the y-axis shows total production cost (M€), and the vertical dashed red line indicates the GHG emissions that would result from the equivalent quantity of fossil fuels at the RED II comparator value of 94 gCO_{2eq}/MJ. All alternative fuel scenarios are positioned substantially to the left of the fossil fuel reference line, confirming that all defined scenarios achieve significant GHG savings relative to fossil fuels.

Scenarios S1 through S7, derived from objective function f1 (minimum GHG, shown in green), are clustered in the upper-left region of the diagram, achieving negative net GHG emissions of -3.1 ktCO_{2eq} (conservative approach) and -4.3 ktCO_{2eq} (optimistic approach), corresponding to a GHG saving of approximately 101% relative to the fossil fuel comparator in both approaches. This saving exceeds 100% because the manure-based biomethane assigns emission credits for avoided uncontrolled manure storage, resulting in a net carbon sink rather than merely a reduction in fossil fuel emissions. Within the f1 group, scenario S2 stands out as the economically most efficient solution, positioned at the lowest production cost of 64.8 M€ (conservative) and 64.7 M€ (optimistic), while sharing the identical GHG performance of all other f1 scenarios.

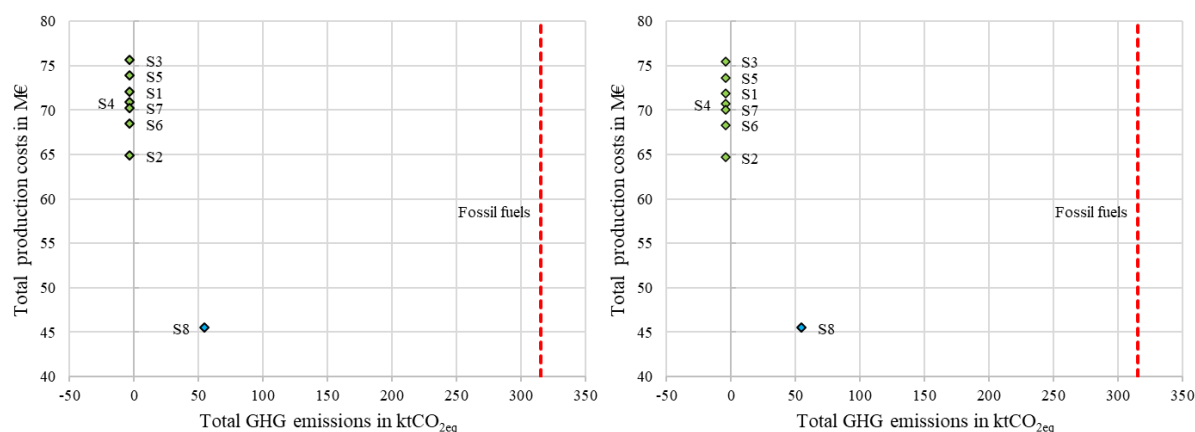


Figure 1. Total GHG emissions and production cost for scenarios for 2030 – left: conservative approach, right: optimistic approach.

Scenario S8, derived from objective function f2 (minimum production cost, shown in blue), achieves the lowest production cost of all scenarios at 45.5 M€ in both approaches, but at the expense of substantially higher GHG emissions of 54.9 ktCO_{2eq}, corresponding to a GHG saving of approximately 83% relative to the fossil fuel comparator. The position of S8 in the lower-right region of the diagram, separated from the f1 cluster by approximately 58 ktCO_{2eq} on the horizontal axis and approximately 19 M€ on the vertical axis, graphically illustrates the fundamental trade-off between cost minimization and GHG minimization in alternative fuel scenario design. Scenario S2 therefore represents the preferred pathway, as it achieves maximum GHG savings while remaining the most economically efficient solution among all GHG-optimal scenarios.

Table 1 presents GHG emissions and production costs for all scenarios under both conservative and optimistic approaches. Within the f1 group, the seven equally optimal solutions share identical GHG performance and an identical biomethane substrate mix in both approaches, differing exclusively in the source of renewable electricity, whether solar, wind, or hydropower, which drives the variation in production cost from 64.8 M€ (S2) to 75.6 M€ (S3) in the conservative and from 64.7 M€ (S2) to 75.5 M€ (S3) in the optimistic approach. For the optimistic approach, the more negative GHG value (-4,266 tCO_{2eq} compared to -3,057 tCO_{2eq} in the conservative approach) reflects a higher share of manure in the biomethane substrate mix, enabled by greater assumed mobilization of manure from small and medium livestock farms. This confirms that manure mobilization policy is a key lever for maximizing the decarbonization potential of biomethane in Serbia. Scenario S2 is identified as the preferred pathway in both approaches, as it simultaneously achieves minimum GHG emissions and the lowest production cost within the f1 group.

In terms of economic optimization, Scenario S8 (f2) represents the cost minimum, delivering the target output at 45.5 M€. While this reflects a substantial financial optimization, reducing expenditure by 19.3 M€ relative to S2, it necessitates a compromise in decarbonization. The GHG abatement potential of S8 is limited to 83% compared to the fossil fuel benchmark, whereas the f1 scenarios consistently exceed 101% savings. In contrast to the f1 scenarios (S1–S7), S8 replaces manure and its associated carbon sink benefits with 1G bioethanol and biomethane from crop residues.

Table 1. GHG emissions and production costs for scenarios derived from f1 and f2 objective functions.

Scenario	S/SN – CA		S/SN – OA	
	GHG (tCO _{2eq})	PC (k€)	GHG (tCO _{2eq})	PC (k€)
Objective function 1 – minimum total GHG emissions				
S1	-3.057,08	72.030,69	-4.265,97	71.877,14
S2	-3.057,08	64.830,99	-4.265,97	64.677,44
S3	-3.057,08	75.615,09	-4.265,97	75.461,54
S4	-3.057,08	70.825,59	-4.265,97	70.672,04
S5	-3.057,08	73.822,89	-4.265,97	73.669,34
S6	-3.057,08	68.430,84	-4.265,97	68.277,29
S7	-3.057,08	70.223,04	-4.265,97	70.069,49
Objective function 2 – minimum total production cost				
S8	54.935,20	45.455,51	54.935,20	45.455,51

CA: conservative approach; OA: optimistic approach; GHG: total GHG emissions;
PC: total production cost

The implicit carbon abatement cost of transitioning from S8 to S2 amounts to approximately 325–334 €/tCO_{2eq}, calculated as the ratio of the additional production cost (19.2–19.4 M€) to the GHG emission reduction achieved (58–59 ktCO_{2eq}) between the two scenarios. This value

provides a quantitative basis for the design of targeted policy instruments, such as biomethane premium tariffs or green gas certificates, that would need to incentivize the deployment of manure-based biomethane as the primary transport decarbonization pathway in Serbia.

CONCLUSIONS

This study demonstrates that Serbia possesses substantial domestic feedstock and resources for alternative fuel production, with an assessed energy potential of 452 ktoe (conservative) and 653 ktoe (optimistic) for the 2030 horizon, substantially exceeding the INECP target of 49.2 ktoe for the S/SN scenario. This surplus confirms that the binding constraint on alternative fuel deployment is not resource availability but rather regulatory, financial, and infrastructure readiness. The surplus potential becomes particularly relevant for the 2050 horizon, where INECP defines a renewable energy share of 44.8–48.6% in transport under S/SN scenarios, requiring full mobilization of all available feedstock categories alongside the introduction of advanced pathways such as e-fuels and green hydrogen.

Among the eight defined scenarios, S2 from objective function f1 delivers the best combination of climate impact and economic performance: negative net GHG emissions exceeding 101% savings against the fossil comparator, at the lowest cost within the GHG-optimal group. The better performance of the optimistic approach over the conservative one traces back to a larger share of organic waste and a smaller share of energy crops in the substrate mix, confirming that waste mobilization policy, alongside manure management, is a practical lever for improving both the carbon and cost profile of biomethane. Scenario S8 shows that cost-only optimization yields a markedly different result: a 30% lower production cost but a GHG saving of only 83%, still well above fossil fuels yet far short of the carbon sink achieved by f1.

The results highlight that the choice between GHG-optimal and cost-optimal scenarios ultimately reflects a policy decision on the relative priority assigned to climate ambition and economic efficiency. Future research should extend the analysis to 2050 and develop a formal multi-criteria ranking that integrates GHG performance, production cost, and technology readiness, providing a more complete basis for that decision.

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REGULATORY CHANGES AND SUSTAINABILITY IMPLICATIONS OF THE NEW WASTE MANAGEMENT LAW IN SERBIA

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Abstract: Although waste generation has long been associated with human activities and economic development, its effective management remains a persistent environmental challenge, particularly in less developed countries where waste management is often insufficiently developed and infrastructure is limited. Inefficient waste management leads to significant environmental impacts, including soil, water and air contamination, resulting in associated risks to human health. In recent years, Serbia has undertaken significant regulatory reforms aimed at improving the efficiency and sustainability of its waste management system. The amendments to the Law on Waste Management introduce several important changes related to waste prevention, improved classification of waste streams, clearer responsibilities of waste management actors, and increased alignment with European Union environmental legislation. This paper analyzes the key regulatory changes introduced by the amended waste management legislation in Serbia through a regulatory and policy analysis and discusses their implications for environmental protection and sustainable resource management. Particular attention is given to new definitions, obligations for waste producers, digitalization of waste tracking, and improved regulatory control mechanisms. The results indicate that the new legislative framework strengthens the principles of circular economy and promotes more efficient waste prevention, recycling, and resource recovery. At the same time, the implementation of these changes requires improved institutional capacity and stronger cooperation between regulatory authorities, industry, and local governments.

Keywords: *Waste Management; Environmental Legislation; Circular Economy; Recycling; Environmental Policy.*

INTRODUCTION

Waste generation has significantly increased worldwide as a result of economic growth, urbanization, and changes in consumption patterns (European Environment Agency, 2023). Inefficient waste management can cause serious environmental problems, including soil contamination, water pollution, and greenhouse gas emissions. For this reason, modern environmental policies increasingly emphasize the principles of waste prevention, recycling, and circular economy (European Commission, 2008; European Commission, 2020). Effective waste management systems require a comprehensive regulatory framework that clearly defines responsibilities of all actors involved in waste generation, collection, transport, treatment, and disposal. Legislative instruments therefore play a key role in establishing

environmental standards, improving environmental protection, and promoting sustainable resource use. The development of such regulatory frameworks is essential for ensuring environmentally sound waste management practices and reducing the negative impacts of waste on ecosystems and human health (European Environment Agency, 2023).

In Serbia, waste management has been regulated through the Law on Waste Management and several accompanying by-laws that define the responsibilities of waste producers, operators, and regulatory authorities (Government of Serbia, 2009). However, the rapid development of environmental policies within the European Union and the growing need for sustainable resource management have required further harmonization of national legislation with European environmental standards (European Commission, 2008). Recent amendments to Serbian waste management legislation represent an important step toward improving the overall efficiency of the national waste management system. The revised framework introduces clearer definitions of waste categories, strengthens responsibilities of waste producers and operators, and introduces mechanisms for improved monitoring and control of waste flows (Government of Serbia, 2025). These regulatory changes are also consistent with the strategic objectives defined in the Waste Management Programme of the Republic of Serbia for the period 2022–2031, which emphasizes waste prevention, recycling, and the development of modern waste management infrastructure (Ministry of Environmental Protection, 2022). The purpose of this paper is to analyze the key changes introduced by the new waste management legislation in Serbia and to assess their importance for the development of a more sustainable and efficient waste management system.

MATERIALS AND METHODS

The research presented in this paper is based on the analysis of selected regulatory documents governing waste management in the Republic of Serbia. The primary sources include the Law on Waste Management and its recent amendments, as well as relevant national environmental strategies and European Union waste management directives (European Commission, 2008; Government of Serbia, 2009; Government of Serbia, 2025; Ministry of Environmental Protection, 2022). The methodological approach combines regulatory analysis and a comparative review of policy documents related to waste management. The analysis focuses on identifying regulatory changes introduced by the amended legislation and evaluating their implications for waste prevention, recycling, and institutional governance within the national waste management system. Special attention was given to identifying the key legislative changes introduced in the updated regulatory framework and evaluating their potential environmental and institutional implications. The analysis focuses on several key elements of the waste management system: classification of waste streams; responsibilities of waste producers and operators; waste prevention measures; waste tracking and reporting mechanisms; and alignment with EU circular economy principles (European Commission, 2008; European Commission, 2020). In addition to legislative analysis, the study also reviews available reports and policy documents addressing the current status of waste management in

Serbia and the challenges related to its implementation (European Environment Agency, 2023).

RESULTS AND DISCUSSION

Regulatory framework of waste management in Serbia

Waste management in Serbia is regulated through a comprehensive legislative framework that defines the responsibilities of waste producers, collectors, transporters, and treatment operators. The central legal document in this field is the Law on Waste Management, which establishes the basic principles of waste prevention, recycling, and environmentally safe waste treatment (Government of Serbia, 2009; Government of Serbia, 2025).

The legislative framework is largely based on the principles defined by the European Union Waste Framework Directive and aims to gradually harmonize national environmental policies with EU standards. The development of waste management legislation in Serbia is strongly influenced by the process of harmonization with European Union environmental policy. In particular, the EU Waste Framework Directive 2008/98/EC establishes key principles such as the waste hierarchy, extended producer responsibility, and the promotion of recycling and resource recovery (European Commission, 2008).

Recent amendments to Serbian waste management legislation reflect these principles and aim to gradually align national regulations with European environmental standards. These changes are also consistent with the broader objectives of the European Circular Economy Action Plan, which promotes waste prevention, recycling, and more efficient use of resources (European Commission, 2020).

In addition, the national Waste Management Programme of the Republic of Serbia for the period 2022–2031 defines strategic goals for improving waste prevention, recycling rates, and the development of waste management infrastructure (Ministry of Environmental Protection, 2022). Harmonization with these European and national policy frameworks is particularly important in the context of Serbia's EU accession process and the requirements related to Chapter 27 on environment and climate change.

Despite the existence of this regulatory framework, the implementation of waste management policies has faced several challenges, including insufficient infrastructure, limited recycling capacity, and inadequate monitoring of waste flows (European Environment Agency, 2023).

Key changes introduced by the new waste management legislation

The revised waste management legislation introduces several important changes aimed at improving system efficiency and transparency.

One of the most important changes is the introduction of new and more precise definitions related to different waste categories. The law aligns definitions of municipal, industrial, and bio-waste with European environmental terminology, which improves the consistency of

waste reporting and monitoring. The legislation also introduces the concept of food waste and emphasizes prevention measures in accordance with EU waste reduction policies (Government of Serbia, 2025; European Commission, 2008).

Another important aspect concerns the responsibilities of waste producers. While the obligation for certain waste producers to prepare waste management plans already existed in previous legislation, the new law further clarifies and strengthens these requirements. Primary waste producers generating significant quantities of waste are required to prepare waste management plans that describe the types and quantities of waste generated and the methods used for its treatment or disposal (Government of Serbia, 2009; Government of Serbia, 2025). The new legislation also clarifies the roles of different participants in the waste management chain, including collectors, transporters, brokers, and traders. This clearer allocation of responsibilities improves the traceability of waste flows and reduces the risk of illegal waste handling (Government of Serbia, 2025).

Digitalization and monitoring of waste flows

An important innovation introduced by the new legislation is the digitalization of waste tracking systems. The revised legislation also establishes a mandatory digital document for monitoring the movement of certain waste streams (Government of Serbia, 2025).

Digital monitoring of waste flows allows regulatory authorities to obtain more accurate information about the quantities and types of waste generated and treated within the waste management system. Such information is essential for planning waste management infrastructure and evaluating the effectiveness of environmental policies (Ministry of Environmental Protection, 2022).

In addition, the legislation strengthens inspection mechanisms and allows more efficient control of waste management operators. Improved inspection procedures contribute to better enforcement of environmental regulations and help reduce illegal waste disposal practices (Government of Serbia, 2025).

Waste prevention and circular economy principles

The new legislative framework places greater emphasis on waste prevention and circular economy principles. Instead of focusing primarily on waste disposal, modern waste management policies prioritize reduction of waste generation, reuse of materials, and recycling (European Commission, 2008; European Commission, 2020).

The concept of material recovery has been further clarified in the legislation and includes processes such as preparation for reuse, recycling, and backfilling, while distinguishing these processes from energy recovery through incineration (European Commission, 2008; Government of Serbia, 2025).

The promotion of circular economy principles can significantly reduce the environmental impacts associated with waste disposal and contribute to more efficient use of natural

resources. In addition, the development of recycling industries can generate new economic opportunities and support the transition toward a green economy (European Commission, 2020).

The main regulatory changes introduced by the new waste management legislation are summarized in Table 1.

Table 1. Key changes introduced by the updated waste management legislation in Serbia.

Regulatory aspect	Previous regulatory approach	Changes introduced in the updated legislation	Expected environmental impact
Waste definitions	Some waste categories were broadly defined, with limited differentiation between certain waste streams.	More precise definitions aligned with EU terminology, including clearer classification of municipal waste, bio-waste, and food waste.	Improved consistency in reporting and monitoring of waste streams.
Responsibilities of waste producers	Waste producers had general obligations for waste handling and reporting.	Introduction of stricter obligations for primary waste producers, including preparation of waste management plans and improved documentation.	Better control of waste generation and improved environmental responsibility of producers.
Waste tracking and documentation	Waste tracking relied mainly on paper documentation and periodic reporting.	Introduction of digital documentation and electronic tracking of waste movement.	Increased transparency and improved monitoring of waste flows.
Inspection and regulatory control	Inspection procedures existed but monitoring of waste flows was often limited.	Strengthened inspection mechanisms and clearer responsibilities of waste operators.	Reduced risk of illegal waste disposal and improved enforcement of environmental regulations.
Circular economy principles	Waste management policy focused primarily on waste collection and disposal.	Stronger emphasis on waste prevention, recycling, and material recovery in accordance with circular economy principles.	Reduction of landfilling and more efficient use of resources.

These regulatory improvements are expected to enhance transparency, strengthen institutional control, and support the transition toward a circular economy-based waste management system. From a policy perspective, these regulatory changes represent a transition from a

predominantly disposal-oriented waste management model toward a more integrated system based on waste prevention, recycling, and resource recovery principles.

The successful implementation of new waste management legislation depends not only on the regulatory framework itself but also on institutional capacity, technical infrastructure, and the cooperation of different stakeholders. Although the updated legislation introduces clearer responsibilities and improved monitoring mechanisms, several practical challenges may influence its implementation. One of the key challenges relates to the development of adequate waste management infrastructure. Many municipalities still rely heavily on landfilling as the primary method of waste disposal, while recycling facilities and waste treatment plants remain limited. Expanding recycling infrastructure and improving waste separation systems will therefore be essential for achieving the objectives of the new legislation. Another important aspect concerns administrative capacity and regulatory control. Effective implementation requires well-trained inspection services and reliable systems for monitoring waste flow. The introduction of digital tracking systems may significantly improve transparency; however, it also requires technical capacity and coordination between institutions. These developments are also particularly relevant in the context of Serbia's European Union accession process, where further alignment with the EU environmental acquis under Chapter 27 requires strengthening regulatory implementation, institutional capacity, and monitoring systems.

Public awareness and participation also play an important role in the success of waste management policies. Waste separation at the source and responsible consumption patterns depend largely on public understanding of environmental issues and the availability of appropriate collection systems.

The introduction of clearer regulatory responsibilities and improved monitoring mechanisms represents an important step toward strengthening the waste management system in Serbia. However, the long-term success of these measures will largely depend on effective implementation, adequate institutional capacity, and continuous investment in waste management infrastructure. At the same time, the relatively low level of public awareness regarding proper waste management practices remains an additional challenge for the successful implementation of these reforms.

CONCLUSION

Recent amendments to waste management legislation in Serbia represent an important step toward improving environmental governance and aligning national regulations with European Union environmental policy. The analysis presented in this paper shows that the new regulatory framework introduces clearer definitions of waste categories, strengthens the responsibilities of waste producers, and improves mechanisms for monitoring and transparency of waste flows. The introduction of digital waste tracking systems and enhanced inspection procedures contributes to better control of waste management activities and

reduces the risk of illegal waste handling. At the same time, the stronger emphasis on waste prevention and circular economy principles reflects broader international trends in sustainable resource management. Nevertheless, the successful implementation of the new legislative framework will depend on the development of adequate waste management infrastructure, strengthening institutional capacity, and improving cooperation between public authorities, industry, and local communities. Further progress in these areas will be essential for achieving the long-term objectives of environmental protection, sustainable resource use, and improved quality of life, which ultimately represents a shared responsibility of institutions, industry, and society.

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OCCUPATIONAL HEALTH AND SAFETY EDUCATION FOR EMPLOYABILITY AND SUSTAINABLE DEVELOPMENT IN SUB- SAHARAN AFRICA

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Abstract: Occupational health and safety (OHS) education is becoming increasingly relevant in the context of labour market transformation, workforce vulnerability, and sustainable development challenges in Sub-Saharan Africa (SSA). Many sectors in the region continue to face high occupational risks, limited practical training opportunities, and insufficient alignment between higher education systems and labour market needs. This paper examines the role of OHS education in supporting employability and sustainable workforce development within the SSA context. The study is based on the analysis of scientific literature, international reports, and policy documents related to occupational health and safety, higher education, employability, and sustainable development. The discussion considers practical learning, interdisciplinary education, digital learning, stakeholder cooperation, and lifelong learning as relevant elements of workforce preparation and higher education modernization. The paper examines the relationship between OHS education, workplace preparedness, and sustainability-related knowledge, while also addressing challenges affecting higher education systems in SSA countries. The proposed analytical framework emphasizes curriculum modernization, applied learning, cooperation between universities and labour market actors, and continuous professional development. Strengthening OHS education may contribute to improved workforce preparedness, stronger prevention culture, and safer and more sustainable working environments in Sub-Saharan Africa.

Keywords: *Occupational health and safety education; Employability; Workforce preparedness; Sustainable development*

INTRODUCTION

Occupational health and safety (OHS) remains a major challenge for workforce wellbeing, productivity, and long-term economic development, particularly in developing regions. According to the International Labour Organization (ILO), occupational accidents and work-related diseases continue to have serious social and economic consequences worldwide,

especially in countries where preventive measures and institutional capacities are insufficiently developed (ILO, 2019). These challenges are often more pronounced in regions characterized by informal employment, limited labour protection systems, and unequal access to education and professional training (WHO, 2010).

Sub-Saharan Africa (SSA) is one of the youngest and fastest-growing regions in the world, with rapid urbanization and increasing labour market demands. Despite significant demographic and economic potential, many countries in the region continue to face high unemployment rates, workforce vulnerability, and insufficient implementation of OHS measures (ILO, 2019). Occupational risks are especially evident in sectors such as agriculture, mining, construction, textile production, and small-scale manufacturing, where workers are frequently exposed to unsafe working conditions, chemical and physical hazards, ergonomic risks, and limited preventive practices (Alli, 2008; Härmäläinen et al., 2017).

The large share of informal employment further complicates the implementation of occupational health and safety practices in SSA countries. Many workers operate outside formal regulatory and social protection systems and often lack access to occupational training, healthcare services, and workplace preventive measures (ILO, 2019). Occupational accidents and work-related illnesses therefore continue to represent an important public health and socio-economic issue in the region.

International development agendas increasingly emphasize decent work, social inclusion, sustainability, and quality education. The United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), and SDG 8 (Decent Work and Economic Growth), stress the need to strengthen educational systems and workforce competences as part of sustainable development efforts (UNESCO, 2020).

Higher education institutions are expected to play a broader role in preparing graduates for changing labour market conditions. Employers increasingly require competences related to communication, teamwork, problem-solving, and organizational practices (Wiek et al., 2011; Mulder, 2017).

Recent studies increasingly discuss practical learning, interdisciplinary education, digital learning, and environmental and sustainability knowledge in relation to workforce preparation and higher education modernization (da Costa et al., 2025; UNESCO, 2023). Higher education institutions in many SSA countries continue to face limitations related to educational infrastructure, unequal access to digital technologies, and limited practical training capacities (UNESCO, 2023; Nyongesa & Van der Westhuizen, 2025). Additional challenges include weaker integration between higher education systems and labour market needs (da Costa et al., 2025).

These limitations point to the need for stronger integration of occupational health and safety education within higher education systems and professional development initiatives.

Occupational health and safety education is therefore increasingly linked with workforce preparedness, professional growth, and broader sustainable development objectives. Accordingly, the aim of this paper is to analyse the role of occupational health and safety education in supporting employability and sustainable development in Sub-Saharan Africa. The paper also discusses approaches for strengthening OHS education within the regional context.

METHODOLOGY

This study is based on the analysis of scientific literature, international reports, and policy documents addressing occupational health and safety, employability, sustainable development, and higher education in Sub-Saharan Africa (SSA). The analysis considered educational and labour market challenges influencing workforce preparedness and OHS education in SSA countries.

The study aimed to identify educational approaches and competence areas relevant to strengthening OHS education and workforce preparedness within the SSA context.

Practical learning approaches, interdisciplinary education, digital learning, and lifelong learning concepts were additionally considered in relation to workforce preparedness and sustainable development (Mulder, 2017; Wiek et al., 2011).

The reviewed literature was used to discuss approaches for strengthening occupational health and safety education in Sub-Saharan Africa through curriculum modernization, practical learning, stakeholder cooperation, and professional development initiatives (Mulder, 2017; UNESCO, 2023; da Costa et al., 2025).

The proposed analytical framework was developed as a conceptual model describing the relationship between OHS education, employability, and sustainable workforce development in Sub-Saharan Africa.

Figure 1 presents the relationship between educational priorities, regional challenges, educational approaches, and expected workforce development outcomes within the proposed conceptual model.

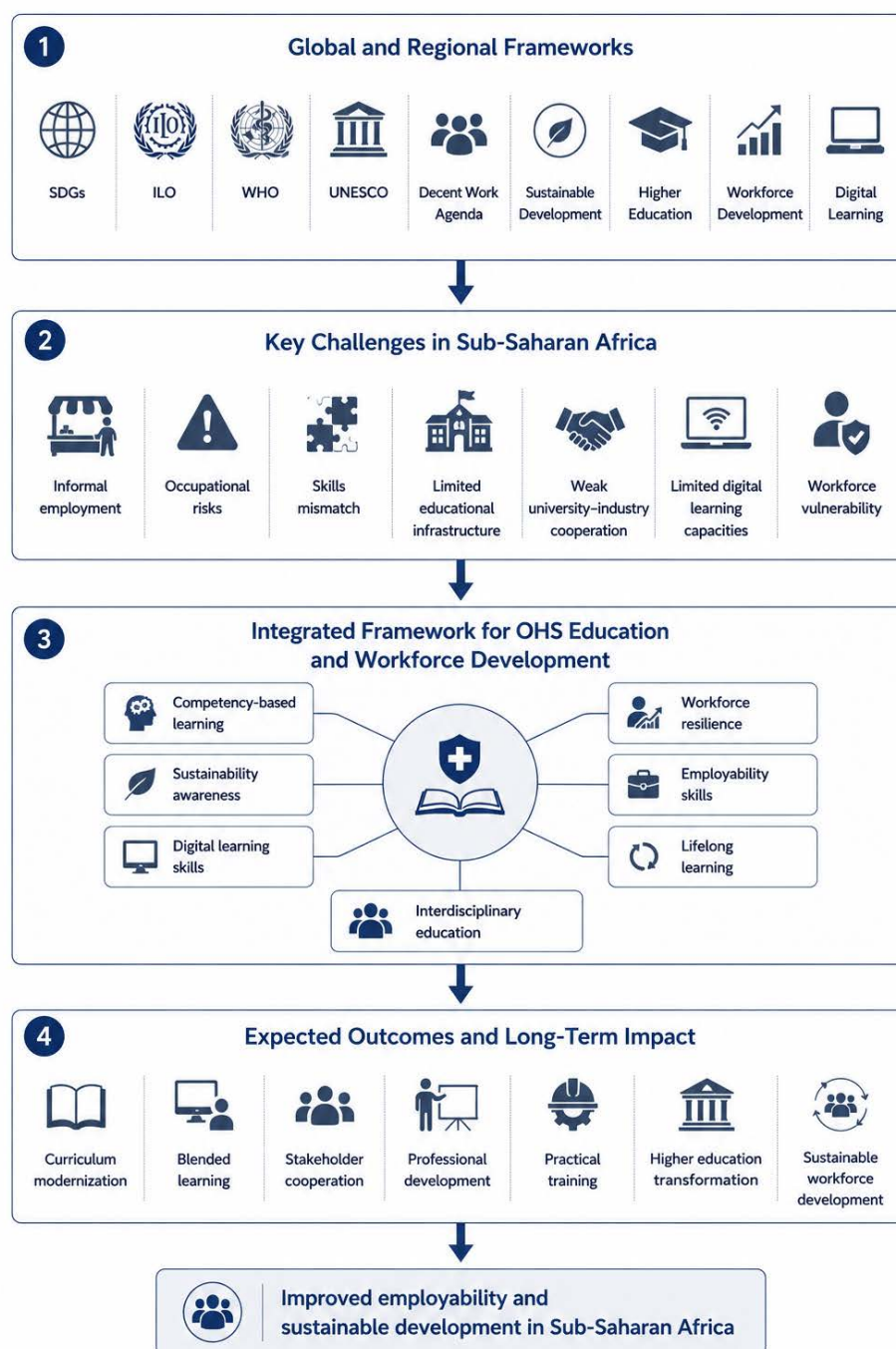


Figure 1. Analytical framework linking OHS education, employability, and sustainable development in Sub-Saharan Africa

RESULTS AND DISCUSSION

OHS Education and workforce preparedness

Occupational health and safety education plays an important role in improving workforce preparedness and employability, particularly in labour markets affected by technological, organizational, and socio-economic changes. Contemporary workplaces increasingly require employees who are able not only to apply technical knowledge, but also to recognize workplace risks, communicate effectively, and participate in preventive activities (Mulder, 2017; ILO, 2019).

In many higher education systems, teaching is still largely focused on theoretical knowledge, while practical training and practice-based learning remain insufficiently represented. As a result, graduates may face difficulties when entering professional environments that require practical problem-solving, decision-making, and implementation of preventive measures.

Employers increasingly expect graduates to demonstrate communication skills, teamwork, applied problem-solving abilities, and understanding of professional organization and occupational risks (Wiek et al., 2011; da Costa et al., 2025). OHS education should therefore include practice-based learning approaches that improve understanding of occupational risks and preventive practices. Case studies, simulations, project-based activities, and practice-based learning may improve students' ability to recognize occupational risks and apply preventive measures in professional environments.

Practical exposure to workplace conditions may contribute to stronger prevention culture, improved workplace communication, and better understanding of occupational health and safety responsibilities.

Integration of sustainability and employability competences

OHS is no longer viewed only as a regulatory obligation focused on accident prevention, but also as part of broader sustainability and organizational development processes. Existing studies also connect OHS with workforce wellbeing, sustainability, and responsible workplace practices (ILO, 2019; WHO, 2010). This requires educational approaches that connect workplace safety with environmental responsibility and environmentally responsible workplace practices.

The integration of sustainability principles into industrial and organizational processes further emphasizes the relationship between workplace safety, environmental protection, resource management, and organizational performance (UNESCO, 2020; European Commission, 2022). These changes require educational approaches that combine technical knowledge with environmental responsibility and practice-oriented problem solving.

Digital technologies increasingly influence workplace communication, monitoring, reporting, and training activities (European Commission, 2021). Recent studies also discuss occupational health and safety education in relation to environmentally responsible workplace

practices and digital skills, particularly in sectors affected by technological change (Wiek et al., 2011; Mulder, 2017; da Costa et al., 2025).

Role of higher education institutions

Higher education institutions play an important role in preparing graduates for changing workplace requirements and professional responsibilities. In the field of occupational health and safety, universities are expected not only to provide theoretical knowledge, but also to support the development of practical knowledge and applied professional skills relevant to real workplace conditions.

One of the major challenges in OHS education is the limited integration of practical learning approaches within existing curricula. Traditional teaching models based predominantly on theoretical instruction may not provide sufficient preparation for professional decision-making, risk identification, and implementation of preventive measures. Curriculum modernization increasingly incorporates practice-oriented learning approaches such as case studies, project-based activities, simulations, and practical training components (Mulder, 2017).

Cooperation between universities and labour market actors may improve the relevance of educational programs and support better understanding of occupational challenges and workplace risks (UNESCO, 2020). Cooperation with labour market actors may additionally contribute to internships, practical training opportunities, and knowledge exchange between academic and professional environments.

Digitalization has also influenced the organization of higher education and professional training, although many SSA countries still face limitations related to digital infrastructure and unequal access to online learning resources (UNESCO, 2023; Nyongesa & Van der Westhuizen, 2025). The use of digital learning platforms, online educational materials, and blended learning approaches are widely used to improve educational accessibility (European Commission, 2020).

Proposed Analytical Framework

Figure 1 summarizes the relationships between labour market challenges, educational limitations, environmental and sustainability challenges, and occupational health and safety education in Sub-Saharan Africa.

The framework positions OHS education within broader discussions related to employability, workforce development, and sustainability challenges affecting higher education systems in SSA countries.

The framework also considers challenges affecting OHS education in SSA countries, including limited practical training opportunities, infrastructure limitations, and weaker cooperation between higher education institutions and labour market actors (ILO, 2019; UNESCO, 2020).

The analysed literature highlights the importance of educational approaches that combine technical knowledge with practical learning and environmentally responsible workplace practices. Educational models that integrate practical learning and cooperation with professional sectors may improve the relevance of educational programs and support practice-oriented learning (Mulder, 2017; da Costa et al., 2025).

Stakeholder cooperation represents one of the central elements of the proposed framework. Collaboration between universities, industry, public institutions, and professional organizations may support the exchange of knowledge, identification of emerging occupational and professional requirements, and development of more practice-oriented educational approaches. In addition, stronger cooperation with labour market actors may contribute to improving practical training opportunities and strengthening professional relevance of educational programs.

The framework also highlights the importance of lifelong learning and professional development. Continuous competence development may become increasingly important in sectors affected by technological change and evolving occupational risks.

Expected contribution and long-term implications

Stronger integration of OHS education within higher education systems may improve the transition from education to professional practice. Educational programs that include practical training and cooperation with professional sectors may support better understanding of professional conditions and occupational risks.

Rapid technological changes, digitalization, and evolving workplace risks increasingly require continuous updating of professional knowledge and occupational health and safety practices (European Commission, 2021).

The proposed approach may also contribute to the development of safer and more sustainable working environments. Improved understanding of occupational risks and preventive practices may contribute to greater awareness of preventive practices and more responsible occupational behaviour (ILO, 2019; WHO, 2010).

Stronger integration of occupational health and safety principles within higher education and professional development systems may also support broader sustainable development objectives related to health, education, and decent work (UNESCO, 2020). Although educational reforms alone cannot resolve structural labour market challenges, strengthening occupational health and safety education may contribute to long-term improvements in occupational safety practices and workforce development in Sub-Saharan Africa.

CONCLUSION

Occupational health and safety education has become an increasingly relevant component of workforce development and sustainable social and economic progress in Sub-Saharan Africa. The analysis presented in this paper indicates that strengthening OHS education requires

broadier integration of practical learning, practice-oriented training, stakeholder cooperation, and continuous professional education within higher education systems.

Although occupational health and safety education alone cannot resolve broader structural labour market challenges in Sub-Saharan Africa, its stronger integration within higher education and professional development systems may contribute to safer working environments, improved workforce preparedness, and more sustainable workforce development. The proposed analytical framework may also provide a basis for future research and discussion related to curriculum modernization, educational policy development, and strengthening cooperation between education systems and labour market stakeholders within the regional context.

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PROJECT OVERVIEW - AI-ASSISTED MONITORING AND MANAGEMENT OF INVASIVE PLANT SPECIES IN CROSS-BORDER REGION

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Abstract: Invasive plant species (IPS) pose a significant ecological and economic challenge in the cross-border region, particularly within protected natural habitats. Their rapid spread threatens native biodiversity, disrupts ecosystems, and increases management costs for conservation authorities. Traditional monitoring and control methods are labour-intensive, time-consuming, and often ineffective in detecting IPS at an early stage. Additionally, existing treatment approaches lack precision, leading to unintended environmental consequences. This paper presents the aims and activities of the AInspec project, which addresses these challenges by introducing an AI-supported drone-driven enhanced spectrum sensing system for IPS detection and a drone-based spraying solution for targeted chemical treatment. By integrating remote sensing and automated treatment technologies, the project aims to improve the efficiency, accuracy, and sustainability of IPS management in protected cross-border areas.

Keywords: *Invasive plant species; Drone; Cross-border region; Chemical treatment*

PROJECT OBJECTIVE AND ACTIVITIES

The project AI-assisted Monitoring and Management of Invasive Plant Species in the Cross-Border Region (AInspec) addresses challenges related to invasive plant species (IPS) by introducing an artificial intelligence (AI)-supported drone-based enhanced-spectrum sensing system for IPS detection with a drone-based spraying solution for targeted chemical treatment. Using modern technologies, the project aims to improve the efficiency, accuracy and sustainability of IPS management in protected areas within the transboundary region.

Invasive plant species (IPS) represent one of the most serious environmental and economic challenges in the management of protected areas in cross-border regions. Their rapid spread

threatens native plant species and overall biodiversity, disrupts ecosystem stability, and generates additional costs for nature protection institutions. Traditional monitoring and control methods are labour-intensive, time-consuming, and often insufficiently effective for early-stage detection of IPS. Furthermore, existing approaches to suppressing IPS spread frequently lack precision, leading to unintended environmental impacts.

The main objective of the project is to develop and implement an advanced and technologically innovative approach for the early detection and precise, targeted treatment of invasive plant species. This approach will enable institutions responsible for managing protected areas to respond more effectively to these threats and strengthen their operational capacities. Special emphasis is placed on cross-border cooperation, as invasive plant species spread irrespective of administrative boundaries, making coordinated action essential for effective control.

Key project activities include the development of an AI-supported drone system equipped with enhanced-spectrum cameras for early detection, as well as the mapping and monitoring of invasive plant species in protected areas. The project also involves the use of drones for precise chemical treatment, pilot testing and field implementation of the proposed solutions, training of staff from protected area management institutions in the use of drones and AI tools, and the development of guidelines and recommendations for integrating advanced technologies into invasive species management.

Pilot testing and field research will be conducted in selected protected areas, including “Obedska Bara” and “Sava nizvodno od Hrušice - HR2001311”, in order to evaluate the effectiveness and scalability of the proposed approaches. Cross-sectoral cooperation is essential in addressing growing environmental, economic, and social challenges, and the AInspec project aims to contribute to significant progress in the sustainable and efficient management of protected natural areas.

BACKGROUND AND LEGISLATIVE FRAMEWORK

One of the most important common territorial challenges to be addressed by AInspec project is the protection of nature through monitoring, management, and spread prevention of invasive plant species. The Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014 on the prevention and management of the introduction and spread of invasive alien species (IAS) sets out rules to prevent, minimize, and mitigate the adverse impact on biodiversity. These impacts arise from the introduction and spread within the Union, both intentional and unintentional, of invasive alien species. A significant subset of alien species can become invasive and have a serious adverse impact on biodiversity and related ecosystem services, as well as other social and economic impacts, which should be prevented (Zhou, 2026). Besides the direct destruction of natural habitats, invasive alien species represent one of the main threats to biodiversity and related ecosystem services. They may take various forms, including severe impacts on native species, the structure and

functioning of ecosystems through habitat alteration, predation, competition, disease transmission, and the replacement of native species across significant ranges. Additionally, invasive alien species can cause genetic effects through hybridization, changes in landscape features, and a reduction in the value of land and water for human activities. Furthermore, they can also have a significant adverse impact on human health and the economy and cause various socio-economic consequences (Xiao, 2025, Mengistu, 2025, Leite, 2026).

The management of invasive species, as well as the damage they cause to agriculture, forestry, and fisheries, results in billions of dollars in global economic losses annually (Guada, 2025). The European Union, as a party to the Convention on Biological Diversity, is bound, as far as possible and as appropriate, to prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species'. Croatia, as an EU member, also needs to meet these requirements. In Serbia, the issue of IAS is primarily regulated by the Law on Nature Protection. The introduction of alien species and their hybrids is prohibited but may be permitted by the ministry based on the risk assessment results. The Law on Nature Protection also provides the framework for adopting a list of invasive alien species; however, this list has not yet been compiled, preventing the implementation of stricter regulations and control measures regarding the use and management of certain alien species both within and outside protected areas. According to the Law on Nature Protection, site managers of protected areas must obtain permission to use herbicides, meaning that rapid response actions may have to be done manually or could be delayed.

TRANSBOUNDARY CHALLENGES AND IMPACTS IN THE SAVA RIVER BASIN

Transnational and cross-sectoral approach is essential for controlling invasive species, especially in cross-border areas. Regardless of whether they are natural or man-made habitats, invasive species spread quickly and easily, particularly along riverbanks, forest edges, canals between arable fields, grasslands, and agricultural areas. One of the key steps in controlling invasive species is developing a common approach to the problem within land management practices in response to upcoming invasions. In all countries of the Sava River Basin, individual examples exist where land users recognize the seriousness of the threat posed by invasive species and implement activities aimed at their removal. At the same time, protected area and ecological networks area managers across all countries are proactively managing invasive species. Furthermore, the causes and consequences of introducing invasive species are transnational and therefore require cooperation. This is certainly a prerequisite for the effective control and management of invasive species, particularly in this case when the project implementation area is a transnational river corridor. The Sava River system is one of the best-preserved transnational river systems, flowing across the borders of EU member and non-member countries, each with different policies and land management systems. However, despite these differences, invasive species have become a serious threat to food production and also affect water supply, flood risk management, crop production, and nature-based tourism. The harmful impact of invasive alien species is reflected in significant economic

losses across the agriculture, forestry, fisheries, environmental protection, and health sectors. Losses are significant in the cross-border area of the Republic of Croatia and the Republic of Serbia. Reducing the harmful impact of invasive species on cross-border ecosystems remains one of the greatest challenges in environmental protection. Although many invasive species have already caused significant economic damage, many others are still arriving, or their impact has not yet been determined. Therefore, it is necessary to predict and assess the extent of their spread and to build an effective control system in response to the threat they pose. Many invasive species found in the cross-border area pose a threat to human health by negatively affecting the quality of life and ability to work, whether through allergic reactions or toxins that enter the food chain and render certain foods unsuitable for human consumption.

AI-SUPPORTED DRONE-BASED SOLUTIONS FOR DETECTION AND CONTROL

Negative impacts of invasive plant species can be mitigated and improvement of their management in protected cross-border areas and ecological networks can be achieved by utilizing an advanced AI-supported enhanced-spectrum drone-based system for detection, alongside an innovative spray drone system with chemical agents for targeted control (Espitalier, 2025, Hidalgo, 2025). Multispectral drones (drones equipped with multispectral cameras, providing high-resolution imagery across various spectral bands) are already being utilized in agriculture and protected natural areas in the participating countries. Multispectral drones perform spectral analysis and map crops intended for treatment. Equipped with multispectral cameras, these drones collect data from images that reveal various plant and crop characteristics not visible to the naked eye. The results are analyzed after capturing the images and are used to assess the condition and health of plants, as well as factors such as growth, quality, and crop yield (Royimani, 2019).

The project will integrate artificial intelligence and convolutional neural network models to improve the recognition of invasive plant species and enhance data accuracy. For this project, low-cost wideband cameras, in addition to multispectral cameras, will be employed to capture a broader spectrum of data, providing more comprehensive insights into plant conditions. While this approach may offer slightly lower accuracy in detecting invasive species compared to commercial drones equipped with hyperspectral cameras, it will significantly reduce costs, making it a more affordable alternative (particularly for the local population).

Another type of drone used in the programme area is the spraying drone mainly tackled for crop pollination in agriculture (Singh, 2024, Takekawa, 2023). These drones provide precise treatment for individual plants or crop areas, optimizing the use of resources. Flying at low altitudes, spraying drones ensure more accurate application and reduce the consumption of sprayed materials and water by up to 90%. This method allows plants to receive treatment tailored to their specific needs. Unlike traditional methods, drone-based spraying prevents soil damage caused by trampling, reducing crop losses by approximately 5 to 15 %. In locations in

both project countries, spraying drones have not yet been used. In this project, drones will be used for the first time for chemical treatment, i.e. preventing the spread of invasive plant species, which will significantly contribute to the preservation and sustainability of these protected natural areas.

CONCLUSION

In addition to developing a standardized protocol and defining guidelines for AI-driven drone-based invasive plant species monitoring, this project aims to identify and utilize the most effective chemical agents for controlling target invasive species while minimizing their impact on native species and ecosystems. Although the initial costs of research and implementation may be high, chemical control programs remain the most appropriate solution. Once established, chemical agents can regulate invasive populations without requiring repeated interventions, making this a cost-effective solution over time. For species that spread across vast areas, such as forests or remote regions, chemical control provides a scalable and efficient solution by naturally dispersing and targeting invasive populations. Scientific research has shown that a combination of chemical and mechanical treatments is the most effective approach for IAS control. By addressing the above-mentioned challenges, this project aims to pave the way for the adoption of these innovative approaches and support their future implementation. The primary beneficiaries of project outputs include public authorities involved in environmental policy and biodiversity conservation, research institutions focusing on ecological monitoring and technological innovation, nature management organizations responsible for IPS control in selected protected areas and local communities who rely on healthy ecosystems for environmental and economic well-being.

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RISK ASSESSMENT REGARDING TO WHOLE BODY VIBRATIONS OF DUMPER TRUCK OPERATORS IN A MINING COMPANY

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Abstract: The technological processes involved in the extraction of ore materials are highly complex and require the engagement of working resources. These processes encompass the transportation of ore from the site of extraction to the processing facilities, utilizing both continuous and discontinuous transport systems. Discontinuous transport systems include various types of vehicular transport, particularly dump trucks. Operators of dump trucks are exposed to a range of occupational hazards, including physical risks such as noise and vibration. Of particular concern are whole-body vibrations, which are transmitted to the operator through the vehicle seat during operation. Prolonged exposure to such physical agents may result in adverse effects on workers' health and their overall work capacity. Exposure to harmful factors in the workplace can lead to significant health impairments and reduced functional ability. The risk assessment process involves the systematic identification and quantification of all hazards to which workers are exposed, serving as a basis for evaluating risk acceptability and implementing appropriate occupational safety measures. Since physical hazards can be accurately measured using specialized equipment, it is possible to determine whether exposure levels exceed the limit values prescribed by relevant standards and legislation. This paper presents an analysis of vibration exposure and a corresponding risk assessment for the position of a dump truck operator within a mining company.

Keywords: *dump truck operator, whole body vibration, risk assessment*

INTRODUCTION

From an occupational safety perspective, mining operations are classified as high-risk activities. This is primarily due to the inherent complexity of the technological processes involved, as well as the presence of numerous environmental factors that influence the safety of workers engaged in these operations. Surface (open-pit) mining is generally considered to pose a lower level of risk compared to underground mining; however, it still involves a wide range of hazards and risks for workers. The principal hazards in mining include exposure to dust, chemicals, and harmful gases; electrical hazards; the risk of fires and explosions; dynamic geological phenomena; radiation; mechanical hazards; as well as adverse workplace environmental conditions. These environmental factors encompass microclimatic conditions, lighting, noise, and vibrations (Heleta, 2010). Surface exploitation of ores necessitates the use of a wide range of work equipment and infrastructure, including facilities with associated installations, machinery and equipment (plants, machines, devices, and tools), as well as

auxiliary and temporary structures. In addition, various systems for collective occupational protection are employed, such as protective barriers, shelters, structural safeguards, and general ventilation systems. The technological process of ore extraction, in addition to excavation, also involves the transportation of material to processing sites, which may include primary, secondary, or tertiary processing stages. For this purpose, both continuous and discontinuous transport systems are utilized. Continuous transport systems include conveyors, elevators, cableways, and screw conveyors, whereas discontinuous systems comprise cranes, various types of truck, most notably dump truck, as well as load haul dump (LHD) vehicles. In the transport of medium hard and very hard ores, including iron ore, dump trucks are the predominant means of discontinuous transport. Mining and transport machinery typically operate under highly complex and demanding working conditions, characterized by dynamic environments and the simultaneous presence of multiple risk factors. As a consequence, these conditions are associated with a relatively high incidence of occupational injuries and fatalities (Sultanbekova et al., 2020).

Dump truck operators work under demanding and adverse working conditions (Zheng et al., 2015), and their position is therefore classified as a high-risk occupation. In order to ensure the implementation of occupational health and safety measures for all employees in mining operations, including dump truck operators, it is necessary to conduct a comprehensive risk assessment of all hazards and harmful factors to which workers are exposed in the workplace. Risk assessment is a mandatory process across all sectors; however, it is of particular importance in industries characterized by multiple and complex risks, such as mining (Sikman et al., 2025). It represents an empirical process involving the identification of workplace hazards, the quantification and evaluation of the risks they pose, and the subsequent design of appropriate occupational safety measures. The outcomes of the risk assessment process are formally documented in a Risk Assessment Act. Operators of mining machinery, including dump truck operators, are exposed to a range of hazards and harmful factors, including:

- Mechanical hazards (exposure to mechanical impacts during inspection and maintenance of dump trucks; collisions with other moving dump trucks; contact with other mining equipment at the site; risk of vehicle overturning, etc.),
- Hazards arising from workplace characteristics (slippery surfaces when entering or exiting the vehicle cabin; contact with sharp edges of the vehicle structure; unfavorable microclimatic conditions and inadequate lighting within the cabin, etc.),
- Harmful agents (exposure to exhaust gases, dust, vibrations, and noise; adverse environmental conditions such as reduced visibility, etc.),
- Other harmful factors (prolonged sitting, fatigue, decreased concentration, monotony, overtime work, night work, and shift work, etc.).

This paper focuses on the analysis of exposure of dump truck operators in open-pit mining operations to physical hazards, specifically whole-body vibration (WBV). Based on input parameters such as vehicle type and characteristics, operating conditions, and the results of

whole-body vibration measurements, the study proposes appropriate preventive measures aimed at improving working conditions and safeguarding the health of workers exposed to vibration.

LEGAL FRAMEWORK IN THE FIELD OF OCCUPATIONAL SAFETY FROM HARMFUL EFFECTS OF WHOLE-BODY VIBRATION EXPOSURE

Whole-body vibration (WBV) is caused by vibration transmitted through the seat or the feet by workplace machines and vehicles. Work that involves exposure to whole-body vibration occurs commonly in off-road work, such as farming, construction and mining. Exposure to vibrations of the whole body can lead to various health problems (back pain, neck pain, and even spinal damage), which affect the quality of life of the driver/handler, can lead to increased absenteeism from work, reduced productivity and the appearance of occupational diseases. Health disorders occur gradually, usually after 2 to 7 years of work at workplaces where workers are exposed to general vibrations (Prokes et al., 2015). Noorloos et al. (2008) reported that the vibration magnitude caused by a vehicle depends on many factors such as conditions of the site, maintenance status, operator's driving style and speed, type of propelling mechanism, type of seat, characteristics of material handled, and operator experience. In the ISO 2631 standard, the International Organization for Standardization, based on conducted research, established a correlation between exposure to acceleration of vibrations that are transmitted to the whole body, exposure time in hours per day, and health effects (Figure 1).

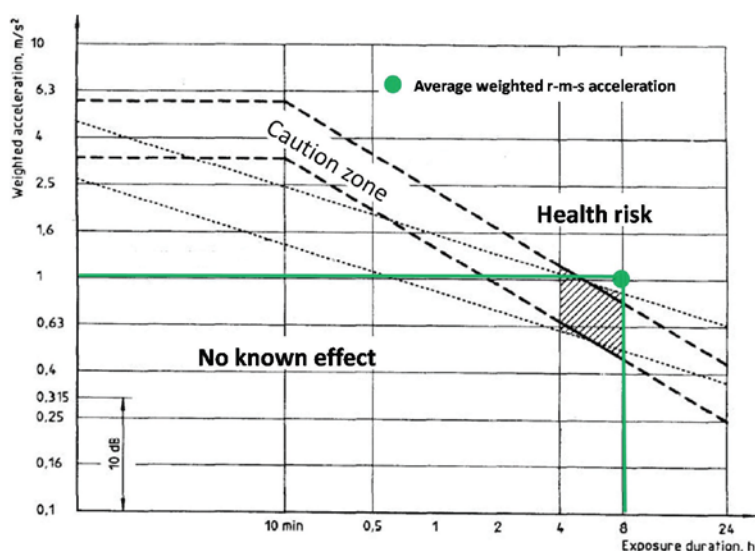


Figure 1. Exposure time and health in the health guidance caution zones from ISO 2631-1 (ISO 2631-1.:1997)

The primary legal instrument of the European Union (EU) concerning the protection of workers from risks associated with mechanical vibrations is Directive 2002/44/EC of the European Parliament and of the Council, commonly referred to as the Physical Agents

(Vibrations) Directive. This Directive addresses the health and safety of workers exposed to risks arising from mechanical vibrations at the workplace and covers two main types of vibrations: hand-arm vibration (HAV) and whole-body vibration (WBV). The Directive sets an exposure action value, above which it requires employers to control the vibration risks of their workforce and an exposure limit value above which employees should not be exposed.

With regard to whole-body vibration (WBV), Directive 2002/44/EC prescribes the following:

- a daily exposure action value (EAV) of 0.5 m/s^2 ,
- a daily exposure limit value (ELV) of 1.15 m/s^2

The two established limit values are expressed as A(8), daily exposure over an eight-hour reference period. The Directive 2002/44/EC mandates that employers implement specific preventive and protective measures:

- Evaluation of Risk: Employers are obliged to assess the risks arising from vibrations to which workers are exposed.
- Exposure Action Value (EAV): If exposure exceeds the EAV, employers must implement a program of technical and organizational measures to remove or reduce exposure to a minimum, provide health surveillance, and inform and train workers regarding risks and preventive measures.
- Exposure Limit Value (ELV): Exposure must never exceed the ELV. Should this occur, employers must take immediate action to reduce exposure below the limit and identify the reasons for the excess in order to prevent recurrence.
- Health Surveillance: The Directive mandates appropriate health surveillance for workers exposed to vibrations above the EAV, ensuring early diagnosis of any vibration-related disorders.
- Information and Training: Workers must be informed of potential risks and the preventive measures currently in place.

In the Republic of Srpska, the legal framework is provided by the Law on Occupational Safety and Health and the Rulebook on Preventive Measures for Safe and Healthy Work During Exposure to Vibrations, published in the *Official Gazette of the Republic of Srpska*, No. 3/2018. In alignment with Directive 2002/44/EC, this national regulation defines the obligations of employers in implementing preventive measures to protect workers from risks arising, or likely to arise, from exposure to mechanical vibrations.

METHODOLOGY FOR THE ASSESSMENT OF RISK RELATED TO WHOLE BODY VIBRATION

Risk assessment is conducted through several steps (ISSA, 2020):

- *Step 1:* Identification of the hazards associated with workers' exposure to vibration;
- *Step 2:* Assessment and evaluation of the risks arising from exposure to vibration;

- *Step 3:* Implementation of preventive and corrective measures.

Step 1: In practice, it is common for work vehicles to operate on uneven surfaces and poorly maintained roads. Under such conditions, the duration of exposure to harmful vibrations may be prolonged, resulting in high daily exposure to elevated vibration amplitudes and, in some cases, impulsive or shock vibrations. If work equipment is poorly maintained or used improperly, these factors contribute to an increased risk of exposure to harmful vibration effects. Therefore, it is useful to employ a structured checklist containing targeted questions that facilitate the identification of exposure to harmful vibrations:

- Is off-road driving or operation over poorly maintained road surfaces involved?
- Is vibrating machinery operated for extended periods on a daily basis?
- Are vehicles appropriately designed to withstand harsh roadway conditions?
- Are poor postures adopted during task performance, or is there exposure to shock vibrations?
- Is machinery manufacturer's warning about risk from whole-body vibrations provided?

Step 2: After identifying a workplace at risk of harmful effects from whole-body vibration, it is essential to assess vibration exposure based on the daily vibration exposure parameter $A(8)$ over an 8-hour reference period. This assessment can be conducted through the following methods:

- By measuring vibrations, which requires the use of measuring equipment designed for measuring vibrations transmitted to the human body. This method is often costly and necessitates technical expertise.
- By utilizing data from catalogs, databases, or information provided by the equipment manufacturer (e.g. user manuals or technical specifications).

Equipment manufacturers, based on the Machinery Directive 2006/42/EC, are required to provide data on the vibrations generated by machines, in the form of "measurement results under test conditions". This data can be of great importance when purchasing equipment, in order to initially select equipment that produces lower levels of vibration.

The parameters required for calculating daily vibration exposure $A(8)$ are the acceleration values measured along the three orthogonal coordinate axes (a_{wx} , a_{wy} , a_{wz}), and the duration of vibration exposure, T_{exp} . For an accurate assessment of human exposure to vibration, the precise determination of the vibration exposure duration is as crucial as the accurate measurement of vibration magnitude. Estimating the exposure duration should be based on a detailed observation of the work process (using stop watch, video recording, or by interviews with the workers). Daily exposure is calculated from the equation:

$$A_x(8) = a_{wx} \cdot 1.4 \sqrt{\frac{T_{\text{exp}}}{T_0}} \quad A_y(8) = a_{wy} \cdot 1.4 \sqrt{\frac{T_{\text{exp}}}{T_0}} \quad A_z(8) = a_{wz} \sqrt{\frac{T_{\text{exp}}}{T_0}} \quad (1)$$

The reference time T_0 is considered to be 8h, corresponding to a standard 8-hour workday. The maximum of these three values is taken as the daily vibration exposure value:

$$A(8) = \max \{A_x(8), A_y(8), A_z(8)\} \quad (2)$$

Step 3: The employer is obliged to implement technological and organizational corrective measures to mitigate risks whenever the action and limit values for daily vibration exposure are exceeded. These measures include, for example, alternative work processes, the selection of appropriate work tools, or the reduction of time and intensity of exposure. Priority is always given to reduction measures at the source of vibrations, generally in the following order:

- Technological measures: replacement of work equipment, i.e. selection of equipment that produces lower vibration levels,
- Organizational measures: limiting the duration of exposure to high-intensity vibrations, implementing regular work breaks, rotating workers during the work process, etc,
- Use of personal protective equipment.

Depending on the measured value of the daily vibration exposure $A(8)$, the following measures must be implemented:

- For $A(8) = 0.5 \text{ m/s}^2$: inform workers about the risk of exposure to vibrations.
- For $A(8) > 0.5 \text{ m/s}^2$ (exceeding the EAV exposure action value): create a program and implement measures to reduce vibrations (technical and organizational). The program for reducing whole-body vibration is structured through the following stages: determination of exposure to vibrations (by measurement or using databases), comparison with the prescribed action and limit values of exposure, identification of the main sources and causes of vibrations, comparison of existing vehicles and equipment with modern technologies, selection of appropriate measures, forecast of the effect of the selected measures, establishment of implementation timeframes, verification of results.
- For $A(8) > 1.15 \text{ m/s}^2$ (exceeding the limit value of ELV exposure): it is necessary to take immediate measures to avoid excessive exposure and ensure regular preventive health surveillance.

Also, the risk assessment should identify other factors that adversely affect health and are directly or indirectly related to vibrations, such as poor body posture when sitting on a machine, sitting for long periods without the ability to change position, poorly adjusted device

controls, or poor visibility, which require the worker to stretch or place themselves in an uncomfortable position, lift loads, etc. All of the previously listed hazards and dangers affect the occurrence of pain in the worker's body, or back pain, which is then exponentially worsened by the influence of the vibrations of the machine that generates them.

CASE ANALYSIS: EVALUATION OF WHOLE BODY VIBRATION RISK FOR DUMP TRUCK OPERATORS IN THE OMARSKA MINE COPE

In surface mining operations, ore is transported from the pit to the ore preparation, beneficiation, and separation plant using both fixed systems (such as various types of conveyors, rail transport, cable cars, etc.) and numerous mobile transport methods, with dump trucks being the most commonly used. The objective of this study was to assess the whole-body vibrations to which operators of mining machinery are exposed during the transport of tailings and valuable mineral raw materials at the Buvač surface mine, operated by ArcelorMittal Prijedor in Omarska, Prijedor.

For this study, vibrations were measured using two types of Caterpillar dump trucks: the CAT 777C (manufactured in 1980) and the CAT 775F (manufactured in 2010), shown in Figure 2. Both vehicles were in operational condition at the time of measurement; however, this does not provide comprehensive insight into the quality of all components that influence vibration generation and transmission. Specifically, factors such as the condition and wear of the tires, shock absorbers, seat quality, and the overall condition of the vehicle chassis are critical in determining the level of vibration exposure.



a)



b)

Figure 2. Caterpillar dumpers: a) the CAT 777C, b) the CAT775F

Vibrations were measured using a human vibration analyzer, model B&K 4447, in conjunction with a seat pad equipped with a triaxial accelerometer, which was attached to the dump truck operator's seat. Under typical operating conditions, one shift theoretically lasts 8 hours; however, the actual effective exposure time, T_{exp} , for the operator is 5.5 hours per day. Measurement results are given in Table 1.

Table 1. Measured accelerations and daily exposure values

Vehicle Caterpillar dump trucks	RMS (m/s ²)			Daily vibration exposure A(8) (m/s ²)
	X	Y	Z	
CAT 777C 86	0.2425	0.3327	0.5238	0.4343
CAT 775F 92	0.2839	0.3900	0.6651	0.5515

Based on the results obtained from experimental vibration measurements, it is evident that the daily vibration exposure value $A(8) = 0.5515 \text{ m/s}^2$ for the CAT 775F/96 dump truck exceeds the daily vibration exposure action value (EAV) of 0.5 m/s^2 for whole-body vibration. In contrast, for the CAT 777C/82, no exceedance was recorded, although the daily vibration exposure value $A(8) = 0.4343 \text{ m/s}^2$ is very close to the exposure action value. These findings underscore the necessity of implementing corrective measures to improve working conditions and reduce operators' exposure to vibrations, thereby ensuring long-term health protection for the workforce.

CONCLUSION

As a result of working in the dynamic working environment of an open pit mine and the presence of a greater number of hazards, harms and efforts during work, the position of dumper operator is treated as a position with increased risk. For such workplaces, in addition to risk assessment and the application of preventive occupational safety measures, periodic control of the health of workers at time intervals defined in the Risk Assessment Act is mandatory. One of the primary hazards to which dump truck operators are exposed is whole-body vibration (WBV), transmitted to the operator's body through the seat of the vehicle. A risk assessment for this type of exposure is conducted, followed by the design of preventive and corrective measures. The results of vibration exposure measurements indicated a slight exceedance of the daily action value for one type of dump truck (CAT 775F/96), while the value for the other type (CAT 777C/82) was very close to the limit. As a result, both technical and organizational preventive protection measures are recommended. Technical measures include ensuring regular maintenance of the dump trucks to maintain their operational integrity, as well as maintaining the quality of the transport routes within the surface mine, involving activities such as eliminating surface irregularities, leveling the roads, and applying dust control measures like sprinkling limestone. Organizational measures encompass rotating operators after specific intervals, scheduling regular vacations and breaks, and reducing the number of material transport cycles to minimize prolonged exposure to vibrations.

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SPECIAL WASTE AND OCCUPATIONAL SAFETY IN THE CIRCULAR ECONOMY: SERBIA CASE STUDY

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Abstract: The transition to a circular economy, while strategically aligned with sustainable development goals and EU policies, often marginalizes occupational health and safety aspects. Introducing recycling models and extending product lifespans transforms work processes but simultaneously generates new chemical, biological, and physical risks that existing safety frameworks fail to adequately address. This paper explores the intersection between circular practices and occupational hazards through an analysis of special waste stream management in the Republic of Serbia. Drawing on data from the Environmental Protection Agency (2018–2023) and spatial analysis via the NRIZ GIS system, the study identifies treatment facilities for special and hazardous waste streams (tires, batteries, waste oils, electrical and electronic equipment, and end-of-life vehicles), quantifies processed volumes, and assesses how specific treatment processes affect workers' exposure to harmful substances. Particular attention is given to risks associated with legacy substances, the unpredictable behavior of recycled materials, and the lack of specialized training. The aim of this work is to empirically demonstrate the need to integrate occupational safety measures into the regulatory and operational frameworks of the circular economy.

Keywords: *Circular economy; Occupational health and safety; Special waste streams*

INTRODUCTION

The circular economy seeks to keep materials in use through recycling, reuse, and extended product lifespans. Although the EU has embedded this transition in its Circular Economy Action Plan and aligned it with SDG 12, occupational health and safety remain peripheral to the agenda (WHO, 2018). This oversight carries significant weight. The International Labor Organization estimates more than 340 million work-related injuries and illnesses occur annually worldwide, underscoring the ongoing difficulty of protecting workers in sectors that depend on hazardous materials and manual labor (Nakpan et al., 2026). Moving toward circularity requires more than technical or environmental adjustments. It reshapes production, consumption, and recovery processes, which directly changes the nature of work, the skills employees need, and the hazards they encounter (Daheim et al., 2021). In practice, hazardous chemicals continue to flow through recycling streams and re-enter industrial or environmental cycles (Bodar et al., 2018). The issue becomes more severe in developing regions, where informal waste pickers handle most of the recycling. These workers typically lack protective gear and formal training, leaving them exposed to sharp debris, biological hazards, and uncharacterized chemical residues (Ferronato et al., 2019). Recycling also introduces

uncertainty, especially when legacy substances are involved. These chemicals face legal restrictions today but remain locked in older products, creating unpredictable hazards during secondary processing (Bodar et al., 2018). Construction faces similar complications. Recycled plastics, reclaimed steel, and novel composites often behave differently under load or release unknown substances when cut or dismantled. Standard safety protocols rarely account for these material-specific risks (Torrecilla-García et al., 2025). New waste processing methods add another layer of complexity by opening exposure and emission pathways that conventional risk assessments overlook (Bodar et al., 2018). Circular practices deliver measurable environmental and economic gains, yet they also introduce workplace hazards that current safety frameworks do not adequately cover. Processing recycled materials can release hidden additives or unknown chemicals, produce dust with unfamiliar particle sizes and compositions that defeat standard respirators, and exhibit unpredictable behavior over time (Torrecilla-García et al., 2025). Workers remain vulnerable because training programs rarely address these material-specific dangers, a problem that intensifies in regions with weak or underfunded occupational safety systems (Ferronato et al., 2019). The occupational impact of circularity is therefore mixed. Gains such as lower toxicity in new materials and cleaner air are offset by exposure to residual chemicals and unsafe conditions at poorly regulated processing sites (WHO, 2018).

MANAGEMENT OF SPECIAL WASTE STREAMS IN SERBIA

The report on products that become special waste streams after use in the Republic of Serbia is a systematic document that presents, analyzes, and evaluates data on the generation and management of special waste streams (tires, batteries and accumulators, waste oils, electrical and electronic equipment, and end-of-life vehicles), with the aim of monitoring compliance with legal obligations prescribed by the Waste Management Law and accompanying regulations (Radovanović et al., 2023). For the purposes of detailed analysis and examination of multi-year trends, this paper also incorporates comparative data from the annual reports of the Environmental Protection Agency for the period from 2018 to 2023.

This analysis is based on official annual reports for the period 2018 to 2023. It shows clear structural changes and varying trends in the management of different waste categories. As shown in Figure 1, data on batteries and accumulators indicate that starter batteries (a) reached a peak of around 14,000 tonnes in 2020 and then steadily declined. In contrast, industrial batteries, after an initial decrease, showed strong growth and by 2023 exceeded the quantity of starter batteries. This may point to changes in industrial consumption or more accurate tracking of this waste stream. In the case of tyres (b), a strong reversal of trends can be observed. Passenger car tyres peaked in 2020 and then dropped sharply to below 10,000 tonnes by 2023. At the same time, tyres for commercial and agricultural vehicles and aircraft, after a significant decline in 2019, showed continuous growth and reached approximately 34,000 tonnes, becoming the dominant category. Waste oil (c) quantities show an overall increase, rising from about 20,000 tonnes in 2018 to nearly 50,000 tonnes in 2022, followed

by a slight decrease in the final year. This may reflect increased industrial activity or improvements in collection and recycling systems. Regarding electronic waste (d), large household appliances and entertainment equipment are the most significant categories. Entertainment equipment recorded a notable increase in 2020, while small household appliances and leisure equipment show gradual growth. Other categories, such as IT equipment, medical devices and tools, remain at lower and relatively stable levels. These trends reflect changes in consumer behavior and product lifecycles, as well as gradual improvements in data reporting and compliance with the Law on Waste Management.

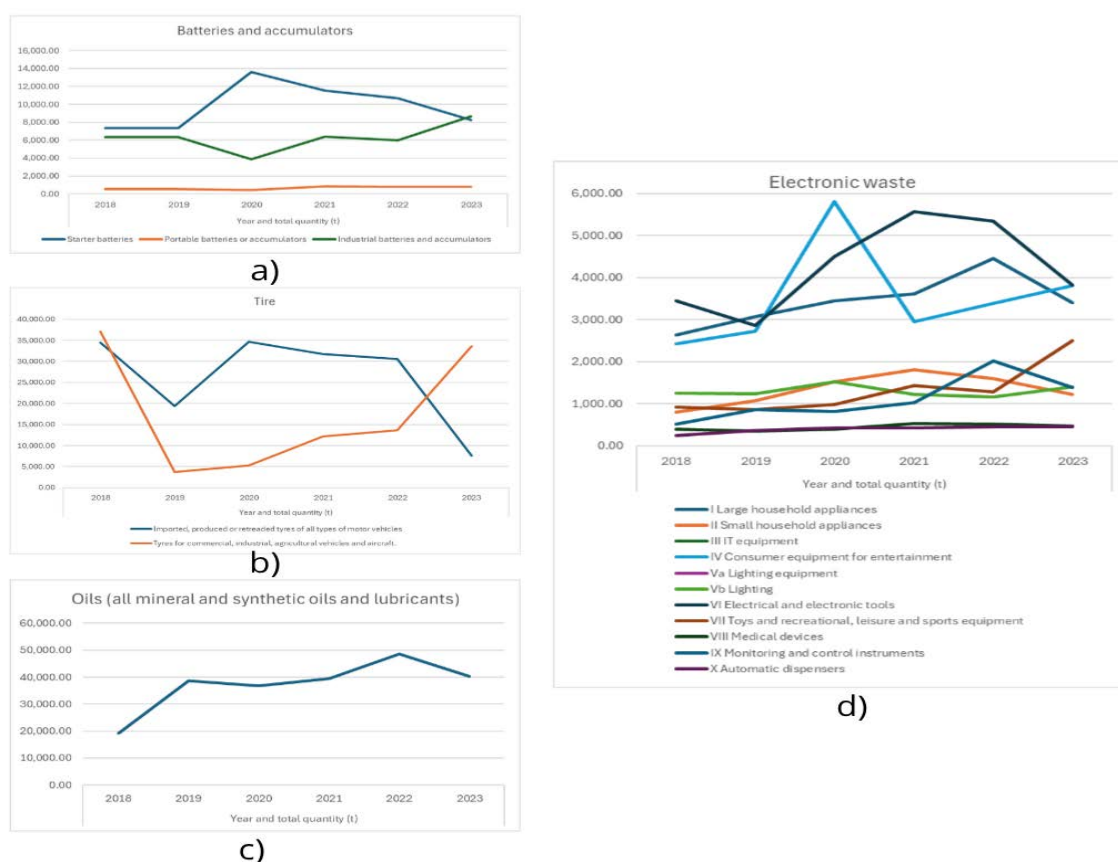


Figure 1. Annual quantities of special waste streams in the Republic of Serbia (2018–2023): (a) Batteries and accumulators, (b) Tires, (c) Oils, and (d) Electronic waste.

SPECIAL WASTE TREATMENT FACILITIES IN SERBIA

Waste management is an essential part of industrial and manufacturing activities, particularly in the context of sustainable development and environmental protection. The following table provides an overview of waste types and quantities, as well as the applied treatment methods across the analyzed facilities. Table 1 presents the operational characteristics of three treatment facilities (TF1–TF4) managing special hazardous waste streams in the Republic of Serbia, with spatial distribution across the Central Serbia, Southeastern Serbia, Bačka, and Banat regions. The total quantities of treated waste vary significantly, reflecting different

degrees of specialization and technological orientation of the facilities. The highest volume was recorded at TF2 (Bačka region) with 24.06 tonnes of lead-acid batteries, indicating a high concentration of capacity for metal recycling and closing the loop for battery streams. TF3 (Banat) treats 2.163 tonnes of packaging contaminated with hazardous substances, while TF1 (Central Serbia) processes smaller but structurally heterogeneous quantities: separately collected electrolytes (3.46 tonnes), hazardous components removed from discarded equipment (0.54 tonnes), and unsorted batteries and accumulators (0.28 tonnes).

Treatment methods correlate directly with the nature of the input material. TF2 applies targeted processes for recovery of metals and metal compounds, which is technologically aligned with circular battery production standards. In contrast, TF1 and TF3 employ a broader spectrum of methods, including recycling/recovery of organic substances not used as solvents, biological transformations, and combined treatment options. This approach indicates a more complex nature of mixed hazardous waste, where the presence of unsorted components and electrolytes increases process variability. The highest volume was recorded at TF4 (Southeastern Serbia) with 378.901 tonnes of discarded electrical and electronic equipment containing hazardous components, indicating a major regional hub for WEEE (waste electrical and electronic equipment) processing and metal recovery

Table 1. Operational characteristics of four treatment facilities (TF1–TF4) in Serbia

<i>Treatment facilities (TF)</i>	<i>Waste management activity</i>	<i>Categories of waste treated</i>	<i>Treated quantity (t)</i>	<i>Treatment</i>
TF1 (Central Serbia)	Industrial waste management and disposal	Hazardous components removed from discarded equipment	0.54	Recycling/recovery of organic substances that are not used as solvents (including composting and other biological transformation processes)
		Separately collected electrolyte from batteries and accumulators	3.46	Several options
		Batteries and accumulators classified under 16 06 01, 16 06 02, or 16 06 03, Unsorted batteries and accumulators containing these types of batteries	0.28	Recycling/recovery of organic substances that are not used as solvents (including composting and other biological transformation processes)
TF2 (Bačka region, northern)	Manufacturing of automotive and truck	Lead-acid batteries	24.06	Recycling/recovery of metals and metal compounds

Serbia)	batteries (lead-acid starter batteries and calcium-based batteries)			
TF3 (Banat region, northern Serbia)	Production of pre-insulated pipes and related equipment for district heating and high-pressure gas pipelines	Packaging containing residues of hazardous substances or contaminated with hazardous substances	2.163	Several options
TF4 (Southeastern Serbia)	Purchase and processing of secondary raw materials: waste iron, aluminum, copper, stainless steel, brass, and waste batteries.	Discarded electrical and electronic equipment containing hazardous components	378.901	Recycling/processing of metals and metal compounds

When damaged or improperly treated, waste **Li-ion batteries** can release heavy metals such as cobalt, copper and nickel, fluorinated compounds, and toxic gases including hydrogen fluoride (Environmental Protection Agency, 2023). Electrolytes from batteries contain hazardous substances such as lithium hexafluorophosphate and acids, making it essential to ensure adequate ventilation, regular air quality monitoring, and the use of personal protective equipment when handling them to protect workers from chemical burns, respiratory problems, and other acute or chronic health risks (industriAll European Trade Union, 2025). This is particularly relevant for facilities processing unsorted batteries or separately collected electrolytes (e.g., **TF1**), where manual handling and heterogeneous input streams increase the likelihood of accidental leakage or exposure. To protect workers from the significant hazards posed by damaged waste Li-ion batteries, including short circuits, thermal runaway and fire, facilities must ensure storage in cool, dry and well-ventilated areas with insulated terminals, immediate isolation of damaged units using inert packing materials, comprehensive staff training in hazard recognition and emergency response, provision of appropriate personal protective equipment, and strict adherence to ADR transport regulations for dangerous goods (Environmental Protection Agency, 2023).

The electrolyte in **lead-acid batteries** consists of sulfuric acid containing dissolved lead, which can cause corrosive skin injuries and contaminate soil and water if not properly contained. In operations specialized in metal recovery from lead-acid batteries (e.g., **TF2**),

where crushing and smelting concentrate lead-containing dust and acid mists, these risks become even more pronounced. Therefore, adequate ventilation, acid-resistant storage surfaces, personal protective equipment and regular health monitoring are essential to protect workers from inhalation hazards, chemical burns and chronic lead exposure (World Health Organization, 2017).

In facilities such as **TF3**, where packaging contaminated with reactive chemicals from pre-insulated pipe production is treated, workers are exposed to the inhalation of vapours and aerosols during the handling of partially emptied containers, necessitating rigorous ventilation and personal protective equipment (Allport et al, 2003). This underscores the broader challenge identified in circular economy transitions: that recycling and recovery operations introduce material-specific occupational hazards requiring tailored safety controls, rather than generic waste-handling protocols (International Labour Organization, 2023).

Data on WEE in Serbia show rapidly grow. It is estimated around 80,000 tons/year, while 5,000–20,000 tons are treated annually. Estimations are 2.78 kg per inhabitant in 2016, which was around 25% of total generated waste, lagging EU standards, while projection is estimated that 15,000 tons of e-waste will be collected in 2024, with expectations to rise to 38,000 tons by 2031. (Diedler et al, 2019). **TF4**'s annual treatment of 378.9 tonnes of hazardous WEEE thus represents a notable share of Serbia's current e-waste processing capacity, highlighting its regional importance in metal recovery from electronic waste.

Spatial and operational mapping of four specialized treatment facilities (TF1–TF4) highlights how treatment methodologies are tightly coupled to input material composition, yet each process generates distinct exposure pathways. From lead-containing dust and sulfuric acid mists in battery recovery to fluorinated compounds in lithium-ion handling and volatile vapors from chemically contaminated packaging, workers face material-specific hazards that standard waste-management protocols consistently fail to address. Workers handling and recycling WEEE can be exposed to hazardous substances, including flame retardants, heavy metals, plasticisers such as phthalates, polychlorinated biphenyls (PCBs) (Gravel et al. 2023) Recent studies from Sweden and Belgium show negative impact of WEEE, where significantly elevated levels of heavy metals were observed in the blood, plasma and urine of WEEE recycling workers, while in Belgium, high levels of exposure to toxic organic pollutants (e.g. brominated flame retardants and dioxins in dust) were noted in three shredder plants (Gravel et al. 2023; Baldé et al. 2020)

In practice, legacy substances, heterogeneous waste streams, and emerging recovery technologies introduce unpredictable chemical, physical, and biological risks. The absence of specialized training, inadequate engineering controls, fragmented regulatory oversight, and reliance on manual handling further exacerbate worker vulnerability, particularly in developing regulatory environments.

The transition to a circular economy, particularly through reuse, repair, and recycling activities, introduces complex occupational safety and health (OSH) challenges that differ from those in linear systems. In reuse processes, workers may face exposure to residual contamination and degraded materials, increasing risks of chemical exposure, structural failure, and ergonomic strain. Repair and refurbishment activities involve hazards such as contact with hazardous substances, electrical risks, and mechanical injuries, often intensified by insufficient training or informal working conditions. Recycling operations present significant dangers, including exposure to toxic substances like heavy metals, inhalation of dust and bioaerosols, and physical injuries from sharp objects and machinery, alongside fire and explosion risks. A major cross-cutting issue is the loss of material traceability and the variability of material conditions over multiple life cycles, which complicates hazard identification and risk management. (EU OSHA, 2021; ILO 2019).

CONCLUSION

The transition toward a circular economy delivers measurable environmental and economic benefits, yet it simultaneously introduces complex occupational health and safety (OHS) challenges that remain largely peripheral to current policy and operational frameworks. This study empirically demonstrates how the management of special and hazardous waste streams in Serbia exemplifies the growing disconnect between circularity objectives and worker protection. Analysis of national data from 2018 to 2023 reveals shifting waste generation and collection patterns, characterized by rising volumes of industrial batteries, commercial vehicle tires, and waste oils, alongside evolving electronic waste profiles. Findings in TF1–TF4 underscore a critical blind spot in circular economy transitions: the assumption that recycling and material recovery are inherently safer or more sustainable for workers. To align circular economy goals with sustainable labor practices, occupational safety must be embedded directly into waste classification systems, facility licensing procedures, and process design guidelines. Regulatory bodies should harmonize environmental and occupational standards, mandate material-specific risk assessments, and enforce continuous exposure monitoring. Facility operators must invest in targeted ventilation systems, automated sorting where feasible, and comprehensive training programs that address legacy chemicals, thermal runaway risks, and emergency response protocols. Future research should expand to longitudinal health outcome studies, cross-national comparative analyses, and predictive risk modeling for novel circular material flows. Ultimately, a genuinely circular economy cannot be achieved without safeguarding the health and safety of the workforce that enables it. Integrating occupational health and safety into the core of circular policy and industrial practice is not a secondary compliance measure, but a fundamental prerequisite for equitable, resilient, and truly sustainable development.

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HAZARDS AND HARMFUL FACTORS AT THE WORKPLACE AND IN THE WORKING ENVIRONMENT

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Abstract: Noise in the working environment represents a significant occupational hazard, especially in industrial sectors such as metal processing. The aim of this paper is to analyze noise as a risk factor at workplaces where CNC machines and other metal processing equipment are used, as well as to examine its impact on workers' health and safety.

The paper discusses the main sources of noise, methods for its measurement, and the conditions in which workers are exposed to increased noise levels. The results indicate that prolonged exposure to noise above permitted limits can lead to hearing damage, increased stress, reduced concentration, and a higher risk of workplace injuries.

Based on the analysis, it is evident that noise significantly affects both the health of employees and overall work efficiency. The discussion highlights the importance of continuous monitoring, proper risk assessment, and implementation of adequate protective measures.

In conclusion, effective noise control requires a combination of technical, organizational, and personal protective measures. Their proper application can significantly reduce risks and contribute to safer and more productive working conditions.

INTRODUCTION

Noise is one of the most common harmful factors in the working environment, especially in industrial production. It is defined as unwanted sound that can negatively affect human health, safety, and work performance (1).

In metal processing industries, workers are exposed to high levels of noise generated by CNC machines and other equipment. Continuous exposure to noise above recommended limits represents a serious occupational risk (2).

The aim of this paper is to analyze noise as a workplace hazard, identify its sources, examine its effects on workers, and present appropriate protection measures.

Work Process and Noise Sources

In metal processing facilities, employees perform operations such as cutting, grinding, drilling, milling, and welding. These processes generate high levels of noise, especially when multiple machines operate simultaneously (3).

The main sources of noise include:

- CNC machines (lathes and milling machines)
- cutting and grinding equipment
- pneumatic systems
- simultaneous operation of machines (4)

These sources create continuous and impulse noise that often exceeds safe exposure limits.

Working Conditions and environment

The working environment must be organized to ensure safety and efficiency. Important factors include:

- sufficient space around machines
- adequate lighting (300–500 lx)
- proper ventilation
- safe and marked working zones (5)

Poor working conditions can increase the negative effects of noise and contribute to additional risks.

Proper organization of the workplace is essential for safe and efficient work. The working area around machines must allow sufficient space for movement and safe operation. Adequate lighting, typically between 300 and 500 lux, is required to ensure precision and reduce eye strain (5).

Ventilation systems must be installed to remove dust, fumes, and heat generated during machining processes. Floors should be slip-resistant and clearly marked to prevent accidents. Safety zones and warning signs should be visible to alert workers to potential hazards, including high noise levels (5).

NOISE SOURCES AND MEASUREMENT

To improve the scientific value of this paper, an example of noise measurement in a CNC metal processing environment is presented.

Noise measurements were performed using a sound level meter in accordance with ISO 9612:2009. The following equivalent continuous sound levels (LAeq) were recorded:

- CNC lathe: 88 dB
- Grinding machine: 92 dB
- Pneumatic system: 85 dB

The total daily noise exposure level (LEX,8h) was calculated using standard methods:

$$LEX_{8h} = 10 \cdot \log_{10} [(1/T) \cdot \sum (T_i \cdot 10^{(L_i/10)})]$$

T = total working time (8h)

T_i = exposure time for each activity

L_i = measured noise level

Assuming the worker is exposed:

- 3 hours to 88 dB

- 3 hours to 92 dB

- 2 hours to 85 dB

The calculated daily exposure is approximately:

LEX,8h ≈ 89.5 dB, this value exceeds the upper exposure action value of 85 dB defined by EU Directive 2003/10/EC, indicating a high risk and the need for mandatory protective measures.

The main sources of noise in metal processing environments include:

- cutting and grinding machines
- rotating tools and spindles
- pneumatic systems
- simultaneous operation of multiple machines (6)

Noise levels are measured using standardized methods and instruments. The most commonly used devices are sound level meters, which measure sound pressure levels in decibels (dB). Measurements are conducted according to international standards, such as ISO 9612 (7).

Integrated sound level meters are used to monitor noise exposure over a longer period, allowing calculation of average exposure levels during a working shift. Frequency analysis is also important, as different frequencies can have different impacts on human health (7).

Noise Exposure Limits

Noise Level (dB)	Exposure Time	Effect
80 dB	8 hours	Safe limit
85 dB	8 hours	Risk begins
90 dB	4 hours	Hearing damage risk
100 dB	15 minutes	High risk

The presented table shows the relationship between noise levels and exposure time. It can be observed that as noise levels increase, the allowed exposure time significantly decreases. This highlights the importance of limiting exposure duration in high-noise environments.

EFFECTS OF NOISE ON WORKERS

Health Effects

Long-term exposure to noise levels above 85 dB can lead to permanent hearing loss and tinnitus. In addition, noise can cause increased blood pressure, headaches, and general fatigue. Continuous exposure also affects the nervous system, increasing the risk of cardiovascular diseases (8).

Psychological Effects

Noise negatively affects concentration and attention, making it more difficult for workers to perform precise tasks. It also contributes to stress, irritability, and reduced overall well-being. These effects can significantly impact workplace relationships and productivity (8).

EFFECTS ON WORK AND SAFETY

High noise levels reduce communication between workers and make it difficult to hear warning signals. This increases the risk of accidents and injuries. Reduced concentration and fatigue also contribute to a higher number of errors during work processes (8).

Table 1. Noise Sources, Effects and Protection Measures

Noise Source	Harmful Effect	Possible Consequences	Protection Measures	PPE
Cutting and grinding machines	High sound pressure	Hearing loss, stress	Acoustic insulation, maintenance	Earplugs, earmuffs
CNC machines	Continuous noise	Fatigue, reduced concentration	Noise control, work organization	Earmuffs
Pneumatic systems	Impulse noise	Temporary hearing damage	Monitoring, exposure limitation	Earplugs
Multiple machines	Increased noise levels	Higher accident risk	Shift planning, noise reduction	Hearing protection

RISK ASSESSMENT

Risk assessment is a key step in managing workplace hazards. In environments with high noise levels, it is necessary to identify all sources of noise and evaluate their impact on workers. The main risks include:

- hearing damage
- reduced concentration
- increased stress levels
- higher probability of accidents (9)

Risk assessment should be conducted regularly, and appropriate preventive measures must be implemented based on the results (9).

Identification of Hazards and Risk Assessment

No.	Source of Hazard	Type of Risk	Possible Consequences	Protection Measures
1	Moving machine parts	Mechanical injuries	Cuts, amputations, body injuries	Protective barriers, PPE, emergency stop
2	Electricity	Electric shock	Burns, serious injuries, death	Regular maintenance, proper installation
3	Compressed air	Pressure injuries	Eye, skin, ear injuries	Safety glasses, controlled use
4	Noise	Hearing damage, stress	Hearing loss, headaches	Noise measurement, hearing protection
5	Vibrations	Musculoskeletal disorders	Joint pain, reduced precision	Maintenance, ergonomic adjustments
6	Lubricants/Coolants	Chemical exposure	Skin and eye irritation	PPE, ventilation
7	Slippery surfaces	Falls	Injuries, fractures	Anti-slip floors, proper cleaning
8	Poor lighting	Reduced visibility	Errors, injuries	Adequate lighting (300–500 lx)
9	Improper tool use	Mechanical injuries	Damage, injuries	Worker training

PROTECTIVE MEASURES

Technical Measures

Technical measures aim to reduce noise at its source. These include:

- installation of sound insulation and barriers
- regular maintenance of machines
- use of modern, low-noise equipment (10)

Organizational Measures

Organizational measures focus on reducing workers' exposure to noise. These include:

- limiting exposure time
- organizing shifts and breaks
- rotating workers between tasks (10)

Personal Protective Equipment

When noise cannot be reduced to acceptable levels, workers must use personal protective equipment (PPE), such as:

- earplugs
- earmuffs (hearing protectors)
- protective clothing and footwear (11)

Proper training in the use of PPE is essential to ensure effectiveness and worker safety (11).

DISCUSSION

The analysis shows that noise is a significant risk factor in metal processing environments. Workers exposed to high noise levels are more likely to experience health problems and reduced work performance. The results indicate that noise not only affects hearing but also concentration and overall safety. Without proper control measures, the risk of accidents increases significantly. Therefore, it is essential to combine different protection strategies and ensure continuous monitoring of noise levels. The results of this study indicate that noise levels in CNC metal processing environments frequently exceed recommended exposure limits. The calculated daily exposure level ($LEX,8h \approx 89.5$ dB) confirms that workers are at significant risk of developing occupational diseases. Compared to EU Directive 2003/10/EC, which defines 80 dB as the lower action value and 85 dB as the upper action value, the analyzed workplace clearly falls into the high-risk category. This requires immediate implementation of preventive measures. In addition to hearing damage, the analysis confirms that noise contributes to reduced concentration, increased fatigue, and a higher probability of workplace accidents. These findings are consistent with previous research in occupational safety studies. It is important to emphasize that technical measures alone are not sufficient. The most effective approach involves a combination of engineering controls, administrative measures, and personal protective equipment. Future research should include real industrial measurements, long-term monitoring, and detailed statistical analysis of noise exposure and its effects on workers.

CONCLUSION

Noise in the working environment is a serious occupational hazard, particularly in industrial sectors such as metal processing. Its impact on workers' health, safety, and productivity makes it necessary to implement effective control measures. Regular monitoring, proper workplace organization, and the use of protective equipment are essential for minimizing risks (12).

A combination of technical, organizational, and personal protective measures provides the best results in reducing the negative effects of noise. Ensuring safe working conditions not only protects employees but also improves overall efficiency and quality of work (12).

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THE IMPACT OF ERGONOMICS ON THE HEALTH OF EMPLOYEES IN OFFICE WORK

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Abstract: Modern office work is characterized by prolonged sitting, repetitive movements, and extensive use of computer equipment, which significantly affect the health of employees. Ergonomics, as a scientific discipline, aims to adapt the working environment to human capabilities and limitations in order to improve efficiency, safety, and well-being. This paper analyzes the impact of ergonomic factors on employee health in office settings, with a particular focus on musculoskeletal disorders, visual strain, and psychosocial stress. Furthermore, the study highlights the importance of preventive measures, including proper workplace design, employee education, and regular physical activity. The implementation of ergonomic principles contributes to reduced health risks, increased productivity, and overall improvement of working conditions.

Keywords: *ergonomics; office work; health; prevention; musculoskeletal disorders*

INTRODUCTION

In contemporary working environments, office-based jobs have become dominant due to rapid technological development and digitalization. Although such work is often perceived as physically undemanding, prolonged sitting and repetitive tasks can lead to numerous health issues. Poorly designed workplaces, inadequate equipment, and lack of movement contribute to the development of musculoskeletal disorders, visual fatigue, and decreased overall well-being.

Ergonomics plays a crucial role in preventing these problems by adapting work conditions to the needs of employees. The primary goal of ergonomics is to optimize the interaction between humans and their working environment, thereby reducing risks and improving performance. This paper examines the key ergonomic factors affecting employee health and proposes preventive measures for improving office working conditions.

ERGONOMIC RISK FACTORS IN OFFICE WORK

Ergonomics takes into account the physical demands faced by the worker, depending on their industry or profession, and addresses several risk factors: repetition, force, poor posture, and inadequate tools. Repeatedly performing the same type of task can strain a worker's musculoskeletal system. Even minimal force, such as typing on a keyboard, using a mouse, staring at a computer screen for too long, or sitting with poor posture, can cause serious injuries over time.

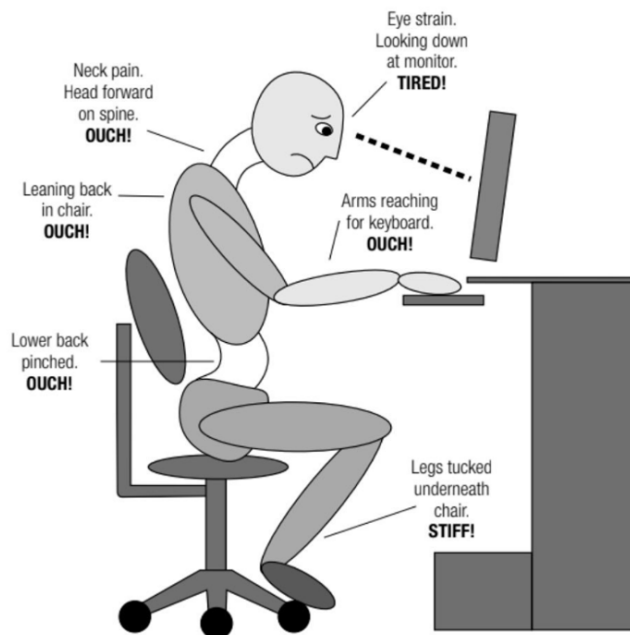


Figure 3.

Figure 1. Illustration of poor ergonomic posture at office table (Michigan Tech- EHS ergonomics)

HEALTH EFFECTS OF POOR ERGONOMICS

Musculoskeletal disorders (MSDs) affect the muscles, nerves, blood vessels, ligaments and tendons. Workers in many different industries and occupations can be exposed to risk factors at work, such as lifting heavy items, bending, reaching overhead, pushing and pulling heavy loads, working in awkward body postures and performing the same or similar tasks repetitively. Exposure to these known risk factors for MSDs increases a worker's risk of injury.

Work-related MSDs can be prevented. Ergonomics --- fitting a job to a person --- helps lessen muscle fatigue, increases productivity and reduces the number and severity of work-related MSDs. Work-related MSDs are among the most frequently reported causes of lost or restricted work time.

Visual strain

Many people suffer from computer vision syndrome (CVS), a combination of eye irritation, dryness, double vision and blurred vision, from working on a computer for hours, CVS can lead to headaches, as well as neck, shoulder and back pain.

Back and neck pain

Upper back and neck discomfort is very common, and it's sometimes accompanied by low back pain as well, the culprit is often lack of a supportive chair and a desk surface that's too

high in relation to the chair (a high desk surface places the keyboard and monitor too high), though it varies by person and by workstation. Back pain can be caused by damaged spinal structures, which can stem from poor sitting posture and prolonged periods of sitting.

Wrist, Hand and Shoulder Pain

Wrist, hand and shoulder pain are among the most common health problems experienced by employees who work at computers. These issues typically arise as a result of repetitive movements, poor posture and improperly adjusted workstations.

PREVENTIVE MEASURES IN OFFICE ERGONOMICS

Monitor Placement

We should consider how the placement and maintenance of the monitor can effect both the eyes and the musculoskeletal system. The following suggestions can help prevent the development of eye strain, neck pain and shoulder fatigue while using your computer workstation:

- Make sure the surface of the viewing screen is clean.
- Adjust brightness and contrast to optimum comfort.
- Position the monitor directly in front of you to avoid excessive twisting of the neck.
- Position the monitor approximately 20-26 inches (arm's length) from you.
- Tilt top of the monitor back 10 to 20 degrees.
- Position monitors at right angles from windows to reduce glare.
- Position monitors away from direct lighting which creates excessive glare or use a glare filter over the monitor to reduce glare.
- The top of the viewing screen should be at eye level when the user is sitting in an upright position.



Figure 2. Illustration of proper workstation ergonomics, including recommended monitor distance (50–60 cm), viewing angle, and correct body alignment in both seated and standing positions. (Computer Ergonomics Illustrations & Vectors)

Adjusting your chair

Contrary to popular belief, sitting, which most people believe is relaxing, is hard on the back. Sitting for long periods of time can cause increased pressure on the intervertebral discs, the springy, shock-absorbing part of the spine. Sitting is hard on the feet and lungs. Gravity tends to pool blood in the legs and feet and create a sluggish return to the heart.



Figure 3. Ergonomic office chair features and proper sitting posture for reducing back pain (Rackora)

The following recommendations can help increase comfort when using a computer:

- Don't stay in one static position for extended periods of time.
- When performing daily tasks, alternate between sitting and standing.
- Adjust height of backrest to support the natural inward curvature of the lower back.
 - o It may be useful to use a rolled towel or lumbar pad to support the lower back.
 - o The backrest angle is set so that your hip-torso angle is 90 degrees or greater.
- Adjust height of chair so feet rest flat on floor (use footrest if necessary).
 - o Sit upright in the chair with the low back against the backrest and the shoulders touching the backrest.
 - o Thighs should be parallel to the floor and knees at about the same level as the hips.
 - o Back of knees should not come in direct contact with the edge of the seat pan (there should be 2-3 inches between the edge of the seat and the back of the knee).
- Don't use armrests to slouch.
- Adjust height and/or width of armrests so they allow the user to rest arms at their sides and relax/drop their shoulders while keyboarding.

- When armrests are used, elbows and lower arms should rest lightly so as not to cause circulatory or nerve problems.

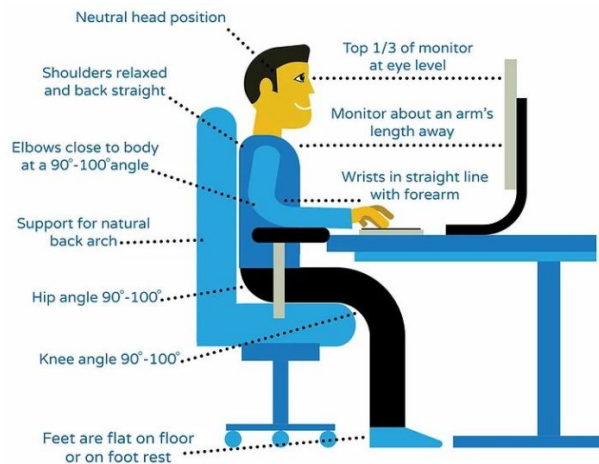


Figure 4. Perfect ergonomic sitting posture (Fargo Ergonomics)

Desktop Placement

If you are like many computer users, your computer, keyboard, and mouse are resting on your desk or a portable computer workstation. There is no specific height recommended for your desktop; however, the working height of your desk should be approximately elbow height for light duty desk work.

To allow for proper alignment of your arms your keyboard should be approximately 1 inch to 2 inches above your thighs. Most times this requires a desk which is 25 inches to 29 inches in height (depending upon size of individual) or the use of an articulating keyboard tray. The area underneath the desk should always be clean to accommodate the user's legs and allow for stretching.

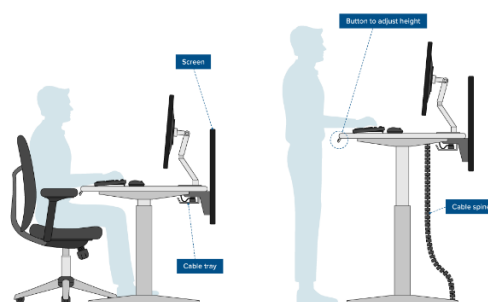


Figure 5. Illustration of desk height adjustment for proper ergonomics (CMD, office ergonomics)

The desktop should be organized so frequently used objects are close to the user to avoid excessive extended reaching. If a document holder is used, it should be placed at

approximately the same height as the monitor and at the same distance from the eyes to prevent frequent eye shifts between the screen and reference materials.



Figure 6. Proper Desktop Setup for Comfort and Efficiency (The University of Texas at Dallas, Ergonomics)

Keyboard and Mouse Placement

Many ergonomic problems associated with computer workstations occur in the forearm, wrist, and hand. Continuous work on the computer exposes soft tissues in these areas to repetition, awkward postures, and forceful exertions.

The following adjustments should be made to your workstation to help prevent the development of an ergonomic problem in the upper extremities:

- Adjust keyboard height so shoulders can relax and allow arms to rest at sides (an articulating keyboard tray is often necessary to accommodate proper height and distance).
- Keyboard should be close to the user to avoid excessive extended reaching.
- Forearms parallel to the floor (approximately 90 degree angle at elbow).
- Mouse should be placed adjacent to keyboard and at the same height as the keyboard (use articulating keyboard tray if necessary).
- Avoid extended and elevated reaching for keyboard and mouse. Wrist should be in neutral position (not excessively flexed or extended).
- Do not rest the hand on the mouse when you are not using it. Rest hands in your lap when not entering data.

Lighting

Lighting not suited to working with a Video Display Terminal is a major contributing factor in visual discomforts including eyestrain, burning or itching eyes, and blurred or double vision. Typical office environments have illumination levels of 75 to 100 foot-candles, but according to the American National Standards Institute (ANSI), computer workstations require only 18 to 46 foot-candles. Use the following recommendations to reduce eyestrain and eye fatigue:

- Close drapes/blinds to reduce glare. Adjust lighting to avoid glare on screen (light source should come at a 90 degree angle, with low watt lights rather than high.) Place monitor at 90 degree angle to windows (where possible). Reduce overhead lighting (where possible). Use indirect or shielded lighting where possible. Walls should be painted medium or dark color and not have reflective finish.
- Use a glare screen to reduce glare (alternatively, place a large manila folder on top of the monitor and let it hang over the monitor 2 inches to 3 inches to reduce glare from overhead lighting).

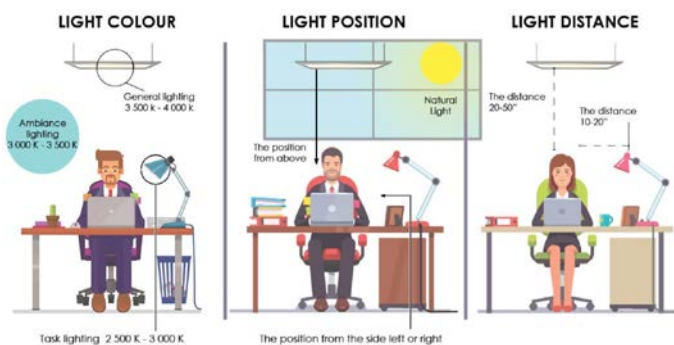


Figure 7. Proper light position in office (Standardpro,How to optimize your work efficiency and concentration)

CONCLUSION

Ergonomics plays a fundamental role in maintaining the health, safety, and overall well-being of employees in modern office environments. Although office work is often considered physically undemanding, prolonged sitting, repetitive movements, and improper workstation setup can lead to serious health problems, including musculoskeletal disorders, visual strain, and chronic pain in the back, neck, wrists, and shoulders. The analysis of ergonomic risk factors shows that even minimal but continuous strain—such as typing, using a mouse, or maintaining poor posture—can have long-term negative effects on the human body. These risks are further intensified by inadequate workplace design, poor lighting conditions, and lack of movement during working hours. However, these issues are largely preventable through the proper application of ergonomic principles. Adjusting workstations, maintaining correct posture, organizing equipment efficiently, and incorporating regular breaks and physical activity significantly reduce health risks. Additionally, employee education and

organizational support are essential in promoting healthy work habits and ensuring long-term effectiveness of ergonomic measures. In conclusion, investing in ergonomics not only improves employee health and comfort but also enhances productivity, reduces absenteeism, and contributes to a more efficient and sustainable work environment. As technology continues to evolve, the importance of ergonomics will remain a key component of occupational safety and health.

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ADVANCED TECHNOLOGIES IN FIRE PROTECTION SYSTEMS: PREVENTIVE AND EMERGENCY RESPONSE MEASURES

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Abstract: Modern technological advancements have fundamentally transformed the field of occupational safety and fire protection. This paper analyzes the integration of advanced solutions, such as Artificial Intelligence (AI), the Internet of Things (IoT), automation, and real-time data analytics into fire protection systems. Although traditional systems remain the cornerstone of safety infrastructure, their effectiveness is increasingly limited by the complexity of contemporary urban and industrial risks, characterized by high-energy loads and the presence of specific flammable materials. Unlike conventional systems that operate reactively, activating only after a fire is detected, modern technologies enable a proactive approach through continuous surveillance and early risk identification.

This research delineates the pivotal role of emerging technologies in redefining the landscape of fire safety, bridging the gap between passive prevention and active, intelligent intervention. By examining the deployment of smart sensor networks, autonomous drones, and sophisticated robotics, this study illuminates the critical trends that are currently reshaping the safety sector. Ultimately, the work serves as a strategic roadmap for the transition toward a more resilient and data-driven future, where the protection of human life and critical infrastructure is governed by unprecedented precision and technological reliability.

Keywords: *Artificial Intelligence; Emergency response; Fire protection; Internet of Things; Prevention.*

INTRODUCTION

In the modern era, technology has permeated nearly every sphere of our lives, and the field of safety and fire protection is no exception. The term "modern technologies" refers to advanced solutions that integrate digitalization, automation, Artificial Intelligence (AI), sensor systems, remote monitoring, and real-time data analytics. These innovations exceed the capabilities of traditional fire protection systems, which, while still playing a significant role, face diminishing effectiveness when confronted with the complexity of contemporary risks.

Rapid urbanization, the escalation of high-energy technological processes, and the widespread presence of flammable materials have created an urgent need for more precise, faster, and more reliable fire safety methods. Conventional fire suppression systems, though essential, often operate reactively, activating only after a fully developed fire has been detected. In contrast, modern systems function preventatively through continuous surveillance and early risk detection, as well as interventionally through automated mechanisms that respond far

more rapidly than human capabilities allow. These innovations leverage the power of Artificial Intelligence, the Internet of Things (IoT), data analytics, and even Virtual Reality (VR) to offer fire protection solutions that are more precise and efficient than ever before .

MODERN TECHNOLOGIES IN FIRE PREVENTION

IoT Technologies in Fire Safety

IoT-enabled fire protection devices are designed to operate as part of an integrated system where every component can both send and receive data (Midsummer Fire Protection, 2023). This interconnectivity allows for a more coherent and instantaneous response to potential fire hazards, drastically improving the speed and efficiency of the overall reaction.

IoT smoke detectors provide instantaneous alerts to users and building managers via smart devices, regardless of their physical location. The core advantage lies in the integration of heat and smoke sensors with suppression systems into a unified network, enabling a synchronized response (MDPI Sensors, 2022). For instance, the detection of critical temperatures automatically triggers sprinklers while simultaneously unlocking emergency exits and illuminating evacuation routes (Figure 1). Through continuous monitoring of gases and flammable materials, data is analyzed in real-time, allowing for the prediction and prevention of fire incidents in their earliest stages.

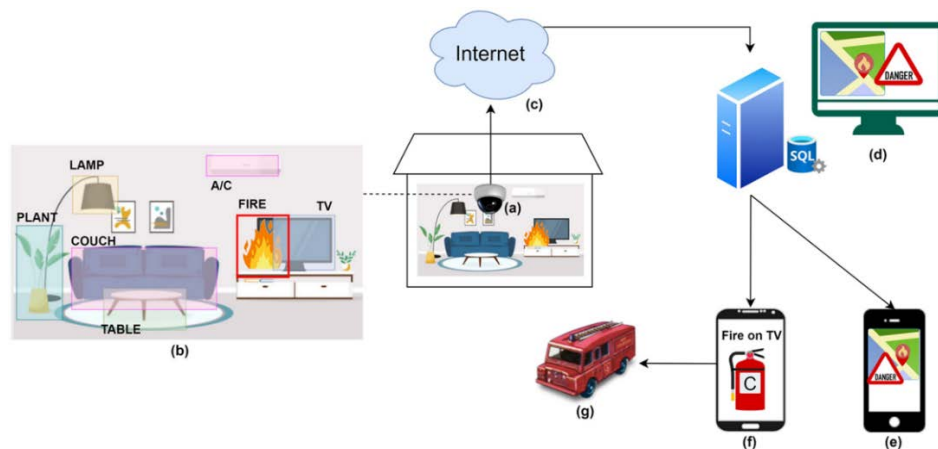


Figure 1. Proposed fire detector (MDPI Sensors, 2022)

Thermal Imaging Cameras

By enabling non-contact temperature measurement, thermal imaging cameras serve as a critical component of early detection systems, providing insights into thermal changes that remain invisible to standard sensors (Fire Protection Association Australia, 2022). Unlike conventional detectors that react to smoke or flames, these systems identify critical hotspots before ignition occurs — a decisive advantage for monitoring large-scale areas that are difficult to supervise manually.

While the hardware performs the sensing, the integration of specialized software is paramount. Upon detecting a thermal anomaly, the system automatically alerts emergency units and can directly trigger suppression mechanisms, such as water cannons or automated sprinklers. When precisely calibrated to specific environmental conditions, these systems significantly enhance the reliability of automated protection, safeguarding personnel and infrastructure from irreversible damage.

Artificial Intelligence in Fire Safety

AI enables rapid analysis of large datasets and automated decision-making, which is critical for early detection and fire spread prediction. By utilizing computer vision algorithms, AI systems analyze thermal and video feeds to identify flames or smoke in their nascent stages, drastically reducing the false alarms typical of conventional sensors.

The primary advantage of AI lies in multisensor integration — the ability to simultaneously process data from cameras, IoT sensors, and weather stations for precise risk assessment. However, implementing this technology presents challenges, particularly regarding the quality of training datasets and the reliability of models in extreme, unforeseen scenarios.

Smart Building Systems and Fire Safety

Integrating fire alarm systems with Building Management Systems (BMS) significantly enhances protective efficiency through real-time data sharing and centralized monitoring of all building subsystems (LDA Audio Tech, 2021). This integration reduces installation costs and streamlines functional testing. A prime example is smoke control, where the operation of fans, dampers, doors, and elevators is synchronized to ensure safe evacuation. Adherence to a strict sequence of operations and prioritization is critical; any failure to follow established protocols can lead to equipment damage and pose a severe risk to human life.

ADVANCED TECHNOLOGICAL SOLUTIONS IN EMERGENCY RESPONSE

Automated Fire Suppression Systems

A fire sprinkler system is a heat-activated detection and suppression solution consisting of a dedicated water supply, a piping network, and sprinkler heads. The sprinkler heads function as water nozzles sealed by a heat-sensitive element (BlazeQuel, 2023). When exposed to the thermal energy of a fire, this element melts or breaks, releasing the water plug and allowing water to discharge through the open nozzle onto the fire (Figure 2). This process effectively manages and extinguishes the blaze. Sprinkler systems are ideal for protecting high-risk, industrial, and commercial facilities.

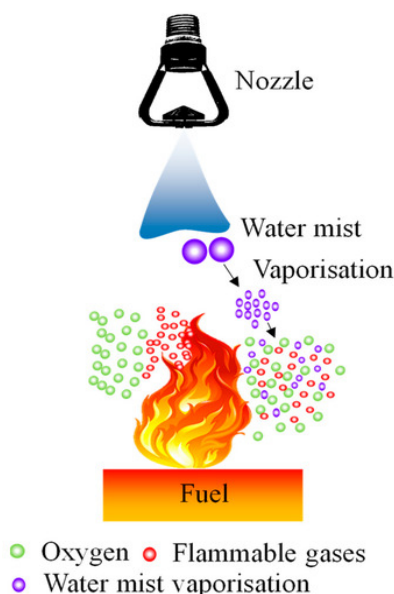


Figure 2. Heat extraction and water displacement of water mist system (MDPI Fire, 2023)

Water mist systems are becoming increasingly popular due to their high efficiency and environmental friendliness, as they suppress fires without the use of harmful chemical agents (Kord Fire, 2023). Unlike conventional sprinklers, these systems utilize significantly smaller pipe diameters and higher operating pressures to create fine water droplets. The distinct advantage of water mist lies in its versatility: it can be precisely targeted for localized protection or used for total flooding of an entire space, providing comprehensive coverage.

Gaseous fire suppression systems offer a waterless solution that utilizes inert gas mixtures (nitrogen, argon, CO₂) to extinguish fires through oxygen displacement. The gas is distributed through a precision nozzle network to create an environment incapable of supporting combustion. These systems are essential for environments where water-based suppression is impractical or damaging, including server rooms, data centers, and telecommunication hubs.

Robotic Systems in Firefighting

Modern firefighting robots, featuring tank-like designs, are equipped with high-capacity monitors that replace the physical effort of multiple firefighters (Robots Guide, 2023). These versatile machines can be reconfigured in under thirty seconds for victim evacuation or debris clearance. Integrated with advanced navigation systems and dual thermal cameras, these robots perform precision fire detection and remote site reconnaissance. By providing real-time visual data, they allow for safer structural entry assessments, significantly mitigating the risk of injury to human personnel.

Unmanned Aerial Vehicles (UAV)

Drones enable rapid reconnaissance of inaccessible and hazardous areas, directly reducing the risks faced by firefighters. Equipped with high-resolution and thermal imaging cameras, they

identify hotspots through dense smoke and locate trapped individuals in real-time (JOUAV, 2023). This data is critical for informed decision-making, prioritizing efforts, and ensuring the efficient allocation of resources on the ground.

Beyond surveillance, drones serve as mobile communication hubs (Figure 3) in areas where infrastructure is damaged, maintaining seamless coordination between emergency teams. Following an intervention, their role continues through detailed aerial surveys and the creation of 3D models, which are essential for precise damage assessment, post-fire investigations, and restoration planning.

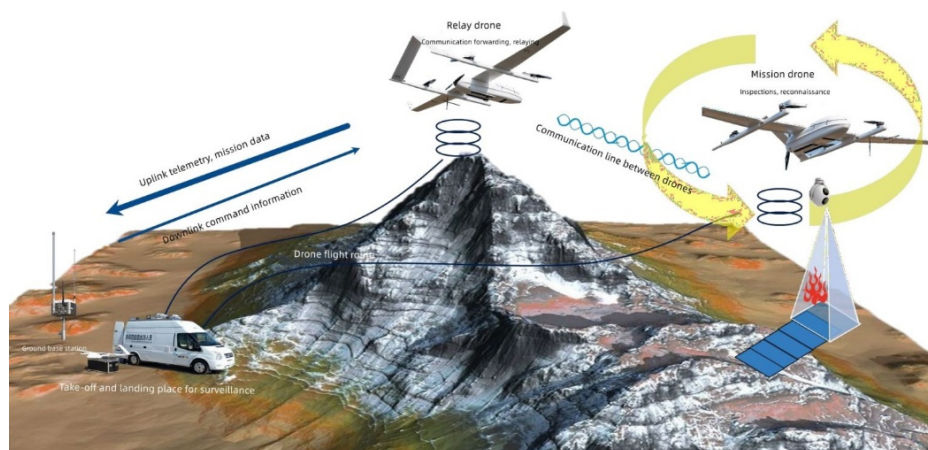


Figure 3. Communication between the drone and firefighting teams (JOUAV, 2023)

Advanced Evacuation Management

Smart Lighting and Wayfinding. Smart lighting systems utilize visual signals and directional indicators when power is lost or visibility is severely compromised by smoke. These systems typically consist of linear lights integrated into floors, walls, or ceilings. Under normal conditions, the lighting remains dim, but it switches to full intensity during an emergency to clearly mark evacuation routes. This type of lighting helps occupants exit the premises faster and more safely, directly reducing panic and disorientation (LDA Audio Tech, 2021).

Fire and Smoke Curtains. In the event of a fire, smoke curtains control and channel the blaze within a building or industrial environment, providing fire separation and containment to prevent further spreading. These automated systems use heat-resistant fabric to form a barrier against flames and smoke (Coopers Fire, 2023). Triggered by smoke or heat detectors, the curtains deploy from concealed housings to seal off openings, offering a flexible protection alternative to rigid fire doors.

Emergency Communication Systems. Emergency communication systems can be activated manually or automatically to broadcast pre-recorded voice messages. These instructions guide occupants toward safe evacuation routes and provide clear sequences of action, which is vital since panic can lead to poor decision-making (LDA Audio Tech, 2021). Key components include main control panels, high-clarity audio systems, and strategically placed intercom

stations that enable two-way communication between building personnel and emergency services.

DIGITAL STRATEGIES IN MODERN CRISIS COORDINATION

Digital Platforms and Control Centers. Modern fire protection systems increasingly integrate digital platforms and control centers to make monitoring, prevention, and intervention more efficient and reliable. Conducting evacuation analyses based on various fire scenarios using advanced technology is crucial for preventing or minimizing loss. Rather than relying solely on traditional detectors and alarms, these systems utilize interactive 3D building maps (CSE Mag, 2023). These maps provide comprehensive data on exits, stairwells, hydrant networks, and high-risk zones, allowing firefighting teams to plan safer, more precise operations while providing occupants with clear evacuation guidance.

Real-Time Monitoring and Simulation. Digital control centers enable real-time situational awareness by analyzing data from sensors, cameras, and thermal imaging devices, coupled with automated emergency alerts. These systems can simulate the spread of smoke or fire and predict the safest evacuation routes. This capability significantly enhances the effectiveness of both preventive measures and active fire interventions.

Digital Twin Technology. The Digital Twin concept represents an advanced technological approach to building management and optimization through a digital replica of the physical structure. It reflects architectural and structural characteristics while relying on parameters from temperature and humidity sensors, cameras, motion detectors, and equipment-tracking software (ScienceDirect, 2024). All data is integrated into a central digital model that utilizes AI and machine learning algorithms to analyze building performance and optimize system operations. This technology enables remote building management and predictive analysis of potential issues before they manifest in the physical environment.

Logistics and Future Outlook. The integration of digital platforms enhances coordination and logistics during emergencies by providing teams with precise insights into available resources, the locations of endangered individuals, and critical zones within the facility. In the future, these systems are expected to become even more intelligent, leveraging advanced AI and predictive algorithms to minimize risks and maximize public safety (ScienceDirect, 2024).

ADVANCED TECHNOLOGICAL SOLUTIONS FOR WILDFIRE MANAGEMENT

AI has the potential to significantly enhance natural disaster management, encompassing preparedness, prevention, suppression, and recovery (Phys.org, 2022). Most wildfires are caused by anthropogenic factors, with human negligence and agricultural activities contributing the most to their ignition. Digital logic methods can integrate weather forecasts, satellite imagery, and burn area datasets to model wildfires, achieving far greater

predictability than conventional methods. This logic is increasingly used to forecast wildfire risks and for susceptibility mapping of vulnerable areas (Figure 4).

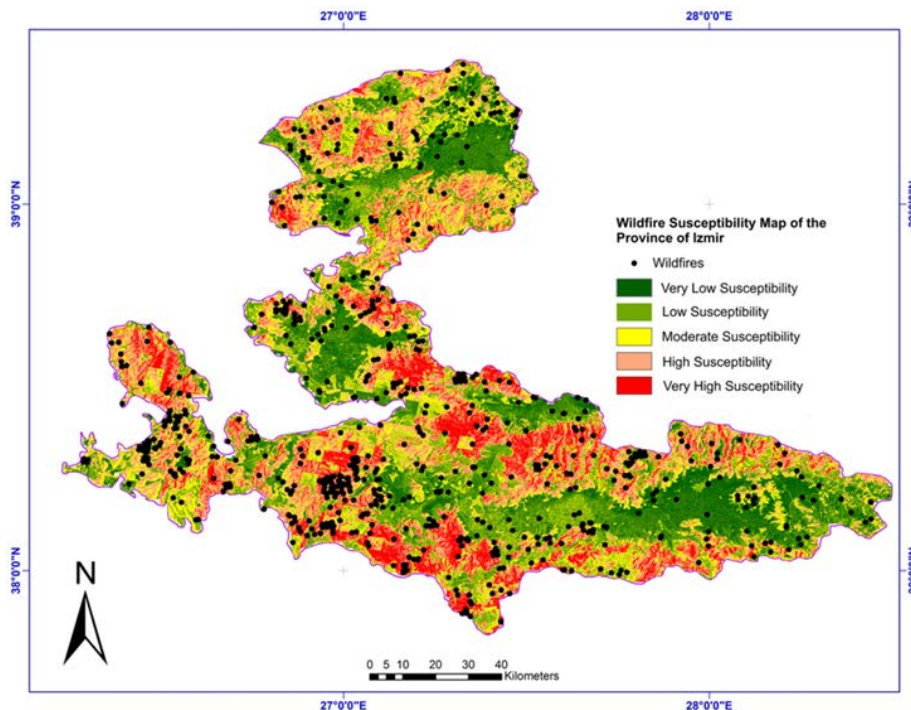


Figure 4. Wildfire susceptibility map for the province of Izmir (ResearchGate, 2024)

Satellites play a pivotal role in monitoring wildfires, covering vast geographical areas and detecting hotspots rapidly (Nature Communications, 2025). The combination of satellite data, meteorological information, and machine learning enables not only early-stage detection but also the prediction of fire spread patterns. This capability is vital for strategic intervention planning, evacuation coordination, and the protection of both lives and property.

For fire prediction, a global satellite network is utilized to detect wildfires within very short timeframes, even in the most remote regions. Current satellite imagery is analyzed alongside historical fire data, topography, vegetation, accessibility, and suppression difficulty to determine potential spread and the likelihood of successful containment.

Another key technology in the fight against wildfires involves high-mounted cameras that continuously monitor the environment (Fire Foresight, 2024). Using daily and thermal video feeds, AI-powered systems can recognize smoke or fire and trigger alarms almost instantaneously (ResearchGate, 2024). The gathered data is processed in real-time using machine learning algorithms that detect environmental anomalies and identify early signs of fire. Such systems are particularly invaluable in dense forests, remote landscapes, and expansive areas where traditional patrols or human surveillance are insufficient.

BENEFITS OF IMPLEMENTATION AND STRATEGIC CHALLENGES

Automated fire suppression systems enable real-time monitoring and an instantaneous response to detected heat or smoke, minimizing infrastructural damage. A key advantage of these solutions is the elimination of human error in high-risk environments, such as chemical plants, thereby ensuring personnel safety and preventing fatal injuries (Synergy Spray, 2023). Modern protection now also incorporates predictive analysis of factors like climatic conditions and historical data, allowing for preventive action before a fire even breaks out. Thanks to their scalability, these integrated systems easily adapt to facility expansions and emerging technological standards.

However, the implementation of these advanced solutions is accompanied by several strategic challenges, with high costs being the primary limiting factor. Initial investments in sensor networks and their sophisticated maintenance are often out of reach for smaller organizations with limited budgets (Midsummer Fire Protection, 2023). An additional hurdle is the system's absolute dependence on stable power and internet infrastructure. Any power outage or network instability can cause critical delays in alerting, posing a serious safety risk in emergencies. Ultimately, the technology's effectiveness is inextricably linked to staff expertise. Without adequate training in data interpretation and emergency procedures, the system loses reliability, as human error can lead to overlooked signals or false alarms, undermining the facility's overall security strategy.

CONCLUSION

The introduction of modern technologies into fire protection systems represents a decisive step toward maximizing the safety of both people and property. The application of these technologies is no longer limited to traditional methods; it has become a strategic tool that merges prevention, risk control, and safe evacuation, significantly raising the safety standards of modern facilities.

Looking toward the future, it is clear that the integration of intelligent and automated fire protection systems will play an increasingly vital role in architecture and urban planning. The key advantage of these systems lies in their ability to enable early response, precise decision-making, and more efficient evacuation, directly reducing the consequences of fire and saving human lives. We believe that this approach will become the future standard in building design and management, as it not only improves safety but also allows for more effective risk control and streamlined emergency interventions. As risks in urban and industrial environments constantly evolve and grow more complex, traditional methods are no longer sufficient to provide the level of protection required by modern structures. Therefore, we believe that advanced sensor systems, intelligent cameras, automated response mechanisms, and predictive risk management tools are not merely technological innovations, but a necessity.

ACKNOWLEDGEMENT

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APPLICATION OF UAV TECHNOLOGY IN PESTICIDE SPRAYING: IMPLICATIONS FOR OCCUPATIONAL HEALTH AND SAFETY

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Abstract: The increasing demand for sustainable food production has intensified the need for safer and more efficient pesticide application methods. Traditional pesticide spraying techniques, such as knapsack and tractor-mounted sprayers, are associated with high levels of occupational exposure and environmental risks. In recent years, unmanned aerial vehicles (UAVs), commonly referred as drones, have emerged as a promising technology for precision pesticide application. This paper provides a comprehensive overview of UAV-based pesticide spraying, including system components, operational workflow, and comparative analysis with conventional application methods. Field studies conducted in the region of Kyiv (2018–2021) were analyzed to evaluate occupational exposure, pesticide drift, and associated health risks across different application technologies. The results indicate that UAVs significantly reduce operator exposure by minimizing direct contact with pesticides and enabling remote operation. However, certain risks remain during mixing, loading, and refueling operations. Additionally, UAVs demonstrate improved application precision and reduced pesticide usage, although limitations such as payload capacity, battery life, and weather sensitivity still restrict large-scale adoption. Overall, UAV technology represents a significant advancement in agricultural pesticide application, contributing to improved occupational safety, environmental protection, and operational efficiency.

Keywords: *Unmanned Aerial Vehicles (UAV); pesticide; exposure.*

INTRODUCTION

The maintenance of food security and the increase in food production are increasingly becoming more problematic. The increasing of the spread of harmful organisms also increases environmental and occupational risks (Arıcak, 2025). The use of pesticides in agriculture is an integral part of modern food production (Borysenko et al., 2025). A pesticide means any substance, or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest, or regulating plant growth (WHO & FAO, 2014).

There is an estimated 5.1 billion pounds of pesticides applied to crops each year, and thousands of farmworkers experience the effects of acute pesticide poisoning, including headaches, nausea, shortness of breath, or seizures. Pesticide exposure leads to chronic health problems, such as cancer, infertility (and other reproductive problems), neurological disorders, and respiratory conditions (Farmworker Justice, 2013). Agricultural workers are

particularly at higher risk of exposure to these substances. In general, pesticide exposure occurs through four main routes: inhalation, dermal contact, ingestion through food, and contaminated drinking water (Işık & Kılınç, 2025).

The application of pesticides, while crucial for modern agriculture, necessitates stringent management to mitigate risks to human health and the environment. The integration of precision agriculture technologies, particularly unmanned aerial vehicles (UAVs) or drones, marks a significant advancement in enhancing the safety and efficiency of pesticide use. These technologies facilitate the precise application of pesticides, reducing the amount of chemicals needed and minimizing exposure to non-target areas. This evolution in pesticide application methods, characterized by continuous innovation, has seen a shift from traditional techniques such as backpack and vehicle-mounted sprayers (which, despite their effectiveness, have been limited by issues of efficiency, spray deposition uniformity and operator safety) to the adoption of drone technology. UAVs overcome these challenges, offering a new paradigm in crop protection and crop management that prioritizes both efficiency and safety. Targeted application not only boosts pest management but also promotes environmental sustainability by reducing the likelihood of chemical runoff and pollution. Moreover, drones can easily reach difficult terrain, such as steep inclines, densely planted areas, or wetlands, ensuring thorough crop protection regardless of location challenges. Drones offer a safer way to apply pesticides by eliminating the need for direct contact with chemicals. This significantly reduces the risk of exposure and potential health issues for operators. Traditional hand-held equipment often leads to higher exposure levels, requiring advanced personal protective equipment (Felkers et al., 2024).

UNMANNED AERIAL VEHICLE TECHNOLOGY IN PESTICIDE SPRAYING

Unmanned aerial vehicles (UAVs), specifically unmanned aerial spray systems (UASS), are garnering worldwide interest as an application technique for crop protection products, generally referred to as pesticides. In this document, the terms drone, UAV, and unmanned aerial spray systems (UASS) are used interchangeably. UASS demonstrates a use case that will help pave the way for a broader digital-agriculture ecosystem with potential benefits for increasing effectiveness, operational efficiency, and environmental and human safety. The application of crop protection products requires expertise and stewardship in the proper use and safe handling of products with specific best management practices (BMPs), especially with a new technology like UASS. BMPs increase the likelihood of environment and operator protection while considering economic factors, availability, technical feasibility, ability to implement, and effectiveness (UAPASTF, 2024).

Unmanned Aerial Vehicles (UAVs) are an inevitable trend of modern aerial equipment based on developments in the direction of intelligence. They can be controlled autonomously via preprogrammed flight paths in many situations where human intervention is considered difficult or dangerous. The use of UAVs for pesticide spraying can be beneficial for reducing

human contact with chemicals, improving the performance of spraying operations, and avoiding the presence of chemicals outside designated areas (Figure 1.). Drones can be integrated with computing capabilities and on-board sensors to support crop management, disaster reduction, early warning systems, wildlife and forestry conservation, and more. They can also be leveraged for crop and growth monitoring, yield estimation, water stress assessment, and weed, pest, and disease detection.

Drones are increasingly being used for pesticide spraying in agriculture, offering several advantages over traditional ground-based methods. Compared to conventional ground-based spraying systems, drones enable more precise and targeted application, particularly in hard-to-reach or uneven terrains. Essentially, a drone is a flying robot that can be remotely controlled or fly autonomously through software-controlled flight plans in their embedded systems, working in conjunction with onboard sensors and GPS. In recent years, drones have gained significant attention due to their ability to perform a wide range of tasks, including aerial photography, delivery, inspection, and surveying. One such application is in pesticide spraying, where drones have been found to be more efficient and effective than traditional methods. Drones are able to cover large areas of farmland quickly and accurately, while minimizing the risks associated with human exposure to pesticides. Furthermore, the use of drones in pesticide spraying has been found to reduce the amount of pesticide needed, resulting in cost savings and decreased environmental impact.

Drones can spray chemicals like fertilizers and pesticides based on the spatial variability of crops and fields, and the amount of chemicals can be adjusted depending on the crop conditions or the severity of the pest attack. Heavy lift UAVs are required for large-scale spraying, providing accurate, site-specific application for crop fields. By detecting pest hotspots and enabling variable rate application of pesticides, drones can potentially reduce the amount of pesticide lost to drift and minimize its impact on neighbouring ecosystems and human health (Kumar et al., 2024). However, despite these advantages, UAV-based pesticide application still faces several challenges, including limited payload capacity, battery constraints, regulatory restrictions, and sensitivity to weather conditions, which may affect its large-scale implementation.



Figure 1. A22 Agricultural Drone

The fundamental system and components of the UAV

The airframe of a UAV consists of the fuselage, landing gear, and arms. The propulsion system includes the battery, motors, electronic speed controllers (ESCs), and propellers. The command and control system encompasses the radio-controlled (RC) transmitter and receiver, flight controller unit (FCU), global positioning system (GPS), ground control station (GCS), and radio telemetry as illustrated in Figure 2 (Bhosale et al., 2025).

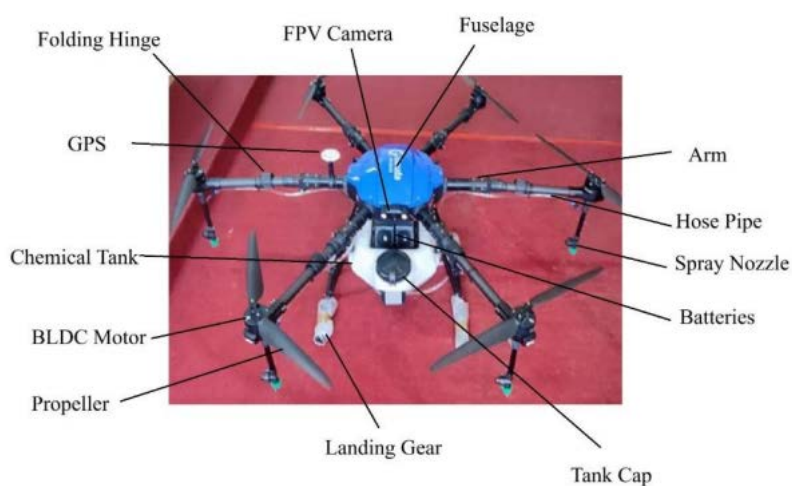


Figure 2. Components of Unmanned Aerial Vehicle

Working of drone in pesticide spraying application

The use of drones for pesticide application offers a new high-tech tool for crop protection. Drone sprayers, featuring autonomous flight control to deliver pesticides to an array of crops,

are now a common substitute for traditional knapsack application. The drone pesticide spraying has become increasingly popular due to their higher work efficiency, lower operator exposure, and improved ability to apply chemicals in a timely and highly spatially resolved manner. The process typically involves several steps, as shown in Figure 3.



Figure 3. Flow chart of working of drone in pesticide application

The first step is mapping the area to be sprayed. This is done using GPS, and software generates a flight path based on the field's size and shape. The drone is programmed to fly autonomously, covering the entire field in a predetermined pattern. This ensures that the entire field is covered evenly, and no areas are missed. Once the field is mapped, the sprayer is calibrated to ensure that the correct amount of chemical is applied per unit area. Calibration involves adjusting the spray volume and flow rate to ensure that the desired coverage and droplet size are achieved. Over- or under-application can lead to crop damage or reduced efficacy of the chemicals. The drone is then loaded with the chemical to be sprayed. The amount of chemicals loaded onto the drone depends on the size of the field to be sprayed and the desired coverage. The chemicals can be stored in tanks on the drone itself or in a separate ground station, which is connected to the drone through hoses. Once the drone is loaded and calibrated, it takes off and flies over the field, spraying the chemical in a controlled manner. The drone follows the predetermined flight path, which is set up to ensure that the entire field is covered evenly. The drone's speed, altitude, and spraying rate are all predetermined and can be adjusted by the operator if necessary. During the flight, the drone's sensors and cameras monitor the spraying process to ensure that the correct amount of chemical is being applied and that the spray is evenly distributed. The drone's sensors can detect changes in wind speed and direction, as well as changes in terrain, and can adjust the spraying accordingly to ensure that the chemicals are applied accurately. Once the spraying is complete, the drone lands and the operator can inspect the results. The operator can review data collected by the drone's sensors and cameras to evaluate the effectiveness of the spraying and make any necessary adjustments for future flights (Kumar et al., 2024).

COMPARISON OF TRADITIONAL AND UAV PESTICIDE APPLICATION

Field studies were conducted in 2018–2021 in the Kyiv region using Amistar Extra 280 SCS (80 g/l of cyproconazole and 200 g/l of azoxystrobin) at the maximum application rate (0.75 l/ha) on soybean. When applying the formulation, knapsack sprayer SOLO-10, a trailed boom sprayer (AMAZON 1201 UF), and fan sprayer (OPV-2000) combined with a tractor (MTZ 82.1 Belarus), as well as an unmanned aerial vehicle (UAV) for field spraying (AgraZ 2 system), and aircraft equipped with a valveless liquid cut-off system were used.

The refueler, tractor driver, signalman, and pilot were dressed in special protective clothing, rubber gloves, and respirators during production operations.

Studies of pesticide content on the skin surface of workers were performed using degreased gauze swabs moistened with a mixture of ethyl alcohol and water (1:1) and patch samplers (cotton cloth, medical gauze, and “blue tape” filter) placed on overalls.

Air samples were taken on a paper filter “blue tape” and silica gel. When performing each production operation, three parallel samples were collected at three sampling points. Quantitative determination of the active ingredients content was performed by high-performance liquid and gas-liquid chromatography.

Occupational risk assessment was performed in accordance with the guidelines. Statistical data were processed using methods of variation statistics, including calculation of the arithmetic mean, variance, standard deviation, and standard error. The significance of differences between two independent samples was assessed using Student's t-test or non-parametric tests when data distribution deviated from normal. Statistical processing of the results was performed using IBM SPSS Statistics Base v.22 (Table 1.).

Table 4. Values of potential risk of dangerous influence of the Amistar Extra 280 SC formulation when applied by different methods of application

Method of application	Active ingredient	Risk values															
		Inhalation, $\times 10^{-2}$				Percutaneous, $\times 10^{-2}$				Complex, $\times 10^{-2}$				Combined			
		R	O/T	P	S	R	O/T	P	S	R	O/T	P	S	R	O/T	P	S
Knapsack sprayer	Azoxystrobin	0.03	0.1**	-	-	0.04	0.03	-	-	0.07	0.13**	-	-	0.1	0.12**	-	-
	Cyproconazole	9.4	11.4**	-	-	0.53	0.5	-	-	9.93	11.9**	-	-				
Trailed boom sprayer	Azoxystrobin	0.01	0.04**	-	-	0.04	0.03	-	-	0.05	0.07**	-	-	0.04	0.14**	-	-
	Cyproconazole	3.4	13.6**	-	-	0.53	0.48	-	-	3.93	14.1**	-	-				
Fan sprayer	Azoxystrobin	0.01	0.12**	-	-	0.04	0.03	-	-	0.05	0.16**	-	-	0.04	0.46**	-	-
	Cyproconazole	3.4	46.2**	-	-	0.53	0.48	-	-	3.93	46.72**	-	-				
Unmanned aerial vehicle	Azoxystrobin	0.04*	-	0.02	-	0.18	-	0.17	-	0.22*	-	0.19	-	0.15*	-	0.09	-
	Cyproconazole	12.4*	-	7.08	-	2.73*	-	2.51	-	15.13*	-	9.59	-				
Aircraft	Azoxystrobin	0.04	-	0.1	0.12	0.18	-	0.25	0.4'	0.22	-	0.35	0.52'	0.13	-	0.13	0.59'
	Cyproconazole	10.2	-	9.2	54.2'	2.43	-	2.91	4.2'	12.63	-	12.1	58.4'				

Note: R – refueler; O/T – operator/tractor driver; P – pilot; S – signalman; * – the risk values of the tank refueler are statistically significantly higher at $p > 0.05$ ($df=17$); ** – the risk values of the operator/tractor driver are statistically significantly higher at $p > 0.05$ ($df=17$); ' – the values of the signalman's risk are significantly higher at $p > 0.05$ ($df=17$)

Significantly lower risks of adverse health effects were observed for sprayer tank refuelers compared to operators/tractor drivers, aircraft pilots, and signalmen. Moreover, inhalation,

percutaneous, and combined risks were significantly higher only in the UAV tank refueler compared to the external pilot during aerial pesticide application. This can be explained by the shorter operating time of the UAV pilot (28–30 minutes) compared to the time required for refueling the drone sprayer (42–45 minutes).

This technology separates the operator (external pilot) from direct contact with the spray, thereby significantly reducing exposure risks to levels comparable to those of a bystander (approximately 2–3 orders of magnitude lower).

No significant differences were observed between the UAV refueler and the knapsack sprayer refueler in terms of working conditions. The advantage of boom and fan sprayers is the single filling of the tank and the presence of an automated system for mixing the working solution.

The results of air drift analysis, obtained using the aspiration method, indicate that pesticide drift did not exceed 500 m during fan and aviation application of the formulation. The drift zone of up to 1% of the total applied amount, when using a UAV and knapsack sprayer, decreased to within approximately 10 m from the field edge under wind conditions.

However, it is suggested that the potential drift is higher when using UAVs than knapsack sprayers due to rotor-induced airflow vortices, which increase droplet dispersion.

The sprayer tank refueler showed a higher risk of harmful exposure than the tractor operator working with a boom sprayer; however, this result does not correlate with the data obtained in the present study. This is primarily attributed to differences in exposure duration during the working shift, where tractor operators are exposed for longer periods.

There is also a higher potential for pesticide drift during boom and fan applications compared to knapsack and UAV spraying, where it may reach more than 25 m.

When comparing UAV-based aerial application with classical aviation methods, inhalation and dermal exposure risks are higher in conventional aviation, since the pilot operates within the treated airspace. In such cases, drift of working solution particles may exceed 300 m, which is significantly higher than values observed in UAV application.

The obtained results indicate that safety of the production environment for workers at all technological stages can be reliably ensured, provided that requirements for transportation, storage, and application of pesticides are strictly followed. Statistical analysis showed that combined risk values were significantly higher for operators/tractor drivers and signalmen compared to refuelers ($p < 0.05$). In addition, combined risk values for the external UAV pilot were significantly lower than those for the refueler during UAV-based pesticide application (Borysenko et al., 2021).

MINIMIZING OCCUPATIONAL EXPOSURE BY APPLYING UAVS

In the area of operator safety, the use of drones has the potential to greatly reduce applicator exposure, specifically in agricultural procedures that primarily rely on handheld application

devices, which are still the predominant application methods in low- and middle-income countries. Instead of being physically present in the field being treated, a drone operator is operating from a distance. Since the use of drones is a more efficient and safer way to apply pesticides, it is becoming more popular as the technology and its availability improve.

While the potential benefits are clear, there are still areas and specific scenarios that require further study and validation to ensure the safe and effective use of UASS for agricultural applications. For example, one area that warrants further investigation is how exposure during drone pesticide application procedures, such as mixing and loading (M&L), product application, battery changes, and handling of the drone itself, potentially differ from conventional pesticide application methods, where the risks have been well-studied and characterized.

It is important to characterize human safety for pesticide applications in a risk-based approach to ensure that operators are adequately protected from the potential health risks associated with pesticide exposure. Additionally, proper personal protective equipment (PPE), specifically chemical-resistant gloves, can often be used to minimize the potential exposure risks to M&L operators. The majority of exposure studies have shown that the main exposure during M&L is on the hands; hence, chemical resistant gloves are the most efficient in significantly reducing exposure (Figure 4.).

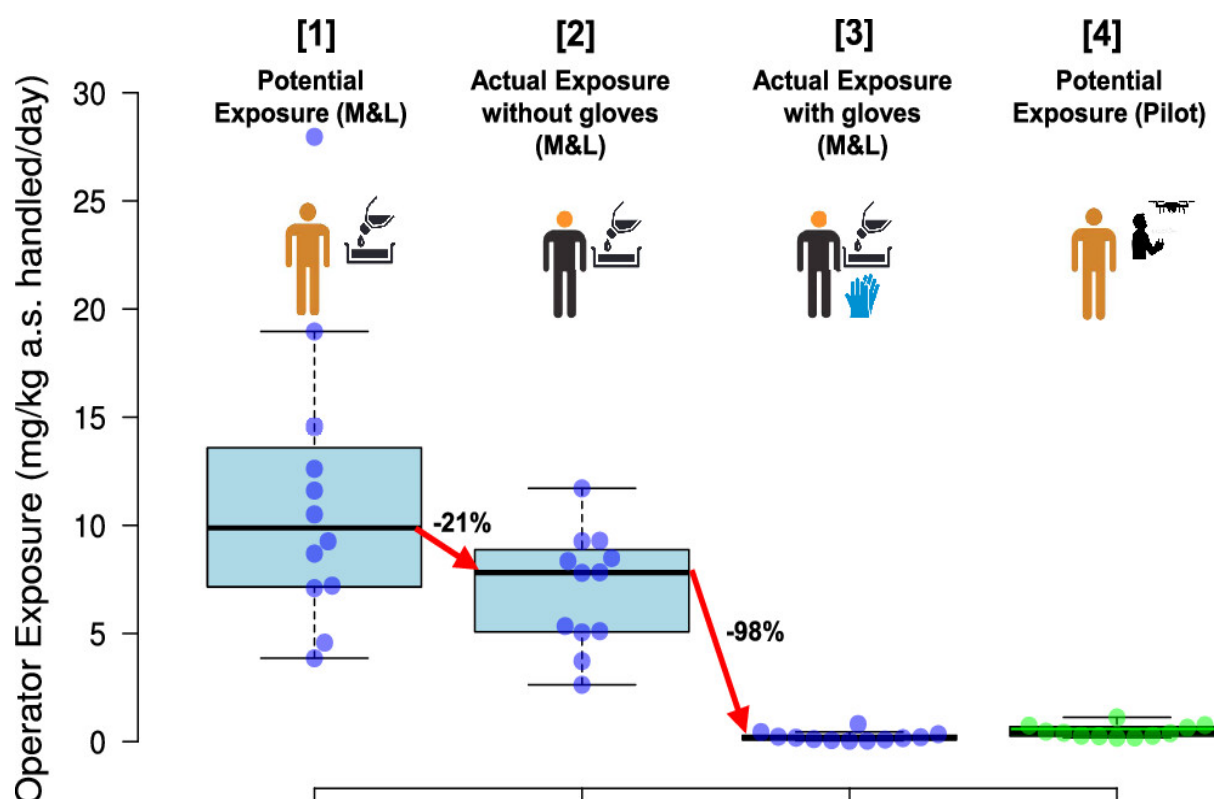


Figure 4. Comparison of operator exposure (M&L vs. pilot) and the effect of PPE on normalized exposure levels (mg/person/kg handled/day).

With respect to the risk assessment using UASS technology, the lacking data are primarily related to exposure, efficacy, and drift. Characterizing potential human safety risks, especially in the case of a new application method, such as with drones, can help to ensure that operators are properly trained and have the right safety equipment in place to reduce the risks associated with handling and applying pesticides (Kuster et al., 2023).

CONCLUSIONS

The use of drones for pesticide application offers significant advantages for modern agriculture. By providing more precise and targeted spraying, drones help reduce pesticide usage, minimize environmental impact, and improve overall efficiency. This technology allows farmers to address pest issues with greater accuracy, ensuring that only the necessary areas are treated, which also reduces the risk of chemical runoff and exposure. Additionally, drones can lead to cost savings and improve safety by reducing direct contact with pesticides. While there are still challenges, such as regulatory concerns and the need for proper training, the continued development of drone technology holds great potential to enhance the sustainability and productivity of farming practices, making them more efficient and environmentally friendly in the long term. Overall, drone technology represents a promising step toward more sustainable agricultural practices.

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SUSTAINABLE REUSE OF THERMAL WASTEWATER IN AGRICULTURE

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Abstract: Agriculture is the largest global consumer of water, accounting for approximately 70% to 90% of total water use for irrigation. Growing water scarcity caused by population growth, urbanization, climate change, and declining water quality highlights the need for sustainable alternatives. The reuse of treated wastewater, including mineral rich thermal spa wastewater, represents a promising solution within a circular economy framework. This paper examines the benefits and risks associated with wastewater reuse in agriculture. The findings suggest that properly treated and managed wastewater can provide a reliable irrigation source, contributing to sustainable agricultural practices while reducing pressure on freshwater resources.

Keywords: *Thermal water; Wastewater reuse; Agriculture; Sustainable irrigation.*

INTRODUCTION

Agriculture represents the predominant consumer of water on a global scale, utilizing approximately 70% to 90% of the world's water resources for crop irrigation (FAO, 2002). The intensification of water shortages, driven by factors such as the expanding global population, increased food demand, urbanization, climate change, and deteriorating water quality in certain regions, underscores the potential of treated wastewater reuse as a sustainable solution. In 2015, the United Nations Sustainable Development Goal 6 highlighted the critical role of wastewater recycling in ensuring universal water availability. The utilization of reclaimed water is anticipated to rise substantially in the near future, with projections indicating that at least 10% of the global population will consume agricultural products cultivated using treated wastewater. The urgency of irrigation water demand is evidenced by the fact that approximately 7% of the world's irrigated land, equating to 20 million hectares across 50 countries, is irrigated with raw or partially treated wastewater (WHO, 2007). In California, approximately 65% of recycled water is utilized for agricultural purposes. The reuse of wastewater for crop irrigation reaches 63% and 86% in Kuwait and Israel, respectively (Leonel and Tonetti, 2021). Conversely, in Europe, water reuse is more restricted in both volume and scope. This practice is implemented in Italy, Spain, and Greece, predominantly on the islands (Palese et al., 2009; De las Heras and Mañas, 2020). The application of treated

wastewater has been investigated in thirteen management plans across these regions, yielding positive outcomes for crops such as cotton, maize, and olive trees, as well as vegetables.

With proper treatment, wastewater can become microbiologically safe, making it suitable for crop irrigation in a circular economy framework. In addition, wastewater contains valuable nutrients that offer an opportunity for agriculture to reduce reliance on chemical fertilizers and decrease the discharge of effluents into water bodies. By harnessing these nutrients, wastewater can become a vital resource, fostering sustainable agricultural practices. However, despite the availability of advanced wastewater treatment technologies that ensure microbiological safety, the global use of treated wastewater remains minimal. This limited usage is due to various social, economic, and regulatory challenges.

IRRIGATION WITH TREATED THERMAL WASTEWATER

Treated wastewater provides valuable nutrients, such as nitrogen, phosphorus, calcium, and magnesium, which can improve soil fertility and reduce the need for chemical fertilizers (Kerboua Faycal, 2018). Its use requires careful monitoring to avoid risks associated with high salinity, heavy metals, sulfur, and pathogens (WHO, 2015). Studies in Mediterranean regions show that treated wastewater can be used for crops such as olive trees, vineyards, cotton, and maize (Palese et al., 2009; De las Heras and Mañas, 2020).

A study conducted between 2000 and 2006 in Southern Italy assessed the effects of irrigating olive groves with treated wastewater on soil and fruit microbiological quality (Palese et al, 2009). The findings indicated that, under suitable conditions, low-quality wastewater could serve as an additional water resource for olive irrigation in water-scarce Mediterranean environments. Research from Spain (De las Heras and Mañas, 2020) examined the use of reclaimed wastewater to irrigate olive groves and vineyards. The study found that irrigating with treated wastewater did not harm soil or crops, suggesting its viability as an alternative irrigation source. These studies collectively suggest that, with appropriate treatment and management, reclaimed wastewater can be effectively used for irrigating crops like olive trees and vineyards in Mediterranean regions. Kerboua Faycal (2018) reported that wastewater reuse (either raw or treated) for irrigation of crops provides the soil with many nutrient elements. However, it also results in organic and metallic contaminants.

Thermal spa wastewater is characterized by elevated concentrations of dissolved minerals. Certain elements, such as calcium and magnesium, have the potential to enhance soil fertility and augment crop yield. Calcium contributes to the fortification of plant cell walls, whereas magnesium plays a critical role in photosynthesis. While these elements can be advantageous for plant growth, others, such as sulphur, may exhibit toxicity to specific crops or soil microorganisms when present in excessive quantities. Therefore, it is imperative to conduct a thorough analysis of the wastewater's chemical composition prior to its application in agricultural contexts. An excessive mineral content, particularly sodium, can lead to increased soil salinity, thereby diminishing soil fertility and reducing crop yields. Additionally, the high

temperatures of some thermal spa waters may alter soil pH, negatively affecting plant growth. In some regions, the presence of potentially harmful elements, such as heavy metals or pathogens, may necessitate additional treatment processes before water can be safely used for irrigation. To mitigate these effects, wastewater must be properly diluted, treated, and monitored.

Standards and guidelines for water reuse applications

The use of thermal spa wastewater for agricultural purposes must comply with local environmental and public health regulations. In many regions, wastewater reuse is governed by specific standards and guidelines to ensure public health and environmental protection. The World Health Organization (WHO) has developed guidelines for Sanitation Safety Planning (SSP) and water reuse, particularly focusing on the permissible limits of microbial presence in treated and untreated wastewater used for irrigation. The thresholds for physico-chemical and microbiological parameters in wastewater used for irrigation, which affect the crops directly, are further outlined by United States Environmental Protection Agency (USEPA), Oman, UAE, Egypt Standards guidelines and summarized in Table 1.

Table 1. Threshold limits of wastewater for reuse applications standardized by the WHO, USEPA, Oman, UAE, Egypt Standards guidelines (Salgot and Folch, 2018; WHO, 2015; Blumenthal et al, 2000; USEPA, 2002; Al-Zubari et al, 2017)

Parameters	Units	WHO	USEPA	Oman	UAE	Egypt	EU
Electrical Cond.(EC)	μS/cm	2225	≤700	-	-	-	≤1000
pH	-	4-8.6	6.9	6-9	7-9.2	6.5-8.5	6.5-8.4
TSS	mg/L	40	-	10	-	≤15	35-60
Turbidity	NTU	2	≤2	2	4	≤10	≤10
Sodium	mg/L	250	-	70	150	-	-
Calcium	mg/L	450	-	-	-	-	-
Magnesium	mg/L	80	-	30	0.4	-	-
Potassium	mg/L	100	-	-	12	-	-
BOD ₅	mg/L	40	≤10	10	5	≤15	25
COD	mg/L	100	-	50	50	≤30	125
NH ₃ -N	mg/L	50	-	1	0.5	-	-
PO ₄ ³⁻	mg/L	25	-	20	2.2	≤2	15
SO ₄ ²⁻	mg/L	-	-	200	250	-	-
Cadmium	mg/L	0.01	0.01	0.01	0.003	0.001	0.01
Nickel	mg/L	0.2	0.2	0.2	0.07	0.2	0.2
Chromium	mg/L	0.1	0.1	0.1	0.5	0.05	0.1
Lead	mg/L	5	5	0.1	0.1	0.01	5.0
Zinc	mg/L	2	2	2	5	0.01	5.0
Copper	mg/L	0.2	0.2	0.2	1	0.01	0.2
Temperature (T)	°C	-	-	30	25	-	-
TKN	mg/L	-	-	5	-	-	2

TOC	mg/L	-	-	20	1	≤3.5	-
Total-Coliform	MPN/100	≤1000		≤200		≤10	≤100
(<i>T.Coli</i>)	mL	CFU		CFU		CFU	

Benefits and challenges of thermal water reuse

Thermal waters from spa resorts must be treated to reduce harmful microorganisms and adjust the mineral content to make them suitable for irrigation. Mineral-rich treated water can enhance plant health and increase yields, particularly in vineyards and olive orchards.

Mineral content helps improve soil fertility, but the treatment process must ensure that the concentrations of certain minerals (such as sodium) are within safe limits to avoid damaging crops. The high temperatures of thermal waters require significant cooling before they can be used in irrigation systems.

The recycling of thermal spa wastewater can reduce agricultural water demand. This is particularly important in regions facing water scarcity or where freshwater is not readily available. Utilizing wastewater from thermal spas can help conserve precious freshwater resources, particularly in areas with high agricultural demands. Wastewater from thermal spas must be treated before being released into the environment. Redirecting this water for agricultural use can reduce the burden on local water treatment facilities and decrease the pollution load in nearby water bodies. For thermal spa operators, reusing wastewater for irrigation can offer a cost-effective alternative to the disposal of wastewater through conventional treatment processes. Farmers can also benefit from reduced water costs, particularly in areas where water resources are limited or expensive. The reuse of treated thermal spa wastewater in agriculture could be of interest according to its potential to address water scarcity in agricultural regions, especially in areas with abundant geothermal resources.

However, some challenges must be addressed. Thermal spa wastewater is only available in regions with geothermal activity, limiting its potential use in agricultural areas. Additionally, spa operations may be seasonal or fluctuate in capacity, making it challenging to rely on this water source for consistent agricultural irrigation purposes. In addition, there is a risk of soil salinity and the presence of different toxic substances in spa wastewater. To minimize the risks of soil salinity and toxicity, wastewater should be diluted with fresh water and filtered to remove suspended solids or harmful chemicals. This can help reduce the negative effects on soil and crops. Treated water must be free from pathogens, heavy metals, and harmful chemicals. Regular water quality monitoring is essential to ensure that irrigation does not introduce contaminants into the food supply chain. Parameters such as total dissolved solids (TDS), heavy metals, nutrients, and microbial contamination should be monitored to prevent negative impacts on crops and the environment. Farmers using treated wastewater should monitor soil health, particularly salinity and nutrient levels. Proper irrigation techniques and the use of amendments, such as organic matter, can help manage soil fertility and prevent salinization.

Different crops have different tolerance levels for mineral contents. Therefore, it is important to tailor irrigation practices according to crop type (Manganiello et al., 2024). For instance, crops that are more sensitive to salinity should be irrigated with a more diluted form of wastewater. Farmers should select crops that are resilient to the specific mineral composition of the treated water. Vegetables, fruits, and certain field crops are often better suited for irrigation with treated wastewater than others. In addition to the mineral content, the temperature of thermal water plays a role in enhancing soil fertility. Warm water can accelerate the decomposition of organic matter, particularly in colder climates, where microbial activity is slower. Increased temperature helps break down organic material into humus, enriching the soil and improving its structure. This can be especially beneficial in areas with cold or temperate climates, where soils tend to be slower in terms of nutrient release rates. Different soils have different capacities to absorb and retain minerals, and not all soils benefit equally from the addition of thermal water to the soil. For example, sandy soils, which drain quickly, may not retain enough minerals from thermal water, whereas clay soils, which retain water for longer periods, may accumulate excessive salts if the discharge is not properly controlled. Therefore, farmers must tailor the use of thermal water to their specific land and crops, ensuring that it contributes to soil health without causing harm.

The economic benefits of using thermal water for agriculture are significant. By utilizing thermal water for irrigation, farmers can reduce their reliance on expensive chemical fertilizers and synthetic amendments. This can result in lower operational costs and a more sustainable long term farming model. Furthermore, the use of geothermal energy in agriculture can support the development of green agricultural practices that consumers increasingly value. Products grown using sustainable and natural methods are often considered more environmentally friendly, making them more appealing in the market.

The main drawbacks include an increased risk of soil salinity and potential threats to human health due to exposure to pathogens and heavy metals. Wastewater irrigation affects water resources, agriculture, and public health in different ways, influenced by factors such as wastewater quality, soil characteristics, climate conditions, plant species, and irrigation methods. The success of such a reuse project also relies on the level of economic investment and the potential returns. Public perception of the use of treated wastewater in agriculture can be a significant barrier. Consumers may be concerned about the safety of crops irrigated with treated wastewater, particularly regarding food hygiene and potential health risks.

OTHER AGRICULTURAL PURPOSES OF THERMAL WASTEWATER

Agricultural use is an important branch of geothermal energy utilization in Hungary. In addition to irrigation, geothermal water can be used in geothermal heating systems. Greenhouses cover more than 80 ha, with more than 250 ha devoted to plastic tents and soil heated using thermal water. Geothermal energy is increasingly utilized in greenhouse agriculture to provide energy-efficient heating and ensure year-round crop production in

various climates. By harnessing heat from naturally occurring geothermal sources, these greenhouses can maintain optimal temperatures even during colder months, reducing the need for conventional heating systems that often rely on fossil fuels. This energy efficient heating method not only lowers operational costs, but also contributes to sustainable farming practices by minimizing carbon emissions.

Vegetable producers are increasingly shifting from fossil fuels to renewable energy sources, with geothermal energy emerging as a promising option for greenhouses in Hungary (Ehret-Berczi & Németh, 2014). Although the initial investment required for establishing a geothermal heating system can be substantial, it offers significantly lower operational costs compared to fossil fuel energy sources. Since 2014, Hungary has not mandated the reinjection of thermal water, thereby reducing the cost of drilling thermal wells and potentially encouraging more vegetable producers to adopt this technology in the future. Thermal water can serve as an effective heat source for maintaining the temperatures necessary for vegetable production in greenhouses. Hungary possesses numerous active thermal wells, particularly concentrated in the southern region, which is also the area with the highest vegetable production.

The integration of geothermal heating with aquaponic systems has proven particularly beneficial, as it allows for the simultaneous cultivation of fish and plants in a closed-loop system. In an aquaponic system, fish waste provides essential nutrients for plant growth, and plants help filter and purify the water for fish, creating a mutually beneficial relationship. Geothermal energy helps maintain the ideal water temperature for both fish and plants, ensuring a stable environment for both species. This synergistic relationship optimizes resource use, rendering the system more efficient and sustainable. Furthermore, the controlled environment provided by geothermal heating allows the cultivation of a diverse range of crops, including those that are typically difficult to grow in certain climates. The use of geothermal energy in greenhouses also reduces dependency on external energy sources, which can be subject to price fluctuations and supply issues. As more research and development are conducted, geothermal greenhouses, particularly those combined with aquaponic systems, are expected to become a key innovation in sustainable agriculture, offering a scalable solution for food production in regions with abundant geothermal resources (Boedijn et al., 2020).

CONCLUSION

The sustainable reuse of thermal waters presents a promising strategy for addressing water scarcity while promoting circular economy principles within the agricultural sector. Treated thermal water has the potential to enhance soil fertility, improve crop yields, and provide renewable energy for greenhouse heating and aquaponic systems. To mitigate risks associated with salinity, heavy metals, and pathogens, it is essential to implement proper treatment, dilution, and continuous monitoring. Economic, social, and regulatory factors influence the adoption of thermal water reuse; however, the benefits of sustainable agriculture and resource

efficiency render it a viable and innovative approach. Integrating thermal water reuse with geothermal heating and aquaponics can foster resilient, low-carbon agricultural systems capable of supporting food production in regions experiencing water scarcity.

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THE IMPACT OF DIGITALIZATION ON OCCUPATIONAL SAFETY AND HEALTH - EMERGING RISKS AND CHALLENGES

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Abstract: Contemporary processes of work digitalization and automation are significantly transforming the working environment, introducing new forms of work organization as well as emerging occupational risks that affect employees' safety and health. The aim of this paper is to analyze the impact of work digitalization on the occurrence and characteristics of occupational risks, with a particular focus on psychosocial, ergonomic, and cognitive risks. The paper examines the effects of implementing information and communication technologies, artificial intelligence, and performance monitoring systems on working conditions and employee workload. The methodological approach includes an analysis of relevant scientific literature, applicable legal regulations, and international standards, including ISO 45001, as well as a comparative analysis of traditional and digitalized work processes. Special attention is given to the identification of emerging risks, such as digital stress, burnout syndrome, increased cognitive workload, and issues related to workplace ergonomics. The results indicate that, although digitalization contributes to improved efficiency and work flexibility, it simultaneously requires the redefinition of existing approaches to occupational safety and health management. The paper highlights the need to integrate new protective measures, including the improvement of ergonomic conditions, effective management of psychosocial risks, and continuous employee training. It is concluded that effective management of occupational risks in a digital environment requires an interdisciplinary approach and the adaptation of existing safety systems to contemporary technological changes.

Keywords: *digitalization, occupational safety and health, occupational risk, psychosocial risks, ergonomics, cognitive workload, burnout.*

INTRODUCTION

The development of information and communication technologies, automation, and artificial intelligence is significantly transforming work organization, working conditions, and the interaction between employees and the working environment. This process, known as work digitalization, represents one of the key drivers of change within the so-called Fourth Industrial Revolution (Industry 4.0), which involves the integration of digital technologies into all aspects of business operations (Peña-Casas, 2018; Leso, 2018). Work digitalization brings numerous benefits, including increased productivity, flexibility, and accessibility of work, as well as the emergence of new forms of employment such as telework and platform-based work (Eurofound, 2020). However, alongside these positive effects, new occupational risks are emerging, and existing ones are being transformed, potentially having significant

implications for employees' safety and health (ILO, 2019). Traditional approaches to occupational safety and health management are often not fully adapted to these new working conditions, characterized by intensive use of digital technologies, constant connectivity, and increased cognitive demands on workers (EU-OSHA, 2018; Cazan, 2020). Psychosocial risks represent a particular challenge in digital work environments, where they are intensified by continuous availability, increased performance monitoring, and blurred boundaries between work and private life. Research indicates a growing prevalence of digital stress, burnout syndrome, and mental fatigue resulting from intensive use of information technologies and high work demands (Dragano, 2020). In addition, remote work is often associated with inadequate ergonomic conditions, which may lead to musculoskeletal disorders and other health problems (Cijan, 2019). Cognitive aspects of work are also becoming increasingly important, due to information overload, multitasking requirements, and decision-making in interaction with automated and intelligent systems (Obasi, 2025). These factors may reduce concentration, increase the likelihood of errors, and contribute to mental fatigue, thereby directly affecting work safety. Managing occupational safety and health in a digital environment requires the adaptation of existing systems and the integration of new approaches based on prevention and a holistic understanding of risks. International standards, such as ISO 45001, provide a framework for systematic risk management; however, their application in the context of work digitalization requires further interpretation and adjustment to contemporary working conditions (ISO 45001:2018). Based on the above, the aim of this paper is to analyze the impact of work digitalization on the emergence and characteristics of occupational risks, with a particular focus on psychosocial, ergonomic, and cognitive risks. The paper seeks to identify key challenges and provide a basis for improving occupational safety and health management systems in the context of digital transformation.

METHODOLOGY

The research is based on a qualitative methodological approach, which includes:

- an analysis of relevant scientific and professional literature,
- a review of documentation from international organizations (ILO, EU-OSHA, Eurofound),
- an analysis of international standards, including ISO 45001,
- a comparative analysis of traditional and digital work environments.

The criteria for source selection included relevance to the topic of work digitalization and occupational safety and health, as well as the timeliness of the research.

DIGITALIZATION AND AUTOMATION IN THE CONTEXT OF OCCUPATIONAL SAFETY AND HEALTH

Work digitalization, understood as the process of introducing and intensively applying information and communication technologies, automated systems, digital platforms,

algorithmic management, and artificial intelligence in work processes, represents a significant factor in the transformation of the working environment and occupational safety and health (OSH) systems. The European Agency for Safety and Health at Work (EU-OSHA) emphasizes that digital technologies create new opportunities for improving work processes, while simultaneously raising concerns related to emerging organizational, psychosocial, ergonomic, and regulatory risks (EU-OSHA, 2019).

At the same time, automation refers to the transfer of specific work tasks from humans to machines, software systems, or artificial intelligence. While traditional automation primarily focused on repetitive physical tasks, modern automation increasingly encompasses cognitive functions, including data processing, decision support, performance evaluation, and automated recommendations. As a result, the role of employees is evolving—from task executors to users, supervisors, and controllers of digital systems. Although such changes may reduce exposure to certain physical hazards, they can increase mental workload, responsibility, technological dependency, and the risk of human-machine interaction errors. The European Foundation for the Improvement of Living and Working Conditions (Eurofound) defines telework as a form of work performed outside the employer's premises, typically using computers and telecommunication technologies. These models enhance flexibility, autonomy, and accessibility of work, but may also disrupt work-life balance, increase stress levels, and negatively affect employees' health by introducing new forms of risk (Eurofound, 2020).

Psychosocial risks represent a particularly significant category in digital work environments. These risks arise from work organization, social relations, job demands, levels of control, and job insecurity. In digital contexts, they are further intensified by constant availability, extensive digital communication, pressure for rapid response, performance monitoring, and blurred boundaries between work and private life. The International Labour Organization (ILO) emphasized in 2026 the growing importance of psychosocial risks, highlighting long working hours, job insecurity, and workplace harassment as key contributors to work-related health problems (ILO, 2026).

A frequently discussed concept in this context is technostress, which arises when employees struggle to cope with the demands of information and communication technologies. It may result from information overload, rapid technological changes, expectations of constant availability, insufficient digital competencies, or fear of job displacement. Recent studies identify techno-overload and techno-invasion as major sources of negative impacts on employee well-being (Mansuroğlu, 2026).

Burnout syndrome represents another critical dimension of psychosocial risk. In digital work environments, burnout is associated with high work intensity, frequent interruptions, multitasking, digital surveillance, and limited opportunities for psychological recovery. Although digital technologies can enhance autonomy, they often extend working hours and

reinforce the expectation of constant availability. The WHO and ILO have reported that working 55 or more hours per week significantly increases the risk of stroke and ischemic heart disease compared to standard working hours, which is particularly relevant in digital work settings where working time boundaries are often blurred (WHO/ILO, 2021).

Ergonomic risks also acquire new dimensions in digital work. Remote and hybrid work often take place in environments not designed as workspaces. Inadequate seating, improper desk height, poor screen positioning, insufficient lighting, and prolonged sitting contribute to musculoskeletal disorders, visual strain, and overall physical discomfort. Studies on remote work during the COVID-19 pandemic have highlighted its negative effects on both physical and mental well-being (Nor Asiah, 2025).

Cognitive risks are associated with mental workload resulting from processing large volumes of information, decision-making under pressure, multitasking, and interaction with complex digital systems. In digital environments, employees are often required to manage multiple platforms, applications, and information streams simultaneously, increasing the likelihood of errors, reducing concentration, and contributing to mental fatigue. This challenge is further amplified by artificial intelligence systems, which require users to interpret outputs, validate results, and assume responsibility for algorithm-supported decisions.

Existing literature indicates that work digitalization has an ambivalent impact on occupational safety and health. On the one hand, it reduces exposure to hazardous physical tasks and improves efficiency and flexibility. On the other hand, it increases psychosocial strain, intensifies work demands, enables continuous monitoring, and creates new forms of technological dependency. Therefore, digitalization should not be viewed solely as technological progress, but as a complex organizational transformation requiring the adaptation of risk management systems. Furthermore, current regulatory and standardization frameworks often fail to provide sufficiently specific guidance for risk assessment in digital and hybrid work environments. This highlights the need for the development of new methodological approaches that enable the identification, assessment, and control of emerging and transformed occupational risks in digital work settings.

COMPARATIVE ANALYSIS: TRADITIONAL VS. DIGITAL WORK ENVIRONMENT

Traditional work environments are characterized by a clearly defined physical workspace, fixed working hours, and direct supervision of work processes by the employer. In contrast, digital work environments are characterized by flexibility in terms of time and place of work, intensive use of information and communication technologies, and increased employee autonomy, but also by a higher degree of digital monitoring and algorithmic management (Table 1).

Table 1. Comparative overview of traditional and digital work environments

Criterion	Traditional work environment	Digital work environment
Workplace	Fixed (office, industrial facility)	Flexible (home, mobile, hybrid)
Working hours	Clearly defined	Flexible, often extended
Work control	Direct (supervisor)	Digital, algorithm-based
Communication	Face-to-face, direct	Digital (e-mail, platforms, applications)
Work organization	Hierarchical	Network-based, platform-oriented
Employee autonomy	Limited	Increased (with digital monitoring)
Work-life boundary	Clearly defined	Blurred
Primary risks	Physical, chemical, and biological hazards, mechanical risks, workplace ergonomics	Psychosocial, cognitive, and ergonomic risks

Work digitalization has led to the “dematerialization” of the workplace, meaning that work is no longer tied to a single location but can be performed across various environments (home, coworking spaces, mobile settings). While this flexibility may enhance employee satisfaction, it also complicates the control of working conditions and the implementation of occupational safety and health measures, thereby partially shifting responsibility to employees, particularly in remote work settings.

One of the key consequences of digitalization is the transformation of the structure of occupational risks. Whereas physical and technical risks dominated traditional work environments, digital work is increasingly characterized by psychosocial, cognitive, and organizational demands. Although physical risks have been reduced in certain sectors due to automation, this has been accompanied by a rise in intangible risks, such as stress, mental strain, and information overload.

This shift indicates that digitalization does not eliminate existing risks, but rather modifies and complements them with new forms of exposure, thereby making their identification and management more complex (Figure 1).

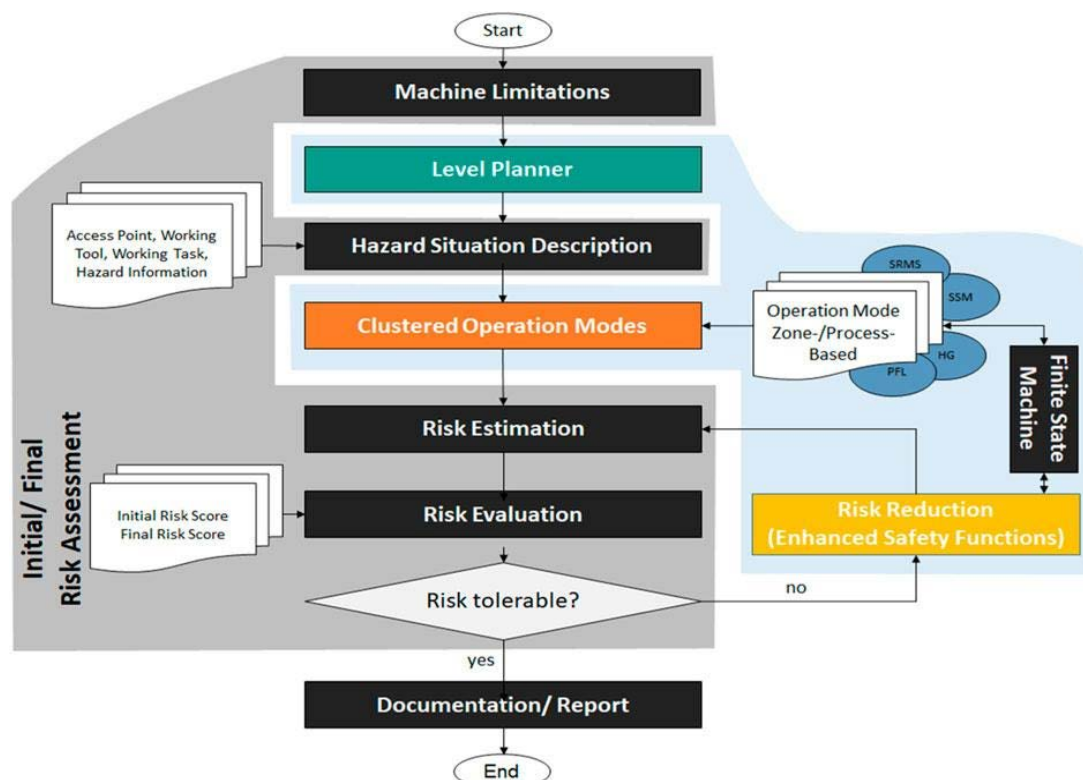


Figure 1. Model of risk assessment and management in a digitalized work environment (Bdiwi, 2022)

Digitalization also introduces new risks associated with human-technology interaction, including dependence on digital systems, increased task complexity, and the potential for technical errors. In this context, a distinction can be made between emerging and transformed occupational risks (Table 2).

Table 2. Emerging and transformed occupational risks

Category	Risk example	Description
Emerging risks	Digital stress	Overload from digital tools and information
	Algorithmic monitoring	Continuous performance tracking through software
	Continuous availability	Inability to disconnect from work
Transformed risks	Information overload	Working with large volumes of data
	Stress → technostress	Stress driven by digital work demands
	Ergonomics → home ergonomics	Inadequate working conditions at home
	Working time → extended working hours	Prolonged working time due to flexibility
	Work control → digital control	Shift from direct supervision to software-based monitoring

The results of the analysis indicate that work digitalization has a multidimensional and complex impact on occupational safety and health. While it reduces exposure to certain physical hazards and enhances work flexibility, it simultaneously introduces new sources of strain, particularly in the domain of psychosocial and cognitive risks.

These findings suggest that occupational safety and health in digital work environments cannot be adequately addressed through traditional risk assessment models alone, but require a broader, interdisciplinary approach that integrates technical, organizational, and psychological aspects of work.

RECOMMENDATIONS AND IMPROVEMENT MEASURES

Contemporary processes of work digitalization require the adaptation of existing occupational safety and health (OSH) management approaches in order to effectively address emerging and transformed occupational risks. Based on the conducted analysis, the recommended measures can be structured into technical, organizational, and psychosocial aspects, with particular emphasis on continuous training and integrated risk management.

Technical measures should focus on improving working conditions and reducing physical and ergonomic strain. In the context of digital work, the standardization of workstations-both in office and home environments-is of particular importance. Recommended measures include:

- provision of ergonomic equipment (adjustable chairs, appropriate work surfaces, properly positioned screens),
- implementation of guidelines for the safe use of computer equipment,
- optimization of lighting and microclimatic conditions,
- introduction of software solutions for monitoring working time and prompting regular breaks.

In addition, the development and implementation of user-centered digital systems can significantly reduce cognitive workload and the likelihood of errors.

Organizational measures play a key role in managing risks arising from work organization in digital environments. Particular attention should be given to clearly defining rules and procedures related to working time, employee availability, and performance monitoring. Accordingly, it is recommended to:

- clearly define working hours,
- limit excessive digital surveillance and ensure transparency in the use of performance monitoring systems,
- ensure balanced workload distribution and avoid continuous work without breaks,
- develop policies for managing remote and hybrid work,
- involve employees in decision-making processes related to work organization.

Effective work organization contributes to reduced stress, increased employee satisfaction, and improved overall safety and health outcomes.

Psychosocial risk management represents a critical component of modern OSH systems in digital environments and requires a systematic and proactive approach, including:

- regular assessment of psychosocial risks,
- implementation of stress management and burnout prevention programs,
- provision of psychological support for employees,
- promotion of work-life balance,
- strengthening organizational culture that encourages open communication and support.

All of the above measures should be integrated into existing OSH management systems. In this context, the application of international standards such as ISO 45001 is particularly important, as it provides a structured framework for risk identification, assessment, and control. It is therefore recommended to:

- update risk assessments to reflect digital forms of work,
- incorporate psychosocial and cognitive risks into OSH management systems,
- develop internal procedures for digital work environments,
- ensure continuous monitoring and improvement of protective measures.

An integrated approach enables organizations to effectively respond to the challenges of digitalization and to ensure a high level of occupational safety and health.

CONCLUSION

Work digitalization significantly transforms both the nature of the working environment and the structure of occupational risks. While it contributes to increased efficiency, flexibility, and the reduction of certain physical hazards, it simultaneously leads to a rise in psychosocial, ergonomic, and cognitive risks, such as digital stress, burnout, and information overload. The findings indicate that digitalization does not reduce overall risk levels, but rather transforms them, shifting the focus from physical hazards to intangible forms of strain. Contemporary work models, including remote and hybrid work, further emphasize the need to adapt existing occupational safety and health management approaches. Effective risk management in digital work environments requires an integrated and interdisciplinary approach, along with the adaptation of existing systems, including ISO 45001. Future research should focus on developing methodologies for assessing emerging risks and improving regulatory frameworks in line with technological advancements.

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APPLICATION OF ENVIRONMENTAL PROTECTION SYSTEM ON THE BIOGAS SECTOR IN SERBIA

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Abstract: The development of the biogas sector in Serbia has been primarily driven by the production of renewable electricity and heat, but its environmental significance extends beyond energy production. Biogas plants are also installations for the controlled biological treatment of manure, agricultural residues and energy plants, agro-industrial by-products and, in specific cases, biodegradable waste streams. For this reason, they must be assessed as complex environmental systems rather than only as renewable energy facilities. Their operation is associated with multiple environmental aspects: air emissions from combustion units, potential methane losses, odour, water protection requirements, digestate handling, waste management obligations and, where applicable, sanitary and veterinary requirements for animal by-products. This paper analyses the environmental protection system applicable to biogas plants in Serbia, with emphasis on environmental impact assessment, air protection, water protection, soil protection and waste treatment. The analysis shows that Serbian legislation already contains a comprehensive regulatory framework for biogas projects. Its practical application requires simultaneous compliance with multiple interconnected regulatory frameworks. The paper therefore provides a structured expert overview of the key obligations of biogas plant operators and identifies the main practical points that should be considered during permitting, operation and compliance monitoring.

Keywords: *Environmental protection; Biogas; Environmental impact; Air emissions; Digestate; Waste management; Serbia.*

INTRODUCTION

Anaerobic digestion is widely recognized as a technology that connects renewable energy production, waste management and nutrient recycling. In agricultural biogas plants may reduce uncontrolled emissions from manure and biodegradable residues, stabilize organic matter and generate energy in the form of biogas, electricity, heat or biomethane. In Serbia, the biogas sector has developed mainly through electricity generation from combined heat and power (CHP) units, while the role of biogas plants as controlled treatment facilities for organic residues and waste streams has often been less emphasized (Djatkov et al., 2024).

This distinction is important for environmental regulation. A biogas plant is not only an energy conversion facility with a gas engine and a generator. It is also a technical system that includes storage of input materials, pre-treatment, anaerobic digesters, gas storage, gas cleaning, combustion or upgrading, digestate separation and storage, internal transport and, in many cases, reception of materials that may be legally classified as waste or animal by-

products. Each of these elements can generate environmental impact and therefore activates a specific segment of the environmental protection system.

Scientific literature generally confirms the environmental benefits of anaerobic digestion when it replaces uncontrolled decomposition of organic materials and when digestate is properly managed. However, several authors also point out that the net environmental performance of biogas systems depends strongly on operational control. Methane leakage may significantly reduce greenhouse gas benefits, while ammonia and odour emissions may occur during substrate and digestate storage. Digestate use may contribute to nutrient recycling, but inadequate storage or land application can increase the risk of nitrogen and phosphorus losses to water and soil (Paolini et al., 2018; Lamolinara et al., 2022; Piadeh et al., 2024). Therefore, environmental protection in the biogas sector must be based on technology specific approach, rather than on just focusing narrow assessment of renewable energy output.

In the Serbian context, biogas projects are regulated through several legal frames. Environmental impact assessment (EIA) determines whether a study is required before implementation. Air protection legislation defines the status of combustion units, emission limit values, measurement and reporting obligations. Water legislation regulates water acts, wastewater management and protection of surface and groundwater. Waste legislation becomes particularly important when the plant receives waste as input material. Soil and agricultural land protection rules are relevant for digestate storage and application, while animal by-product regulations apply when substrates include slaughterhouse residues or other materials of animal origin.

The aim of this paper is to identify and systematize the obligations of biogas plants in Serbia within the environmental protection system. The paper is written as an expert analysis of regulatory requirements, with focus on practical interpretation for biogas facilities. The purpose is not to quantify emissions or environmental benefits, but to clarify which legal obligations arise, why they arise, and how they should be understood in the operational reality of the biogas sector.

LEGISLATIVE FRAMEWORK OF ENVIRONMENTAL PROTECTION SYSTEM

The environmental protection system applicable to biogas plants in Serbia is multi-layered. A single facility may simultaneously fall under the Law on Environmental Impact Assessment, the Law on Air Protection, the Law on Waters, the Law on Waste Management, regulations on animal by-products, and legislation on agricultural land and soil protection. From an operator's perspective, the key issue is not whether one regulation applies, but how several regulations interact within one technical and technological system.

Table 1. Overview of environmental protection obligations relevant for biogas plants in Serbia.

Environmental area	Main regulatory instrument	Typical obligation for biogas plants
Environmental impact assessment	Law on Environmental Impact Assessment; Regulation on project lists	Screening request for all biogas production plants; EIA study if required by competent authority.
Air emissions	Law on Air Protection; Regulation on ELVs from combustion plants; Regulation on emission measurements	Classification of CHP units as combustion plants, generally medium combustion plants; periodic measurements; compliance with ELVs; annual reporting to NRIZ/LRIZ.
Water protection	Law on Waters; rulebooks on water acts and wastewater quality	Water conditions, water consent and/or water permit where relevant; control of process wastewater, sanitary wastewater, stormwater and impermeable digestate storage.
Soil protection and digestate use	Law on Environmental Protection; Law on Agricultural Land; fertiliser and waste-related rules depending on digestate status	Prevention of leakage, nutrient overload and contamination; controlled application of digestate as fertiliser or management under waste rules if classified as waste.
Waste treatment	Law on Waste Management; rulebooks on waste records and reporting	Waste management permit if waste is officially treated on a biogas site; waste acceptance, classification, records, annual reporting and traceability.
Animal by-products	Veterinary and animal by-product legislation	Approval/registration, hygienisation or processing requirements, categorisation of input material and sanitary control when animal by-products are used. Strict rules for biogas plant monitoring

Environmental impact assessment

The Law on Environmental Impact Assessment defines the basic procedure and gives the Government authority, under Article 5, to prescribe the list of projects for which EIA is mandatory and the list of projects for which a screening request must be submitted. The current Regulation on project lists is particularly relevant because it explicitly includes biogas production plants in List II, under the category of projects for which there is an obligation to submit a request for deciding on the need for an EIA.

This means that a biogas plant is not automatically subject to a full EIA study solely because it produces biogas. However, the project holder is obliged to initiate the screening procedure. The competent authority then decides whether a full EIA study is necessary, applying the criteria related to project characteristics, location and expected impacts. For biogas plants, these criteria are especially relevant because even a moderate installed electrical capacity may

involve substantial quantities of substrates, digestate storage and transport, odour potential, water protection issues and possible waste treatment operations.

If the biogas plant also performs treatment of waste, the EIA relevance becomes stronger. The project may then be assessed not only as a biogas production plant, but also as a waste treatment activity. In practice, this means that the study or screening documentation should describe input materials, storage capacities, treatment technology, digestate status, wastewater and stormwater management, air emission sources, odour control, accident risks and monitoring measures. For projects located in protected areas, in the vicinity of ecological network areas, water protection zones or settlements, the probability that the competent authority will require a full EIA study is higher.

Table 2. Practical interpretation of EIA obligations for biogas projects.

EIA question	Interpretation for biogas plants
Is biogas explicitly listed?	Yes. The 2025 Regulation includes "plants for production of biogas" in List II, meaning that a screening request is required for all projects of this type.
Is full EIA always mandatory?	Not automatically. It becomes mandatory if the competent authority decides that significant environmental impacts are expected.
What changes if waste is accepted?	The plant must also be analysed as a waste treatment installation; waste codes, quantities, storage, treatment and outputs become central elements of the assessment.
What should the documentation emphasize?	Substrate reception, odour, gas handling, CHP emissions, digestate storage and use, wastewater, stormwater, accident prevention and monitoring.

Impact on air

Air protection obligations for biogas plants arise primarily from the Law on Air Protection. Article 40 of this law authorises the Government to prescribe emission limit values (ELV) for stationary sources, measurement methods, measurement frequency, criteria for measurement points, evaluation of results and reporting. On this basis, the Regulation on emission limit values of pollutants into air from combustion plants regulates combustion plants, including biogas CHP units.

A biogas CHP engine is a combustion plant because biogas is oxidised for the purpose of energy production. The Regulation defines combustion plants by installed thermal input and fuel type. It explicitly recognises biogas as a gaseous fuel relevant for medium combustion plants. For most agricultural and industrial biogas plants in Serbia, the installed thermal input of the gas engine is below 50 MW_{th} and the fuel is biogas; therefore, such units are generally treated as medium combustion plants. This classification is important because Article 20 of the Regulation refers to the emission limit values for existing and new medium combustion plants to Annex 2.

For new medium combustion plants using gaseous fuels, the relevant emission limit values

are given in Annex 2, Part B, Table 6. For biogas plants, the practically most important pollutants are carbon monoxide (CO), nitrogen oxides (NO_x expressed as NO₂), sulphur oxides (SO_x expressed as SO₂), and, where the threshold applies, particulate matter. The Regulation sets values in mg/Nm³, and for new medium combustion plants using gaseous fuels the reference oxygen content is 3%. The table below summarises the values most relevant for biogas combustion units.

Table 3. Emission limit values relevant for new medium combustion plants using biogas. Values are based on Annex 2, Part B, Table 6 of the Serbian Regulation on ELVs from combustion plants.

Pollutant	Relevant category for new medium combustion plants using gaseous fuels	Emission limit value (mg/Nm ³)	Comment for biogas CHP
Carbon monoxide (CO)	All gaseous fuels	80	Relevant indicator of combustion quality and engine adjustment.
Nitrogen oxides (NO _x as NO ₂)	Other gaseous fuels or combustion units where the heat transfer medium is not water	200	Most relevant regulated pollutant for gas engines in practice.
Sulphur oxides (SO _x as SO ₂)	Other gaseous fuels	350	Relevant because raw biogas contains H ₂ S; effective desulphurisation reduces SO ₂ after combustion.
Particulate matter	Natural gas, LPG, refinery gas, wastewater treatment gas and biogas, for thermal input ≥20 MW _{th}	5	Usually less critical for smaller biogas CHP engines; applies where threshold is met.

The practical compliance chain consists of: (i) defining the installed thermal input of each engine and, where applicable, considering aggregation rules; (ii) establishing measurement points on the exhaust system; (iii) performing measurements by an authorised legal entity in accordance with the regulation on emission measurements; (iv) evaluating results against the appropriate ELVs; and (v) reporting annual emissions. Measurements during trial operation and periodic measurements are required for stationary sources, while the frequency and scope depend on the type of plant, permit conditions and applicable measurement regulation.

Reporting is performed through the National Register of Pollution Sources (NRIZ) or the local register, depending on the competence and reporting threshold. Article 31 of the Regulation on ELVs from combustion plants requires the annual emission balance report for combustion plants to be submitted electronically by entering data into the information system of the National Register or the local register. Where continuous measurements do not exist, annual quantities are calculated based on periodic measurements performed during the reporting year; estimation is used only when measurement data are not available. In addition to air emission reports, the operator may have separate reporting obligations for waste, wastewater or other environmental data, depending on the activities performed at the site.

Impact on water

Water protection is one of the most sensitive aspects of biogas plant regulation because the plant handles large quantities of liquid and semi-liquid organic material. The Law on Waters regulates the legal status of waters, integrated water management, water facilities and water acts. Article 113 defines water acts as water conditions, water consent and water permit. For biogas projects, water acts become relevant whenever the facility may influence surface water, groundwater, drainage systems, water land, stormwater runoff or wastewater discharge.

In the permitting phase, water conditions define the technical and environmental requirements that must be incorporated into the project documentation. Water consent confirms compliance of project documentation with issued water conditions, where required. Water permit is relevant for the use of water, discharge of wastewater, operation of water facilities or activities that may affect the water regime. In practice, a biogas plant may require water acts even if it does not abstract groundwater, because water protection is also linked to stormwater collection, process areas, digestate storage, wastewater treatment, sanitary wastewater and possible discharge to a recipient or public sewerage system.

The key technical issue is prevention of leakage and uncontrolled discharge. Digesters, reception pits, silage clamps, lagoons, digestate tanks and manipulation areas must be designed as impermeable systems, with controlled collection of leachate and contaminated stormwater. Clean stormwater should be separated from contaminated flows where possible. If wastewater is discharged, the operator must comply with emission limit values for pollutants in water and with the conditions defined by the recipient or sewerage operator. If wastewater is not discharged but returned to the process, stored or transported, this must be documented and controlled.

Table 4. Water protection aspects relevant for biogas plants.

Water-related element			Environmental risk	Regulatory/practical requirement
Substrate	reception	and storage	Leachate and runoff with high organic load	Impermeable surfaces, controlled drainage, stormwater separator, prevention of contact with clean stormwater
Digesters and tanks			Leakage to soil and groundwater	Construction integrity, secondary containment where necessary, monitoring and maintenance, piezometer.
Digestate lagoons or storage tanks			Overflow, seepage, odour and nutrient loss	Adequate capacity, impermeability, freeboard, inspection and controlled emptying, piezometer.
Manipulation areas			Contaminated stormwater	Collection and appropriate routing to digesters, treatment or approved discharge system.
Sanitary wastewater			Organic pollution and pathogens	Connection to sewage or approved treatment/disposal system.
Discharge to recipient/sewage			Exceedance of water ELVs	Permit conditions, sampling, reporting and compliance with prescribed limits.

Impact on soil and digestate management

Soil protection in biogas plants is closely linked to digestate management. Digestate is a valuable product or by-product when it is used as an organic soil improver under controlled conditions, but it may become an environmental burden if stored or applied improperly. The main risks are nutrient overload, nitrate leaching, phosphorus accumulation, salinity, heavy metals or organic contaminants depending on the feedstock, and microbiological risks where animal by-products are used.

From the environmental protection perspective, digestate management should be based on mass balance: quantities of input material, produced digestate, separated solid and liquid fractions, storage capacities and agricultural application areas must be mutually consistent. Storage capacity is particularly important because land application is seasonally limited by agronomic conditions, crop needs and soil moisture (in the future is expected full implementation of the EU Nitrates Directive (91/676/EEC)). Application should be planned according to nutrient content, crop nutrient demand and soil characteristics. Uncontrolled application shortly before heavy rainfall, on frozen or water-saturated soil, or near watercourses increases the risk of nutrient losses.

The regulatory status of digestate depends on input materials and the intended use. When only agricultural substrates and manure are used, digestate may be managed as an organic soil improver, subjected to agricultural requirements defined by Law on Plant Nutrition Products and Soil Improvers. When waste is used as substrate, digestate status becomes more complex and may depend on waste permit conditions, proof of treatment, quality testing and whether end-of-waste or product status can be justified. Therefore, the operator must not assume that digestate is automatically a soil improver in all regulatory contexts.

Waste treatment obligations

The Law on Waste Management becomes central when the biogas plant accepts materials that are legally classified as waste. In such cases, the plant is not only an energy facility but also a waste treatment installation. The operator must obtain the appropriate waste management permit, identify accepted waste codes, define maximum annual quantities, maintain daily records and submit annual reports through the national reporting system. The permit must be consistent with the technological capacity of the plant, storage capacity, environmental protection measures and the planned management of outputs.

For biogas plants that treat waste, the critical regulatory question is traceability. Each waste stream must be accepted under a defined waste code and accompanied by adequate documentation. The operator must control whether the waste corresponds to the permitted category and whether it contains substances that may disturb anaerobic digestion or compromise digestate quality. Waste acceptance procedures should include supplier control, visual inspection, documentation check, rejection criteria and records. The environmental permit documentation should clearly distinguish between substrates that are products/by-

products and substrates that are waste.

Annual waste reporting is submitted electronically through the National Register of Pollution Sources. According to the current SEPA reporting practice (SEPA., 2024) and the waste reporting rulebook, annual waste reports are submitted by 31 March of the current year for the previous year. In addition to reporting input waste, the operator must also record waste generated at the plant, such as used oils, filters, contaminated packaging, laboratory waste, sludge from separators, or waste from maintenance activities.

Table 5. Waste management obligations for biogas plants receiving waste substrates.

Waste-related obligation	Practical meaning for a biogas plant
Waste management permit	Required if the plant treats waste; the permit defines waste codes, quantities, treatment operation and conditions.
Waste acceptance procedure	Control of documentation, waste code, quantity, contamination risk and compatibility with anaerobic digestion.
Daily records	Input waste and generated waste must be recorded according to prescribed forms and procedures.
Annual reporting	Reports are submitted electronically to NRIZ, generally by 31 March for the previous year.
Output management	Digestate status must be clarified; if it remains waste, further management must comply with waste legislation.
Generated waste	Maintenance waste, oils, filters, packaging and separator residues require separate classification and management.

Treatment of animal by-products

A specific regulatory framework applies when a biogas plant treats animal by-products, including slaughterhouse residues or materials of animal origin. These materials may create sanitary risks and are not regulated only as ordinary biodegradable inputs. The operator must consider veterinary requirements related to categorisation, transport, reception, processing or hygienisation, record keeping and approval or registration of the facility. The exact requirements depend on the category of animal by-product and on whether the material is treated before entering the digester.

From a practical expert perspective, this is one of the most important distinctions in biogas permitting. A plant receiving maize silage and manure is not in the same regulatory position as a plant receiving slaughterhouse waste or other animal-derived residues. The latter requires a stronger demonstration of sanitary control, substrate reception procedures, separation of clean and dirty zones, prevention of pest access, cleaning and disinfection, and proof that the process conditions are suitable for risk reduction. These obligations must be reflected in environmental documentation because they also affect odour, wastewater, waste, digestate quality and accident scenarios.

DISCUSSION AND RECOMMENDATIONS

The Serbian regulatory framework is sufficiently broad to cover the main environmental aspects of the biogas sector. The main challenge is not the absence of rules, but their integrated application. A biogas plant may be simultaneously assessed as an energy plant, a combustion source, a water-risk facility, a waste treatment installation and, in some cases, an animal by-product treatment plant. If these roles are not recognised at the design and permitting stage, later compliance problems are likely.

Air protection is a good example of the need for expert interpretation. Operators often focus on the electrical capacity of the CHP unit, while the Regulation classifies combustion plants according to installed thermal input and fuel type. Since biogas is explicitly listed as a gaseous fuel for medium combustion plants, and since CHP engines generally produce electricity using gaseous fuel below 50 MW_{th}, all Serbian biogas CHP units fall under the medium combustion plant regime. This requires correct identification of applicable ELVs, measurement points, measurement frequency and annual reporting obligations.

The most demanding practical area is often water and digestate management. The environmental acceptability of a biogas plant strongly depends on impermeability, storage capacity, separation of clean and contaminated water flows, and responsible use of digestate. Even where the CHP emissions are within prescribed limits, poor substrate storage or inadequate digestate management may create more significant local environmental impacts through odour, leachate or nutrient losses.

For biogas plants that use waste, the recommendation is to prepare a detailed substrate legality matrix before applying for permits. This matrix should identify each input material, its legal status, waste code if applicable, annual quantity, storage method, pre-treatment, environmental risks and expected influence on digestate. Such a document supports EIA screening, waste permitting, water protection planning and later inspection control.

Regulatory clarity could be improved through sector-specific guidance for biogas plants. Such guidance should explain the relationship between EIA, air permits and measurements, water acts, waste permits, animal by-product approval and digestate use. It should also define minimum technical expectations for substrate reception, covered storage, gas tightness, H₂S removal, emergency flaring or safe gas handling, drainage and digestate quality monitoring.

Serbian biogas plants are not IPPC installations due to their energy capacity, but integrated logic is still necessary. The environmental obligations do not arise in isolation: air emission control depends on biogas quality and H₂S removal; water protection depends on storage and drainage design; digestate quality depends on input materials; waste permit conditions affect EIA conclusions; and animal by-product requirements affect both waste and sanitary management. For this reason, the environmental protection system for biogas plants should be interpreted as an integrated compliance matrix rather than as a list of separate permits.

CONCLUSION

Biogas plants in Serbia have a dual environmental role. They contribute to renewable energy production and circular management of organic materials, but at the same time they may generate significant local environmental pressures if not properly designed and operated. Therefore, their regulatory treatment must reflect both aspects.

The analysis shows that biogas plants are explicitly recognised within the environmental impact assessment system and that all biogas production plants are subject to screening under the current project list regulation. In the air protection system, biogas CHP units are generally classified as medium combustion plants, with clearly defined emission limit values, measurement and reporting obligations. Water protection, soil protection, digestate management and waste treatment obligations depend on technical design and substrate structure, but they are essential for environmental compliance.

The key recommendation is that environmental protection for biogas plants should be managed as an integrated system. Compliance cannot be achieved only by measuring exhaust gases from the CHP unit. It also requires control of inputs, storage systems, wastewater and stormwater, digestate quality and use, odour, waste records and reporting. A mature biogas sector in Serbia therefore requires not only investment in technology, but also consistent regulatory interpretation and high-quality environmental management at plant level.

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THE FUTURE OF WASTE MANAGEMENT: STRATEGIC DIRECTIONS AND SERBIA'S GREEN TRANSITION

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Abstract: Waste management represents one of the key environmental challenges in the Republic of Serbia, particularly in the context of aligning national legislation with the European Union acquis and moving from a linear towards a circular economy model. This paper analyses the current state of the Serbian waste management system, with emphasis on the legislative and institutional framework, infrastructure, municipal and packaging waste flows, collection, recycling and disposal practices, and the main limitations affecting the implementation of modern solutions. Particular attention is given to the Law on Waste Management, the Law on Packaging and Packaging Waste, the Decree on Waste Landfilling, and strategic documents defining development directions up to 2030 and 2035. The analysis shows that Serbia has achieved considerable progress in regulatory alignment, regionalisation and the expansion of organised waste collection. Nevertheless, the system remains strongly dependent on landfilling and is characterised by insufficient primary separation, limited recycling and treatment capacities, unreliable or non-comparable data, and uneven enforcement at the local level. Non-sanitary and illegal landfills, inadequate financial and institutional support for infrastructure development, and the slow establishment of effective systems for special waste streams remain major challenges. Further transformation requires full implementation of extended producer responsibility, economically sustainable financing, stronger regional systems, additional treatment facilities, remediation of historical pollution, and digital monitoring of waste flows to improve transparency and traceability. The success of reform will depend on integrating the infrastructural, economic and social dimensions of the green transition so that waste management becomes a basis for resource efficiency, technological innovation and employment rather than only an administrative obligation in the European integration process.

Keywords: *Waste management; Municipal waste; Circular economy; Landfills; Green transition.*

INTRODUCTION

Waste management has become a central component of environmental policy, resource security and climate action. The European waste hierarchy gives priority to prevention, preparation for reuse and recycling, while disposal is treated as the least desirable option. This approach has been reinforced by the European Green Deal and the Circular Economy Action Plan, which connect waste policy with product design, resource efficiency, industrial competitiveness and greenhouse gas mitigation (European Parliament and Council, 2008; European Commission, 2020). For candidate countries, waste management reform is therefore

not limited to legal harmonisation. It also requires infrastructure, financial mechanisms, reliable data, capable institutions and behavioural change.

During the last two decades, Serbia has gradually replaced a predominantly disposal-oriented framework with legislation and strategic documents based on regionalisation, producer responsibility and circular economy principles. The adoption of the Law on Waste Management, the Law on Packaging and Packaging Waste and the Decree on Waste Landfilling established the foundations for organised planning, permitting, waste classification, regional systems and sanitary disposal. More recent programmes have linked waste management with circular economy and low-carbon development. However, national and international assessments repeatedly show a persistent gap between formal alignment and implementation, particularly in primary separation, recycling, biological treatment, remediation of non-compliant landfills and sustainable financing (Vujić et al., 2015; World Bank, 2023).

This paper aims to provide an integrated assessment of the current Serbian waste management system and to identify strategic directions for its green transition. The analysis combines the legislative and strategic framework with recent data on waste quantities, composition and treatment. Its contribution is a structured interpretation of the transition from a system focused mainly on collection and disposal towards one that treats waste as a resource and links infrastructure development with economic instruments, digitalisation and social capacity.

METHODOLOGY

The study applies a qualitative desk-research approach based on the review and synthesis of national legislation, strategic documents, official statistical reports, European Union policy documents and relevant scientific literature. The principal sources include the Waste Management Programme of the Republic of Serbia for 2022-2031, the Circular Economy Development Programme, the Low-Carbon Development Strategy, reports of the Serbian Environmental Protection Agency (SEPA), data of the Statistical Office of the Republic of Serbia (SORS), European Commission progress reports, World Bank analyses and selected peer-reviewed studies.

The analytical framework covers four mutually connected dimensions: regulatory alignment, physical waste flows, system performance and transition capacity. Regulatory alignment was assessed through the obligations and objectives defined by key laws and programmes. Physical flows were examined through reported quantities, hazardous characteristics and municipal waste composition. System performance was interpreted through collection, treatment, recovery and disposal patterns, while transition capacity was assessed through infrastructure, financing, data quality, institutional coordination and social participation. SEPA and SORS datasets were treated as complementary rather than directly interchangeable because they apply different reporting scopes and classifications.

LEGISLATIVE AND STRATEGIC FRAMEWORK

The Law on Waste Management is the core legal instrument governing waste classification, planning, responsibilities, permits, special waste streams, transboundary movement, reporting, financing and supervision. The 2025 law defines waste management as an activity of general interest and reinforces objectives related to prevention, recovery, the use of secondary raw materials, remediation of non-sanitary and illegal landfills, and protection of human health and the environment (Narodna skupština Republike Srbije, 2025). Its effectiveness, however, depends on by-laws, enforcement, administrative capacity and the availability of infrastructure for separate collection, treatment and safe disposal.

The Law on Packaging and Packaging Waste introduced shared responsibility and extended producer responsibility for producers, importers, packers, fillers and suppliers. Obligations may be fulfilled individually or through authorised operators, while national targets are intended to increase recovery and recycling. Packaging is especially important because it represents a visible municipal and commercial stream containing paper, cardboard, plastics, glass and metals with significant secondary-material value. Future alignment will also have to consider the more demanding requirements of Regulation (EU) 2025/40 concerning packaging reduction, reuse and recyclability (Narodna skupština Republike Srbije, 2009; European Parliament and Council, 2025).

The Decree on Waste Landfilling provides technical and operational requirements for site selection, construction, waste acceptance, environmental monitoring, closure and aftercare. It establishes the basis for replacing dumpsites with sanitary landfills and requires pre-treatment before disposal, except in narrowly defined cases (Vlada Republike Srbije, 2010). In practice, this transition remains incomplete. Mixed municipal waste is still commonly disposed of without prior recovery, while leachate, landfill gas and long-term site stability require stronger monitoring and control.

Strategic direction is defined primarily by the Waste Management Programme for 2022-2031, which recognises that the objectives of the previous strategy were not fully achieved. The programme prioritises organised collection, primary separation, recycling, regional infrastructure, closure of non-compliant landfills and sustainable financing. The Circular Economy Development Programme and the Low-Carbon Development Strategy broaden this perspective by connecting waste prevention and resource recovery with industrial policy, innovation and emission reduction (Vlada Republike Srbije, 2022b; Vlada Republike Srbije, 2023a). These documents create a coherent normative direction, but European Commission reports indicate that implementation remains slow and uneven (European Commission, 2024; European Commission, 2025).

CURRENT STATE OF WASTE FLOWS AND SYSTEM PERFORMANCE

Official data confirm that Serbia manages several large and structurally different waste streams. According to SEPA, 11.21 million tonnes of waste were recorded in 2024. Non-hazardous waste accounted for 11.10 million tonnes, while hazardous waste amounted to 104,520 tonnes, or 0.93% of the recorded total. Waste from thermal processes was the largest Waste Catalogue group, with 6.55 million tonnes, followed by municipal waste with 3.04 million tonnes (Agencija za zaštitu životne sredine, 2025a). The dominance of thermal-process waste reflects the importance of the energy sector, particularly ash and slag, whereas municipal waste remains the most relevant stream for local public services and everyday environmental quality.

Table 1. Selected waste management indicators for the Republic of Serbia in 2024

Indicator	Value	Analytical significance
Total waste recorded by SEPA	11,205,070 t	Overall pressure on the formal waste management system
Waste from thermal processes	6,553,381 t (58.49%)	Largest recorded stream; strong link with the energy sector
Municipal waste	3,041,289 t (27.14%)	Key stream for local services, public health and visible pollution
Hazardous waste	104,520 t (0.93%)	Low mass share but high environmental and health relevance
Biodegradable share of municipal waste	48.7%	Priority stream for separate collection and biological treatment
Waste generated by economic sectors (SORS scope)	209,669,877 t	Mining dominates the sectoral statistical presentation
Disposed share of treated sectoral waste	98.8%	Confirms the continued dominance of disposal

Source: Agencija za zaštitu životne sredine, 2025a; Republički zavod za statistiku, 2025.

The significance of hazardous waste cannot be evaluated only by its share in total mass. Its toxic, flammable, carcinogenic or ecotoxic properties require specialised collection, storage, transport, treatment and final disposal. The increase in recorded hazardous waste from 59,336 tonnes in 2021 to 104,520 tonnes in 2024 may reflect both changes in industrial activity and improved reporting. In either case, it underlines the need for traceable management of critical substances and special waste streams (Agencija za zaštitu životne sredine, 2025a).

Municipal waste composition further demonstrates why a disposal-based approach is inadequate. In 2024, biodegradable waste represented 48.7% of municipal waste, while paper

and cardboard accounted for 6.1%, PET packaging 5.5%, glass 4.0%, textiles 3.9% and composite materials 3.2%. No individual fraction other than biodegradable waste exceeded 10% (Agencija za zaštitu životne sredine, 2025a). Earlier research also identified biodegradable components as the dominant part of the municipal stream, although category definitions differed (Tošić and Vasović, 2020). The composition therefore requires a combination of separate collection, recycling, biological treatment and residual-waste management rather than reliance on a single technology.

The SORS sectoral presentation provides a different but complementary picture. Economic sectors generated 209.67 million tonnes of waste in 2024, of which mining accounted for approximately 95.2%. Of the 208.4 million tonnes treated, 98.8% were disposed of and only 1.2% were recovered (Republički zavod za statistiku, 2025). These values should not be directly compared with SEPA totals, but they reveal the scale of mining waste and confirm that disposal remains the dominant route across the broader economy.

Regionalisation and organised collection have advanced, but the operational system remains uneven. The World Bank reports that 28 waste management regions were planned, with regional companies established in 13 regions and inter-municipal agreements signed in a further 12. The existence of agreements and facilities does not automatically ensure full system functionality, because transfer stations, sorting lines, biowaste treatment, access roads, equipment, operating budgets and trained personnel must develop together (World Bank, 2023). Non-sanitary and illegal landfills continue to generate risks for soil, water, air quality and public health, while their remediation is slowed by incomplete records, unclear responsibilities and insufficient financing.

KEY BARRIERS TO THE GREEN TRANSITION

The first major barrier is the implementation gap between legislation and practice. Serbia has achieved a relatively high level of formal alignment in the waste sector, yet enforcement is inconsistent among local self-government units. Permitting, inspections, reporting and public-utility performance are affected by differences in administrative capacity and financial strength. As a result, national objectives may be interpreted uniformly but implemented at different speeds, which reduces the overall effectiveness of regional systems (European Commission, 2025; Koalicija 27, 2025).

The second barrier is insufficient and unstable financing. Modern waste management requires long-term capital investment and predictable operating revenues. Construction of facilities without sustainable tariffs, cost recovery and maintenance budgets can create infrastructure that operates below capacity or becomes technically unreliable. At the same time, low service affordability in some municipalities limits the rapid introduction of full-cost pricing. The transition therefore requires transparent tariff design, targeted social protection and clear allocation of revenues from producer-responsibility and environmental charges (World Bank, 2023; Koalicija 27, 2024).

The third barrier is the limited development of primary separation and treatment capacity. Mixed collection reduces the quality and market value of recyclables and makes biological treatment more difficult. The high share of biodegradable waste indicates that separate biowaste collection, composting and anaerobic digestion could substantially reduce the quantity sent to landfills, but these options depend on local density, logistics, end markets and operational competence. Similarly, packaging recovery targets cannot be achieved only through operator reporting; they require accessible collection systems and effective control of all obligated entities.

Data quality is a further systemic constraint. Waste flows are reported through different institutions and methodological frameworks, while smaller generators and informal activities may remain outside complete records. Incomplete, delayed or non-comparable data weaken infrastructure planning, investment appraisal and enforcement. The problem is particularly relevant for construction waste, special waste streams, illegal dumping and secondary materials. Without reliable mass-flow information, the system cannot accurately measure progress towards prevention, recycling and landfill-diversion targets.

STRATEGIC DIRECTIONS FOR FUTURE DEVELOPMENT

The future system should be organised around the waste hierarchy and adapted to regional conditions. Prevention and reuse should be strengthened through product and procurement policies, while separate collection must become the operational foundation of recycling and biological treatment. Regional centres should integrate transfer, sorting, treatment and sanitary disposal capacities instead of functioning primarily as final disposal sites. Investment decisions should be based on realistic waste quantities, composition, transport distances and markets for recovered materials, thereby avoiding technological lock-in and oversized facilities.

A second priority is the full implementation of extended producer responsibility and economically sustainable financing. Producer-responsibility systems should provide traceable material results, support collection infrastructure and include effective control of free riders. Municipal tariffs should gradually reflect real service costs while remaining socially acceptable. Environmental charges and national or international funds should be used strategically for infrastructure with clear operating plans rather than for isolated capital projects. Transparent financing is essential for building trust among citizens, municipalities, operators and investors.

Digitalisation can significantly improve transparency and management quality. A unified national system should connect waste generators, transporters, operators, local authorities and inspection bodies through interoperable records. Digital waste tracking, geographic information systems, electronic manifests and automated consistency checks could reduce reporting gaps and support the identification of illegal flows. At the municipal level, route optimisation, container monitoring and performance dashboards may improve collection

efficiency, but digital tools should complement rather than replace adequate equipment, maintenance and trained staff.

The remediation of historical pollution and the development of systems for special waste streams must proceed in parallel with municipal reform. Non-sanitary and illegal landfills require prioritisation according to environmental risk, followed by closure, remediation and monitoring. Construction and demolition waste, sewage sludge, ash, batteries, waste oils and other special streams need dedicated collection and treatment routes. Where recovery is technically and environmentally justified, these materials can replace primary resources; where it is not, secure final sinks and long-term monitoring remain necessary.

Finally, the green transition must include social and institutional development. Public participation, communication and convenient collection services are essential for source separation. Local administrations and public utility companies require training in planning, procurement, data management and facility operation. The development of recycling, repair, remanufacturing and digital services can generate new employment, but job quality, occupational safety and formalisation of informal collection activities must be addressed. Waste management reform should therefore be viewed as an industrial and social development policy, not only as an environmental compliance task.

Table 2. Priority actions for the green transition of the Serbian waste management system

Strategic priority	Key actions	Expected contribution
Waste hierarchy and regional systems	Prevention, separate collection, sorting, biowaste treatment, recovery and sanitary disposal	Lower landfilling and better use of material and energy resources
Sustainable financing and EPR	Cost-reflective tariffs, social safeguards, producer responsibility, control of free riders	Stable operation and stronger investment capacity
Data and digitalisation	Interoperable reporting, electronic tracking, GIS, performance indicators	Greater transparency, traceability and evidence-based planning
Historical pollution and special streams	Risk-based remediation, dedicated collection and treatment routes	Reduced environmental liability and safer final management
Human and institutional capacity	Training, public participation, formalisation and occupational safety	Higher service quality, public trust and green employment

Source: Authors' synthesis based on the reviewed legislation, strategies and reports.

DISCUSSION

The analysis indicates that Serbia's waste management transition is primarily constrained not by the absence of strategic direction, but by the capacity to convert that direction into coordinated operational change. The legal framework already recognises prevention, recycling, regionalisation, producer responsibility and controlled disposal. Nevertheless, physical waste flows remain dominated by large industrial and energy-related streams, mixed municipal collection and disposal. This confirms that regulatory alignment is a necessary but insufficient condition for green transition. A central policy risk is the creation of new infrastructure without simultaneously developing separate collection, markets, operating revenues and institutional competence. Regional facilities can improve environmental performance, but only if designed as integrated systems rather than as extensions of landfill capacity. Conversely, decentralised measures such as home composting, local collection points and reuse schemes may be more suitable in some rural or low-density areas. The transition therefore requires differentiated regional solutions within a common national framework. The green transition also changes the economic meaning of waste management. Better separation and traceability can turn part of the waste stream into a source of secondary materials and local business activity, while remediation and safe disposal reduce long-term environmental liabilities. Digital systems can support this change by making flows and performance visible, but their value depends on data governance and institutional use. The most realistic path is therefore a phased approach that combines regulatory enforcement, targeted infrastructure, sustainable financing, reliable data and continuous public participation.

CONCLUSION

Serbia has made substantial progress in developing a legislative and strategic framework compatible with European waste and circular economy policy. Regionalisation, organised collection and reporting have advanced, while recent laws and programmes provide a clearer basis for prevention, recovery, producer responsibility and safe disposal. However, the current system remains strongly dependent on landfilling, and important limitations persist in primary separation, recycling and biological treatment, financing, data quality, local implementation and the remediation of non-compliant disposal sites. The future of waste management in Serbia depends on integrating infrastructure with economic, institutional, digital and social measures. Priority should be given to separate collection, regional systems designed around the waste hierarchy, full implementation of extended producer responsibility, sustainable cost recovery, digital traceability, dedicated solutions for special waste streams and risk-based remediation of historical pollution. If these elements are developed in a coordinated manner, waste management can become an important driver of resource efficiency, innovation, green employment and Serbia's broader transition towards a circular and low-carbon economy.

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PLANNING AND IMPLEMENTING MSW SOURCE SEPARATION SYSTEMS: INSIGHTS AND CHALLENGES FROM SERBIA

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Abstract: Municipal solid waste (MSW) source separation is a key prerequisite for improving recycling performance and reducing landfill dependency within emerging circular economy systems. However, many transition countries still face significant technical, economic and institutional barriers in the implementation of separate collection systems at municipal level. This work presents experiences from the planning and implementation of municipal source separation systems in Serbia, based on activities conducted across seventeen municipalities with different demographic and spatial characteristics. A dedicated methodology was developed for estimating required bins, containers and collection vehicles using data on population structure, housing typology, waste generation and composition, collection logistics and transport distances. In parallel, investment requirements for introducing separate collection infrastructure were assessed at municipal and regional level. The implementation process revealed several operational challenges typical for transition economies, including workforce shortages, limited institutional capacity, delayed commissioning of equipment, lack of downstream treatment infrastructure and difficulties in market placement of collected recyclables. Despite these constraints, monitoring results from participating municipalities demonstrated that measurable improvements are achievable once infrastructure rollout is combined with communication activities and institutional support. The presented experiences highlight the importance of integrating technical planning, financial considerations and operational preparedness when developing municipal source separation systems in transition contexts.

Keywords: *Municipal waste, source separation, circular economy, system planning, Serbia*

INTRODUCTION

Rapid urbanization, population growth, and economic development have influenced the generation of increasing amounts of municipal solid waste (MSW). MSW management has been and will continue to be one of the major issues facing countries worldwide, especially in the cities of countries in transition and developing countries (Dong et al., 2001). Global municipal solid waste generation reached approximately 2.01 billion tonnes in 2016 and is

projected to increase to 3.40 billion tonnes by 2050. Landfilling remains the dominant disposal practice worldwide, contributing not only to the loss of valuable secondary resources but also to significant greenhouse gas emissions. In 2016, solid waste treatment and disposal generated an estimated 1.6 billion tonnes of CO₂-equivalent emissions, accounting for approximately 5% of global greenhouse gas emissions, with this figure expected to increase to 2.6 billion tonnes of CO₂-equivalent by 2050 if current waste management practices remain unchanged. These trends highlight the need for well-planned source separation systems capable of increasing recycling rates, reducing landfill dependency, and mitigating greenhouse gas emissions associated with municipal waste management (Kaza et al., 2018). Past research has identified factors influencing the elements of waste management systems. According to Hazra and Goel (2009), an improper bin collection system, old and inadequate vehicles, poor route planning, lack of information about collection, and insufficient infrastructure affect collection and transport practices. Some studies have shown that an inadequate supply of waste containers and longer distances to these containers increase the likelihood of waste dumping in open areas and on roadsides (Tadesse et al., 2008). Also, the number of fractions that people separate and collect at home increases as the distance to the recycling bins decreases (Gonzalez-Torre and Adenso-Diaz, 2005). Regulation factors, financial support for recycling projects, and organization of the informal sector are reasons why some municipalities have better recycling habits (Nissim et al., 2005; Sharholly et al., 2008).

Municipalities that are usually responsible for waste management in the cities have the challenge to provide an efficient and effective system, but they often face problems due to a lack of organization, financial resources, and system complexity (Burnley, 2007). With limited resources, backward technologies for waste treatment and disposal, and ineffective enforcement of relevant regulations, serious problems in MSW management exist in countries in transition, especially in the field of safe disposal and efficient recycling of MSW, leading to concern about how to improve MSW management in these countries (Chen et al., 2010; Jiang et al., 2009).

Support from local authorities, an adequate legal framework, and strategic plans for waste management that allow monitoring and evaluation annually can contribute positively to the development of the integrated waste management system (Asase et al., 2009; Guerrero et al., 2013).

Waste management data are critical to creating policy and planning for the local context. Understanding how much waste is generated, especially with rapid urbanization and population growth, as well as the types of waste being generated, allows local governments to select appropriate management methods and plan for future demand. This knowledge allows governments to design systems with a suitable number of vehicles, establish efficient routes, set targets for diversion of waste, track progress, and adapt as waste generation patterns change. With accurate data, governments can realistically allocate budget and land, assess

relevant technologies, and consider strategic partners, such as the private sector or nongovernmental organizations, for service provision (Kaza et al., 2018).

Municipal solid waste (MSW) source separation is a fundamental prerequisite for increasing recycling rates, reducing landfill dependency, and supporting the transition towards a circular economy. While separate collection systems are well established in many European Union Member States, countries in the Western Balkans continue to face significant challenges related to limited collection coverage, insufficient recycling infrastructure, weak institutional capacity and continued reliance on landfilling (European Environment Agency [EEA], 2022). According to Eurostat (2023), approximately 49% of municipal waste generated in the EU-27 was recycled, whereas Serbia recycled less than 5% of its municipal waste, indicating a substantial gap between current performance and the recycling targets established by the revised Waste Framework Directive (European Commission, 2018). The effectiveness of municipal source separation systems depends on integrated planning, appropriate infrastructure dimensioning, optimized collection logistics, sustainable financing mechanisms and active citizen participation (Albizzati et al., 2023; Dubois et al., 2020). However, these elements remain insufficiently developed in many transition economies, where financial constraints, fragmented institutional responsibilities, shortages of qualified personnel and limited downstream treatment capacity continue to hinder successful implementation (EEA, 2022).

To support the introduction of municipal source separation systems in Serbia, a national programme was implemented across seventeen municipalities involving the procurement of bins, containers and collection vehicles, accompanied by public communication and awareness campaigns, with a total investment exceeding EUR 8 million. This initiative provided a unique opportunity to evaluate planning assumptions, infrastructure dimensioning, investment requirements, and the practical challenges encountered during the early implementation phase under real municipal conditions.

The objective of this work is to present an integrated planning approach for municipal source separation systems and to discuss the technical, economic, and operational lessons learned that may support the implementation of similar systems in other transition economies.

METHODOLOGY

The planning methodology was developed to estimate the infrastructure and investment requirements for municipal source separation systems. The required numbers of bins, containers and collection vehicles were calculated using quantitative indicators derived from established approaches to municipal waste collection planning, incorporating demographic characteristics, housing typology, waste generation, collection logistics and transport distances (Albizzati et al., 2023; Tchobanoglous et al., 1993). Input data included population, households (individual vs collective), waste generation per capita, composition and density, settlement typology (number and size of settlements, distance from main town), and

operational logistics (vehicle capacity, loading times, travel distances). Equipment needs were calculated separately for “door-to-door” and “bring-point” systems, aggregated at the municipal level and corrected for existing equipment. Vehicle utilization rates and requirements for residual and co-mingled fractions were derived from daily collection quantities, assumed utilization, and total collection–transport–unloading cycle time. Investment needs were estimated by multiplying net equipment quantities by unit prices.

RESULTS AND DISCUSSION

Application of the methodology enabled harmonized equipment and investment plans for all 17 municipalities. The aggregated proposal included: 26 waste collection vehicles (12–20 m³); 87,183 bins of 240 L; 1,788 containers of 1.1 m³ (co-mingled recyclables) and 1,357 containers of 1.1 m³ (glass). Based on planning, implementation, and monitoring feedback, lessons were grouped as follows:

- Technical dimensioning and system design - methodology enabled municipalities to quantify bin, container and vehicle needs based on settlement typology, waste generation and logistics; sizing was sensitive to population density, housing structure and distance to regional centres, confirming that uniform system designs are unsuitable in transition contexts; integration of new recyclables routes required optimization of frequencies and routing, particularly in dispersed rural areas.
- Economic considerations - CAPEX for basic separate collection infrastructure was feasible when externally co-financed; standalone municipal financing would have been insufficient in most cases; OPEX increased due to additional routes, reduced payload utilization and workforce needs; downstream market conditions influenced economic performance, highlighting the need for contractual arrangements with regional facilities and buyers.
- Operational constraints - workforce shortages (drivers and collection crews); slow distribution of bins; non-operational waste separation lines (WSLs); lack of contractual acceptance models at RWMCs; data gaps for municipal-level monitoring.

Overall, the implementation experience demonstrated that infrastructure procurement alone does not guarantee successful source separation. The effectiveness of the system depended on coordinated planning, institutional readiness, and continuous communication with citizens. The practical implications of these findings are reflected in the monitoring results obtained after system deployment. These findings are consistent with recent European guidance emphasizing that technical infrastructure should be complemented by organizational and behavioural measures to ensure long-term system performance (Dubois et al., 2020; Albizzati et al., 2023).

The effectiveness of the implemented source separation system was evaluated using monthly monitoring data from participating municipalities. An example of the early performance

achieved in the municipality of Bajina Bašta is presented in Figures 1 and 2. Figure 1 shows the increase in the percentage of municipal solid waste prepared for recycling, whereas Figure 2 illustrates the monthly quantities of separately collected recyclable fractions.

Percentage of total MSW prepared for recycling

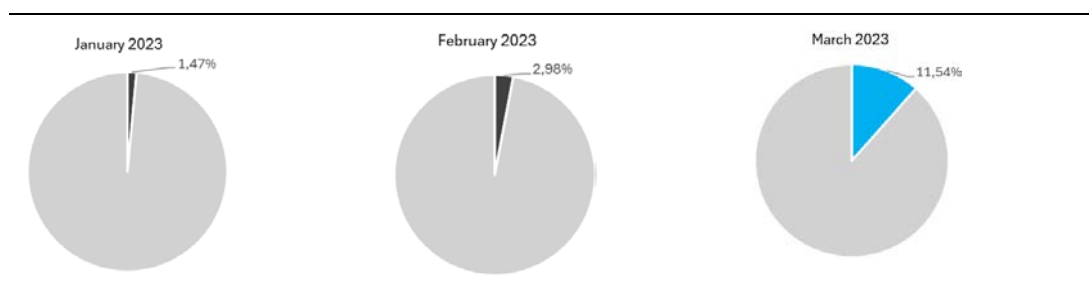


Figure 1. Percentage of municipal solid waste prepared for recycling during the first three months following the implementation of source separation activities in Bajina Bašta municipality

The proportion of municipal solid waste prepared for recycling increased from 1.47% in January to 11.54% in March, indicating rapid improvement after the introduction of separate collection infrastructure and public awareness activities.

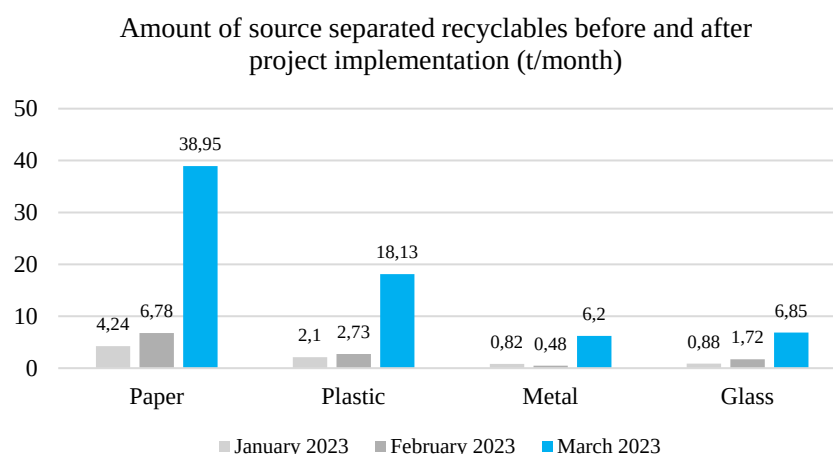


Figure 2. Monthly quantities of separately collected recyclable fractions during the first three months following the implementation of the source separation system in the municipality of Bajina Bašta

Paper and plastic represented the dominant recyclable fractions, while all monitored materials exhibited a continuous increase during the monitoring period, demonstrating the progressive stabilization of the newly established collection system.

Despite these constraints, performance data (for example, of Bajina Bašta municipality) demonstrate that measurable improvements are achievable once equipment rollout and communication campaigns are combined. In this case, the share of separately collected recyclables prepared for market supply increased from negligible levels to more than 11.5 %, indicating that infrastructural and behavioral measures can reinforce each other even in low-performing waste systems.

CONCLUSION

The experience gained from planning and implementing municipal source separation systems in seventeen Serbian municipalities demonstrates that successful implementation requires the integration of technical planning, economic assessment, and operational preparedness. The proposed methodology enabled a systematic estimation of collection infrastructure requirements based on demographic characteristics, housing typology, waste generation, settlement structure and transport logistics, providing a practical tool for supporting municipal decision-making during the planning phase.

The implementation process confirmed that infrastructure procurement alone is insufficient to ensure the effective operation of source separation systems. Several constraints typical for transition economies were identified, including workforce shortages, delays in equipment deployment, insufficient downstream treatment capacity, limited market opportunities for collected recyclables, and inadequate institutional coordination. These challenges significantly influenced the pace of implementation and highlighted the importance of considering operational readiness alongside technical system design.

Despite these constraints, monitoring results demonstrated that measurable improvements in separate collection performance can be achieved when infrastructure deployment is combined with communication activities and institutional support. The observed increase in the quantities of separately collected recyclables confirms that appropriately dimensioned collection systems, supported by public awareness campaigns and coordinated municipal management, can substantially improve recycling performance even under constrained operating conditions.

The presented experiences indicate that the proposed planning methodology is transferable to other municipalities facing similar demographic, financial, and institutional conditions. By integrating technical, economic, and operational aspects into a single planning framework, the approach provides practical support for municipalities and policymakers seeking to establish efficient and sustainable source separation systems within emerging circular economy frameworks.

Future research should focus on long-term monitoring of system performance, optimization of collection frequencies and transport logistics, assessment of citizens' participation, and evaluation of the economic and environmental benefits achieved after full implementation of source separation systems.

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APPLICATION OF IOT-BASED ENVIRONMENTAL MONITORING AND HYBRID ANN MODELING FOR AIR QUALITY AND OCCUPATIONAL SAFETY AT CONSTRUCTION SITES

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Abstract: Environmental pollution and occupational health risks resulting from construction activity is caused primarily by pollutants, such as particulate matter (PM) and nitrogen dioxide (NO₂). Traditional environmental monitoring techniques do not provide sufficient temporal resolution to adequately capture the rapidly changing levels of pollutants present at construction sites. This study utilizes an integration of Internet of Things (IoT) based environmental monitoring and hybrid Artificial Neural Networks (ANN) based predictive models to provide real-time management of air quality. Field measurements were taken from deployed IoT sensors consisting of RS-MG111-WIFI-1 air pollutant detection sensors and CC-M12 meteorological stations with a temporal resolution of 5 minutes. A hybrid modeling framework was developed, combining physical dispersion principles of pollutant emissions and the predictive capabilities of an ANN. The measured pollutant concentrations were shown to have significant temporal variability, with construction activity being the primary cause of the variability; however, meteorological variables had little impact on pollutant concentrations under steady-state conditions. The ANN model produced very high predictive accuracy ($R^2 = 0.87$), thereby demonstrating its ability to make real-time predictions regarding pollutant concentrations. The proposed method will help improve occupational health and safety, aid in the management of environmental pollutants from construction activities, and help facilitate the realization of sustainable and climate-resilient construction methods.

Keywords: *IoT, air quality; PM₁₀; ANN; construction site; occupational safety; environmental monitoring.*

INTRODUCTION

The construction industry is key for the economic growth and advancement of a nation; however, it is also one of the most significant sources of environmental pollution and occupational health hazards. The most significant pollutants generated at construction sites are particulate matter (PM_{2.5} and PM₁₀), which can enter the deepest recesses of the respiratory system and cause serious illnesses. In addition, gaseous pollutants such as nitrogen dioxide (NO₂) add to air quality deterioration. Workers in the construction industry are especially susceptible because they are often exposed to variable levels of pollutants for

prolonged periods. In addition, the surrounding community may also be affected because substantial construction activity occurs in densely populated areas, such as cities. As a result, monitoring and controlling air quality has become essential for protecting both workers and the environment. (WHO, 2021)

Conventional methods of monitoring environmental conditions generally require numerous fixed monitoring stations, performing infrequent sampling, and fail to adequately capture the wide ranges of temporally variable sources of pollutants you could find around a construction site. The advent of Internet of Things (IoT) technologies in the last couple of years has enabled continuous, real-time surveillance of environmental parameters by means of interconnected sensor networks.

Because construction sites are rapidly changing, micro-environments where the emission of pollutants is not continuous but depends on short-term tasks such as excavation, cutting concrete, delivering materials to the site, driving vehicles on and off the site to transport goods or services, and disposing of excess materials, average daily or hourly monitoring periods may provide a false indication of short-term exposures that could put the health and safety of construction workers at risk and compromise effective environmental management at the site level. Therefore, real-time monitoring is essential in the workplace when exposure levels can change so rapidly and unexpectedly. (EEA, 2023)

Despite being heavily used in the research of pollution in urban areas, the combined use of IoT based air quality monitors with machine learning models remain largely underappreciated in the fields of construction occupational safety. Currently the majority of works in this area are either focusing solely on monitoring the environment or developing predictive models, with some having started to explore how best to create a practical decision support system for construction managers that includes both real-time sensing, meteorological data and predictive algorithms. Meanwhile, improvements in data analytics and machine learning are providing new opportunities for enabling predictive modelling of environmental systems. Artificial Neural Networks (ANNs) are a perfect example of how to model complex, and nonlinear relationships between a number of variables, and therefore have a potentially high place in the environmental monitoring industry. (Kumar et al., 2015; Morawska et al., 2018; Rai et al., 2017; Zhang et al., 2020).

The main objectives of this study are:

- to implement an IoT-based environmental monitoring system at a construction site,
- to analyze the temporal variability of pollutant concentrations,
- to evaluate the influence of meteorological parameters,
- and to develop a hybrid ANN model for predicting PM₁₀ concentrations.

MATERIALS AND METHODS

The research was carried out on a working city's construction project in Belgrade in September 2025 with lots of work taking place (excavating, transporting materials, and performing all types of construction work). The area and surrounding buildings are within a city so the amount of vehicle traffic close to the construction site caused a large amount of emissions. The main sources of emissions at the construction site were excavating, moving equipment on site, storing materials on site, transporting soil and debris, and handling construction waste with machine equipment. The location of the monitoring station was placed in a representative area of the construction site. This location was selected to be close enough to the actual construction site to capture emissions caused by construction, but far enough to be protected from direct mechanical damages and obstructions from the construction work. Measurements of emissions were taken while the site was actively working with a majority of the construction work being performed between the hours of 07:00 a.m. and 05:00 p.m. Monitoring equipment to measure emissions was installed in an area of the site that would be representative of all emissions from the main sources of emissions associated with the construction.

The monitoring system consisted of:

- RS-MG111-WIFI-1 sensor for PM_{2.5}, PM₁₀, and NO₂ measurements,
- CC-M12 meteorological station for temperature, relative humidity, wind speed, wind direction, and atmospheric pressure.

All sensors were installed in a protective housing and connected to a cloud-based platform via Wi-Fi/4G communication. Measurements were recorded at 5-minute intervals, enabling high-resolution analysis of temporal variability. Collected data were processed using a multi-step approach:

1. Data validation and removal of outliers,
2. Calculation of descriptive statistics (mean, maximum, standard deviation),
3. Identification of pollution peaks,
4. Correlation analysis between pollutants and meteorological parameters.

Measured values were compared with international air quality guidelines (e.g., WHO standards) to assess exceedances and potential risks.

The dispersion of pollutants in the atmosphere can be described using the advection–diffusion equation, which accounts for transport, diffusion, and emission sources. However, due to the complexity and variability of construction activities, deterministic models alone are often insufficient. At construction sites, pollutant concentrations are primarily influenced by localized emission sources, such as machinery operation and material handling, rather than large-scale atmospheric processes.

Artificial Neural Network (ANN) Model

To address the limitations of physical models, an ANN-based predictive model was developed.

Input variables:

- Temperature (T),
- Relative humidity (RH),
- Wind speed (WS),
- Wind direction (WD),
- PM_{2.5} concentration.

Output variable:

- PM₁₀ concentration.

The dataset was divided into training (70%), validation (15%), and testing (15%) subsets. A feedforward neural network with one hidden layer was used. The ANN structure consisted of an input layer containing five predictor variables, one hidden layer with nonlinear activation functions, and one output neuron representing predicted PM₁₀ concentration. Input data were normalized before training in order to reduce the influence of different measurement units and improve convergence. The training process was repeated until the validation error reached a stable minimum, while the testing subset was used only for independent model evaluation. (LeCun et al., 2015; Bishop, 2006)

Model performance was evaluated using:

- Mean Squared Error (MSE),
- Coefficient of determination (R²).

RESULTS AND DISCUSSION

The analysis of measured data revealed significant variability in pollutant concentrations. PM₁₀ concentrations showed frequent exceedances of recommended limits, particularly during peak construction activities. PM_{2.5} values followed similar trends, although at lower magnitudes. NO₂ concentrations were generally lower but exhibited occasional peaks associated with machinery operation.

Table 1. Descriptive statistics (in µg/m³)

Parameter	Mean	Max	Std Dev
PM _{2.5}	38.5	112.3	21.4
PM ₁₀	64.2	185.7	35.8
NO ₂	29.1	71.5	14.2

Temporal analysis showed that pollutant concentrations were strongly influenced by construction activities. Peak values were observed during:

- excavation works,
- transportation of materials,
- intensive mechanical operations.

These findings confirm that local emission sources play a dominant role in air pollution at construction sites.

Correlation analysis indicated relatively weak relationships between pollutant concentrations and meteorological variables. This can be explained by the relatively stable weather conditions during the monitoring period and the dominance of local emission sources. However, wind direction was found to influence the spatial distribution of pollutants within the site, indicating its importance in exposure assessment.

The ANN model demonstrated strong predictive capability, with $R^2 = 0.87$. The model successfully captured nonlinear relationships between input variables and PM_{10} concentrations. The strongest relationship was observed between $PM_{2.5}$ and PM_{10} , which is expected because both pollutants originate from similar dust-generating activities. Wind speed showed a negative correlation with PM_{10} , suggesting that stronger air movement contributed to pollutant dispersion. Temperature and humidity had weaker effects, while wind direction influenced the spatial distribution of pollutants depending on the position of active emission sources.

The results indicate that $PM_{2.5}$ concentration is the most influential predictor, followed by wind speed. Temperature and humidity showed lower influence. The results highlight the limitations of traditional monitoring approaches and demonstrate the advantages of integrating IoT systems with machine learning models. The comparison between measured and predicted PM_{10} values showed that the ANN model successfully followed the general concentration trend and captured most pollution peaks. Minor deviations were observed during abrupt concentration changes, which may be explained by sudden construction activities not fully represented by meteorological input variables (US EPA, 2022; EC 2020).

The hybrid IoT–ANN approach enables:

- real-time monitoring and prediction,
- improved understanding of pollutant dynamics,
- proactive environmental management.

This represents a significant advancement over conventional methods, which are typically limited to either monitoring or modeling, but rarely both in an integrated framework.

This study provides a unique contribution by allowing the combination of two previously independent technologies (high resolution IoT monitoring and ANN prediction) into one

coherent system that allows for the management of construction sites. Unlike traditional methods of monitoring, which primarily provide historical data, the proposed system is capable of providing an interpretation of current air quality with regard to hazardous levels (i.e., PM₁₀) in the near real-time and as well as short-term prediction.

The authors would also like to acknowledge several limitations: the relatively brief nature of the monitoring period, the fact that the data were collected from one specific site, which limits the ability to generalize the findings beyond that site, and the limited number of input variables used in developing the ANN model. Further research should investigate the possibility of longer monitoring periods, multiple construction sites, the addition of other pollutants, noise, vibration, and more details about the types of activities that occur at construction sites. The proposed system provides a foundation for improving occupational safety by:

- enabling real-time identification of hazardous conditions,
- supporting decision-making,
- reducing worker exposure to pollutants.

The integration of predictive modeling further enhances safety by allowing anticipation of high-risk situations.

Based on the results, several practical measures can be implemented:

- scheduling activities to avoid peak pollution periods,
- applying dust suppression techniques,
- optimizing logistics,
- reducing worker exposure time.

These measures contribute to both environmental protection and occupational safety.

CONCLUSION

This study demonstrates the effectiveness of integrating IoT-based monitoring systems with ANN predictive modeling for managing air quality at construction sites.

The proposed approach provides:

- high-resolution data,
- predictive capability,
- improved decision-making support.

It contributes to safer, more sustainable, and climate-resilient construction practices.

The findings suggest that PM₁₀ pollution at construction sites is mainly activity-driven, while meteorological conditions modify pollutant dispersion rather than fully determine concentration levels. The ANN model showed good predictive performance and can be used

as a practical tool for early warning, exposure reduction and planning of dust-control measures.

Future research should focus on:

- expanding the monitoring system to include additional parameters,
- integrating advanced machine learning techniques,
- applying the approach in different environmental conditions.

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OPERATIONAL FAILURE AND MICROBIOLOGICAL RISKS IN DECENTRALIZED DRINKING WATER SYSTEMS: EVIDENCE FROM TRIPOLI, LIBYA

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Abstract: Safe drinking water is a fundamental determinant of public health. However, the increasing reliance on decentralized water treatment units in public facilities may pose health risks if maintenance and monitoring are inadequate. This study aimed to evaluate the quality of drinking water produced by decentralized treatment units Reverse Osmosis (RO) Treatment Unit System in Hay Al-Andalus Municipality, Tripoli, Libya, and assess compliance with Libyan standards and World Health Organization (WHO) guidelines. A descriptive analytical study was conducted on 12 water treatment units, Randomly selected from a total of 25 treatment units. Physical (turbidity, electrical conductivity), chemical (pH, total dissolved solids), and microbiological (total coliforms, *Escherichia coli*, fungi, and yeasts) analyses were performed following American Public Health Association standards (APHA, 2017). Data were analyzed using SPSS with descriptive statistics, One-Sample T-test, and ANOVA (Tukey's test), correlation at ($p < 0.05$). Results showed a complete absence of maintenance practices across all units. While most physicochemical parameters were within permissible limits, microbiological contamination was detected in the majority of samples. Significant differences were observed between measured values and standard limits. The study concludes that water quality deterioration is primarily due to poor operation and maintenance rather than treatment technology. Immediate regulatory and technical interventions are recommended.

Keywords: *Drinking water quality, decentralized treatment, microbiological contamination, public health, Libya*

INTRODUCTION

Access to safe drinking water is essential for human health and well-being. According to the World Health Organization, over two billion people globally consume contaminated water, leading to waterborne diseases such as diarrhea, cholera, and typhoid (Organization 2022). In recent years, decentralized water treatment units have been widely adopted in public institutions to improve water accessibility. However, improper maintenance and lack of

monitoring may transform these systems into sources of contamination (Edzwald 2011). Poorly maintained filtration systems can facilitate the accumulation of chemical contaminants and microbial growth, including total coliforms and *E. coli* (Baird, Rice, and Eaton 2017). In Libya, particularly in Tripoli, reliance on such systems has increased, yet limited studies have assessed their performance. Despite their widespread use, decentralized Reverse Osmosis (RO) systems are particularly vulnerable to operational failure when maintenance protocols are not strictly followed. Inadequate system management can lead to microbiological contamination even when physicochemical parameters appear acceptable. Previous studies have highlighted that the absence of routine disinfection and monitoring significantly increases public health risks in such systems. However, comprehensive assessments integrating operational performance with microbiological and physicochemical quality remain limited, particularly in developing urban settings. Therefore, this study evaluates drinking water quality from decentralized treatment units in Hay Al-Andalus Municipality and compares results with national and international standards. Despite the widespread use of decentralized reverse osmosis (RO) systems in public facilities in Tripoli, there is a lack of systematic evaluation of their operational performance and water quality. In particular, the impact of inadequate maintenance and monitoring on microbiological safety remains insufficiently investigated. This gap raises concerns regarding the reliability of these systems as safe drinking water sources and highlights the need for comprehensive assessment.

MATERIALS AND METHODS

This study was conducted in Hay Al-Andalus Municipality, Tripoli, Libya. A total of 12 reverse osmosis (RO) treatment units were randomly selected from 25 available units. Sampling was performed in triplicate and repeated twice, yielding 72 water samples. Samples were collected in sterile containers in accordance with World Health Organization guidelines and transported at 4°C to the laboratory within 24 hours.

Water quality was assessed through physical, chemical, and microbiological analyses following standard methods of the American Public Health Association. Physical parameters included turbidity and electrical conductivity (EC), while chemical parameters comprised pH and total dissolved solids (TDS). Microbiological analysis targeted total coliforms, *Escherichia coli*, fungi, and yeasts. Turbidity was determined by nephelometry (NTU), EC by conductivity meter ($\mu\text{S}/\text{cm}$), pH by calibrated digital pH meter, and TDS by TDS meter or estimated from EC. Microbial analyses were performed using membrane filtration (0.45 μm) followed by cultivation on selective media, and results were expressed as CFU/100 mL for bacterial indicators and CFU/mL or CFU/100 mL for fungi and yeasts. Statistical analysis was conducted using IBM SPSS Statistics, where descriptive statistics (mean) were calculated, and inferential analyses including one-sample t-test, Tukey's post hoc test, and correlation analysis were applied to evaluate differences and relationships among variables. Statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

OPERATIONAL ASSESSMENT OF TREATMENT UNITS

Table 1. clearly indicates complete non-compliance (100%) with all essential operational and maintenance requirements across the studied treatment units. The absence of filter replacement, disinfection, and monitoring reflects a systemic failure in operational management. According to the World Health Organization, proper maintenance and continuous monitoring are critical components of safe water supply systems (Organization 2022).

Table 1. Operational checklist of decentralized water treatment units

Parameter	Yes (%)	No (%)
Regular filter replacement	0	100
Maintenance records available	0	100
System disinfection	0	100
Clean and closed storage tank	0	100
Regular quality monitoring	0	100
Leakage or corrosion present	100	0

The lack of these practices significantly increases the risk of microbial contamination. These findings are consistent with those reported by Michael, W (LeChevallier, Welch, and Smith 1996), who demonstrated that poorly maintained water systems can become reservoirs for microbial growth. Similarly, (Edzwald 2011) emphasized that inadequate maintenance leads to deterioration in water quality despite the presence of treatment technologies. Importantly, this operational deficiency provides a strong explanation for the microbiological contamination observed later in Table 3.

PHYSICOCHEMICAL CHARACTERISTICS OF WATER SAMPLES.

As presented in Table 2, pH values ranged from 5.8 to 7.2, with several samples (S2, S3, S5, S7, S10) falling below the recommended range (6.5–8.5) established by the World Health Organization. This indicates slight acidity, which may promote pipe corrosion and heavy metal leaching (WHO, 2017). TDS values ranged between 10 and 242 mg/L, well below the WHO guideline limit (1000 mg/L) as observed in table 2. While this indicates good removal of dissolved solids, extremely low values (e.g., S3 = 10 mg/L) may suggest over-treatment, which can reduce mineral content and affect water palatability.

Table 2. Physicochemical parameters of drinking water samples

Sample code	TDS (mg/L)	EC (μ S/cm)	pH	Turbidity (NTU)
S1	35	70	6.9	0.11
S2	25	49	6.0	0.10
S3	10	18	5.9	0.09
S4	47	94	6.3	0.14
S5	57	114	6.0	0.10
S6	28	55	6.4	0.08
S7	40	80	5.8	0.11

S8	118	235	6.2	0.12
S9	41	81	6.8	0.11
S10	40	79	6.1	0.08
S11	37	73	6.3	0.11
S12	242	484	7.2	0.08

EC values ranged between (18–484 $\mu\text{S}/\text{cm}$) were within acceptable limits ($<1500 \mu\text{S}/\text{cm}$). However, noticeable variation between samples reflects differences in source water quality or filtration efficiency. All turbidity values were extremely low ($<0.15 \text{ NTU}$) as shown in table 2., indicating effective removal of suspended particles. However, the World Health Organization emphasizes that low turbidity does not guarantee microbiological safety.

OVERALL INTERPRETATION

The physicochemical results suggest that water is acceptable in appearance and basic chemical quality, which aligns with findings by (Edzwald 2011). However, these parameters alone are insufficient to ensure safety without microbiological validation.

MICROBIOLOGICAL QUALITY OF WATER SAMPLES

Table 3 clearly demonstrates a widespread microbiological deterioration in the analyzed drinking water samples. The results significantly exceed permissible limits established by the World Health Organization, which require zero detection of total and fecal coliforms (0 CFU/100 ml) in potable water (WHO, 2022). This indicates that the studied decentralized treatment units are not ensuring microbiological safety. The total Bacterial Count (Heterotrophic Plate Count) ranges from 10 to 242 CFU/ml, with the highest contamination observed in sample S12. Such variability suggests inconsistent treatment efficiency and possible post-treatment contamination within the distribution system.

Table 3. Microbiological analysis of drinking water samples

Sample code	Total Count (CFU/ml)	Total Coliform (CFU/100ml)	Fecal Coliform	<i>Pseudomonas</i>	<i>Streptococci</i>	<i>Fungi</i>	<i>Yeasts</i>
S1	35	70	+	0	4	0	0
S2	25	49	+	0	2	0	0
S3	10	18	+	0	>100	>100	0
S4	47	94	+	0	53	0	0
S5	57	114	+	0	12	90	0
S6	28	55	+	0	>100	>100	0
S7	40	80	+	0	4	23	0
S8	118	235	+	0	>100	>100	0
S9	41	81	+	0	>100	>100	0
S10	40	79	+	0	>100	>100	0
S11	37	73	+	0	>100	>100	0
S12	242	484	+	0	3	6	0

Elevated heterotrophic counts are often associated with biofilm formation and regrowth in water systems. According to (Edberg et al. 2000), high heterotrophic bacterial levels may not always indicate direct pathogenic risk but reflect favorable conditions for microbial survival and potential pathogen persistence. Recent studies (Prest et al. 2016 ;Organization 2022) further confirm that elevated HPC levels are linked to inadequate disinfection and poor infrastructure maintenance. The total and Fecal Coliform Bacteria, all samples tested positive for fecal coliforms, with total coliform counts reaching up to 484 CFU/100 ml (S12). This represents a critical violation of drinking water standards and strongly indicates recent fecal contamination, posing serious public health risks due to potential presence of pathogens such as *Escherichia coli*, *Salmonella*, and enteric viruses. These findings strongly support the conclusions of (LeChevallier, Welch, and Smith 1996), who demonstrated that the presence of coliform bacteria in treated water reflects either ineffective disinfection or contamination within distribution systems. More recent research confirms that decentralized systems are particularly vulnerable to such contamination when monitoring and maintenance are inadequate. High levels of Streptococci (Fecal Indicator Bacteria) , exceeding 100 CFU in several samples (S3, S6, S8–S11), provide additional confirmation of fecal or environmental contamination. These organisms are considered more reliable indicators of persistent fecal pollution, especially in comparison to coliforms. A recent study by (Bain et al. 2018) highlighted that fecal streptococci are strong indicators of contamination from human and animal waste, particularly in urban systems with compromised sanitation infrastructure. Fungal counts exceeding 100 CFU were recorded in multiple samples, whereas yeasts were largely absent. The presence of fungi at such high levels suggests: Biofilm formation within pipes, water stagnation, and insufficient or ineffective disinfection processes. Recent findings by (Wang et al. 2014) indicate that fungi are integral components of biofilms in drinking water systems and can enhance microbial resistance to disinfectants, thereby compromising water safety. The absence of *Pseudomonas* spp. across all samples may appear favorable; however, it does not offset the significant microbiological risks indicated by the presence of coliforms and streptococci. The latter remain more critical indicators of contamination and health risk. The microbiological profile of the samples indicates: Failure of disinfection processes, Possible regrowth of microorganisms, and poor operation and maintenance of decentralized treatment units. These results align with the findings of LeChevallier, who emphasized that inadequate maintenance promotes microbial proliferation even after treatment (LeChevallier, Welch, and Smith 1996). Similarly, (Alfadul and Khan 2011) reported microbial contamination in treated water under insufficient monitoring conditions. The results clearly demonstrate that microbiological safety is not achieved, despite any acceptable physicochemical characteristics. This represents a serious public health concern and highlights the urgent need for: Improved and consistent disinfection (e.g., chlorination control), Regular maintenance of distribution systems, and implementation of rigorous microbiological monitoring programs.

CORRELATION BETWEEN VARIABLES

The correlation results obtained in this study demonstrate a strong and systematic relationship between physicochemical and microbiological water quality parameters, as reflected in the Pearson analysis of the dataset. Specifically, strong positive correlations between TDS, EC, total bacterial count, and total coliforms indicate that increases in dissolved ions are closely associated with increased microbial contamination levels. This finding is consistent with recent literature on drinking water quality assessment. The extremely strong correlation observed between TDS and EC ($r \approx 1.00$) is scientifically expected, as both parameters measure the ionic content of water. Recent research confirms this relationship, showing that EC is a reliable proxy for estimating TDS in water systems due to their shared dependence on dissolved salts and ions (Dewangan and Shrivastava 2024). Similarly, a study in a hydrogeochemical context reported a strong statistical correlation ($R^2 = 0.98$) between EC and TDS across different water sources, confirming their near-linear relationship. This supports the present findings, where both parameters behaved almost identically across samples, reinforcing their redundancy in correlation-based water quality interpretation. The strong association between TDS/EC and microbial indicators (total coliforms and total count) suggests that higher mineral and ionic loads are indirectly linked to microbial proliferation. This pattern has been reported in multiple environmental studies. For example, Aram and colleagues found that physicochemical parameters such as conductivity and TDS were positively correlated with coliform contamination in groundwater systems, indicating that degraded geochemical quality often coexists with microbial pollution (Aram, Saalidong, and Osei Lartey 2021). Similarly, a study on drinking water systems confirmed that TDS and EC show positive associations with total coliform presence across multiple environmental conditions (Gomaa et al. 2022). These findings strongly align with the present study, where microbiological contamination increased in parallel with rising physicochemical loads. In contrast, pH showed weak or negligible correlation with microbial indicators, confirming that pH alone is not a reliable predictor of microbial contamination. This is supported by recent studies indicating that microbial survival is influenced more by nutrient availability and system hygiene than by minor pH variations. Similarly, turbidity showed only moderate correlation with microbial parameters. Recent research has demonstrated that water can remain microbiologically unsafe even when turbidity is low, due to the presence of dissolved or biofilm-associated microorganisms that are not reflected in turbidity measurements (Organization 2022; Bain et al. 2018). Moderate to strong correlations between *Streptococci*, *fungi*, and *coliform* indicators reinforce their role as supplementary contamination markers. Recent studies have shown that *fecal streptococci* are highly reliable indicators of persistent fecal pollution, especially in environments affected by inadequate sanitation systems (Bain et al. 2018). In addition, fungal presence in drinking water systems has been linked to biofilm development and microbial persistence within distribution networks, which enhances the survival of pathogenic organisms even after treatment (Wang et al. 2014). Overall, the combined evidence from this study and recent literature indicates that: Physicochemical

indicators such as TDS and EC are strongly associated with microbial contamination, pH and turbidity are weak predictors of microbiological safety, and Microbial indicators (*coliforms*, *streptococci*, *fungi*) provide a more direct assessment of water safety. Water quality degradation is often systemic rather than isolated, reflecting distribution system failures rather than treatment inefficiency. This supports the conclusion that chemically acceptable water can still be microbiologically unsafe, a finding consistently emphasized in modern water safety research and WHO guidelines.

CONCLUSION

The results demonstrate a clear discrepancy between operational performance, physicochemical quality, and microbiological safety across all analyzed tables. Table 1 confirms a complete operational failure (100% non-compliance), which directly explains the microbial contamination observed in Tables 2 and 3. Although Table 2 shows acceptable physicochemical conditions (low turbidity, acceptable EC and TDS), these parameters alone are insufficient to ensure safety. In contrast, Table 3 reveals widespread microbiological contamination, including fecal coliforms and high heterotrophic bacterial counts, exceeding WHO limits. The correlation analysis further confirms strong associations between TDS, EC, and microbial indicators, while pH and turbidity show weak predictive value. Overall, the integrated findings highlight that physically acceptable water can still be microbiologically unsafe due to system failure rather than treatment inefficiency. Based on these findings, immediate actions are required, including the implementation of mandatory maintenance programs, continuous disinfection systems (e.g., chlorination or UV), and routine microbiological monitoring. In addition, adopting Water Safety Plans as recommended by the World Health Organization and enforcing regulatory inspections are essential to ensure safe drinking water quality. Operator training is also critical to improve system performance and sustainability.

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WORKPLACE NOISE ASSESSMENT IN A LABORATORY: A CASE STUDY FROM NOVI SAD, SERBIA

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Abstract: This study assess noise exposure in a laboratory for environmental and occupational monitoring at the Faculty of Technical Sciences, Novi Sad, Serbia. Measurements were conducted in accordance with ISO 9612:2025 at four characteristic measuring points related to typical laboratory activities, such as sample preparation, instrumental analysis and general ventilation. The equivalent continuous sound pressure levels ranged from 60.5 to 94.8 dB, with the highest value measured during sample analysis using atomic absorption spectrometer (AAS), caused by local ventilation. Daily noise exposure levels ($L_{EX,8h}$) were calculated and compared with the national regulation aligned with Directive 2003/10/EC. The results indicated that the lower action value of 80 dB(A) was exceeded only at one measuring point, with a value of 85.3 dB(A). This exposure occurs only occasionally, is short in duration and restricted to a specific area. The findings highlight that, although overall noise exposure in the laboratory is within acceptable limits, specific activities may pose an increased risk, emphasizing the importance of targeted preventive measures and continuous monitoring of noise levels.

Keywords: *Noise measurement; Laboratory; Workplace noise.*

INTRODUCTION

The increase in noise pollution is caused by rapid industrialization, urbanization, transportation development, and population growth, which is especially dominant in developing regions, where inadequate urban planning and overcrowding contribute to environmental noise (Al-Mutairi et al., 2009). However, workplace exposure remains predominantly important, especially in industrial and laboratory conditions where noise levels may be elevated. According to the World Health Organization (WHO), exposure to noise causes adverse psychological effects, making noise pollution a significant environmental and public health problem. Noise is recognized as one of the most harmful forms of modern pollution, primarily caused by human activities (Bouzir et al., 2017, Templeton et al., 2016).

Exposure to high levels of noise can cause not only physical effects, but also has a substantial impact on cognitive processes and mental well-being. Industrial epidemiological studies confirm that noise negatively affects attention, concentration, and overall cognitive performance (Kamp et al, 2003). A relevant concept in this context is auditory irritation,

which refers to feelings of discomfort, dissatisfaction, and emotional disturbance caused by disruptions in thought processes and daily functioning (Zamanian et al, 2012; Zamanian et al, 2013). Although individuals may develop a certain degree of adaptation to noisy environments, such adaptation does not eliminate the negative effects, and prolonged exposure continues to result in exhaustion and reduced work capacity (Saremi and Rohmer, 2008), as well as a greater likelihood of occupational accidents (Zamanian et al., 2014).

The relationship between noise and workplace safety is well established. Elevated noise levels are associated with increased error rates, particularly in tasks that require sustained attention, working memory, and precision, which is critical in complex systems (Zamanian et al, 2012). Laboratory and field studies further show that when tasks depend on the perception and interpretation of auditory signals, interfering noise can significantly impair performance. Sudden or unfamiliar loud sounds may also lead to distraction, agitation, and decreased task accuracy (Ising and Michalak, 2004). In this context, workplace accidents can often be interpreted as indicators of the adverse effects of noise on human performance. The assessment and management of noise exposure are essential for improving working conditions and protecting employee health. Modern approaches to noise assessment include measurement, analysis, and mapping techniques, which have proven effective in evaluating exposure levels.

Noise framework

In workplace environments, sound becomes an occupational hazard when it is supposed as physically or psychologically disturbing, particularly when it interferes with concentration and communication. Under such conditions, sound is no longer considered a neutral environmental factor but rather a pollutant, and its characterization shifts to noise. According to the National Institute for Occupational Safety and Health (NIOSH, 1998), noise in occupational settings is regarded as harmful when exposure exceeds 85 dB over an eight-hour work period, while extremely high levels, above 104 dB, pose an immediate risk.

From an acoustic perspective, noise can be broadly classified into steady and non-steady types. Steady noise includes sounds with either discrete or continuous frequency distributions, while non-steady noise is characterized by variations in intensity and frequency over time, making it less predictable and often more disruptive (Fredianelli et al., 2020).

The significance of workplace noise is further emphasized in international regulatory frameworks. The Occupational Safety and Health Administration (OSHA) identifies occupational noise as a major health concern and regulates it through the Occupational Noise Exposure Standard (29 CFR 1910.95). This standard requires the implementation of hearing conservation programs when workers are exposed to a time-weighted average of 85 dB over an eight-hour workday, while the permissible exposure limit (PEL) is set at 90 dB. Exposure durations must be reduced as noise levels increase; for example, at 95 dB, permissible exposure is limited to four hours per shift. NIOSH recommends an exposure limit of 85 dB

over an eight-hour period. Comparable guidelines have been adopted in Europe by the European Agency for Safety and Health at Work, where stricter criteria may apply depending on task complexity. Recommended noise levels in Germany for mentally demanding tasks are around 55 dB, with even lower thresholds suggested for continuous noise in office environments. In Serbia, occupational noise exposure is regulated in line with EU Directive 2003/10/EC, setting lower and upper action values at 80 dB and 85 dB, respectively, and a strict exposure limit of 87 dB (Official Gazette of the Republic of Serbia, 2019).

Sources of laboratory noise

Laboratories are specialized environments where noise exposure levels may be elevated, depending upon the nature of the experiments conducted and the number of individuals present. To effectively manage noise levels and ensure safe working conditions within laboratory environments, it is important to identify the various sources of noise. While each laboratory possesses different characteristics and equipment, several common sources are dominant across different types of laboratories.

A significant source of noise originates from equipment used in routine laboratory activities. The type and intensity of noise depend on the function of the laboratory. Chemical laboratories frequently use fume hoods, refrigerators, compressors, nitrogen generators, and freezers, all of which contribute to background noise. Quality control laboratories frequently utilize pneumatic injectors within gas or liquid chromatography systems. An important characteristic of laboratory noise is its temporal variability. Certain devices, such as ventilation systems or fume hoods, generate continuous noise, whereas others, like compressors operate occasionally.

The total noise level at any given moment represents the combined effect of multiple sources operating simultaneously. In addition to operational equipment, laboratories often contain secondary noise sources that are not directly related to experimental processes. These include telephones, and background music systems, which can further contribute to the overall noise level. External environmental factors may also significantly affect indoor noise conditions. Laboratories located near industrial zones or areas with heavy traffic are exposed to additional noise from vehicles and surrounding activities. Since noise is cumulative, the combination of internal and external sources can result in elevated sound levels. This may interfere with verbal communication, which typically occurs at around 50 dB, making it difficult for workers to communicate clearly and increasing the likelihood of misunderstandings and potential safety risks.

A similar risk is present in laboratories within educational institutions. Laboratory personnel, including technicians and research assistants, as well as students engaged in educational activities, are subjected to noise, which may lead to adverse health effects. This study was conducted to assess the noise levels in laboratory associated with environmental and occupational safety and health engineering education, where several noisy experiments are

performed for research and demonstration purposes. The aim of this paper is to assess different sources of noise in laboratory workplace.

MATERIALS AND METHODS

The noise was measured during students' exercises in laboratory for environmental and occupational monitoring, at the Faculty of technical sciences in Novi Sad, Serbia. Laboratory is periodically ventilated through doors and windows; however during experiments ventilation systems are used. Therefore, physical conditions in laboratory are not affected by outdoor noise sources such as traffic. Even though there are door crashes, speech and step sound from the workers and students during students' exercises in the laboratory, the test equipment used in the experiments establish the basic noise sources. Prior to in-situ measurements, field observation studies were performed to identify the most conducted experiments in laboratory. As a result, four different locations were selected for noise level measurement, which are presented in Figure 1. General ventilation system (MP3) is constantly used during working hours in laboratory, hence it presents background noise. During samples preparation fume hood is used (MP1). Analyses performed using an atomic absorption spectrometer (AAS) require the use of local ventilation (MP2), since gases such as nitrous oxide or acetylene are used in the flame technique. Analyses of organic compounds using a High-Performance Liquid Chromatograph (HPLC) are performed temporarily (MP4), and the instrument is turned off upon completion of the analyses.

Figure 1. Measuring points of noise levels in laboratory for environmental and occupational monitoring



Measurements were performed based on ISO standard 9612:2025. The measurements have been carried out with Sound Level Meter 1352A. The configuration of the sound level meter is as follows: range from 30 to 130 dB, spectrum used is fast time weighting and A frequency weighting, 31.5 Hz to 8 kHz. The measurements were repeated 3 times for each experiment.

RESULTS AND DISCUSSION

The mean values of the three measurements of noise levels ($L_{A,eq,Te}$) are shown in Table 1. As it could be seen from the Table 1, the equivalent level of exposure values varied between 60.5 and 94.8 dB. The highest noise level was measured during analysis of samples by AAS (94.8 dB), caused by local ventilation. The noise level of 75.4 dB measured during sample preparation (MP1) was indicated by fume hood. $L_{EX,8h}$ is defined as daily sound exposure level for a nominal 8 hours working day calculated according to ISO standard 9612:2025.

For comparing the noise exposure levels with the current standard, daily noise exposure levels ($L_{EX,8h}$) were calculated according to the assessed total duration of related laboratory activities during the day and were given in Table 1. Considering daily noise exposure levels, the highest noise exposure level was 85.3 dB during analyses of samples by AAS. The results were evaluated based on the applicable legislation in the Republic of Serbia. The following regulation was used in the assessment Rulebook on preventive measures for safe and healthy work when exposed to noise ("Official Gazette of the RS", No. 96/2011, 78/2015, 93/2019), harmonized with Directive 2003/10/EC of the European Parliament and of the Council on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise).

Table 1. Results of measured noise levels in laboratory

Measuring point	Related activities	Total duration for a day (h)	$L_{A,eq,Te}$ (dB)	$L_{EX,8h}$ (dB)
MP1	Sample preparation (Fume hood)	2.50	75.4	70.4
MP2	Sample analysis (AAS)	0.90	94.8	85.3
MP3	Ventilation	5.50	63.8	62.2
MP4	Sample analysis (HPLC)	2.30	60.5	55.1

Based on obtained results, it can be stated that the lower action value of $L_{EX,8h} = 80$ dB(A) was exceeded at only one measurement point (MP2) during sample analysis using AAS, primarily due to the operation of local ventilation. It is important to note that work involving AAS is conducted only occasionally, typically for less than one hour per day. Furthermore, the local ventilation system is activated only during the use of AAS and is turned off during

periods of inactivity, significantly limiting overall exposure. Additionally, the room for AAS sample analysis is situated at a distance from the classroom where students engage in educational activities and exercises, as well as from areas where researchers most frequently work. This spatial separation contributes to reducing noise exposure for both students and other laboratory personnel not directly involved in AAS operations.

Although the exposure is of limited duration, it is advisable to implement preventive measures to further mitigate noise levels and ensure adherence to occupational health standards. Such measures may include the regular maintenance and inspection of the local ventilation system to reduce unnecessary noise generation. Figure 2 presents an overview of the proposed mitigation measures for occupational noise management during AAS operation.

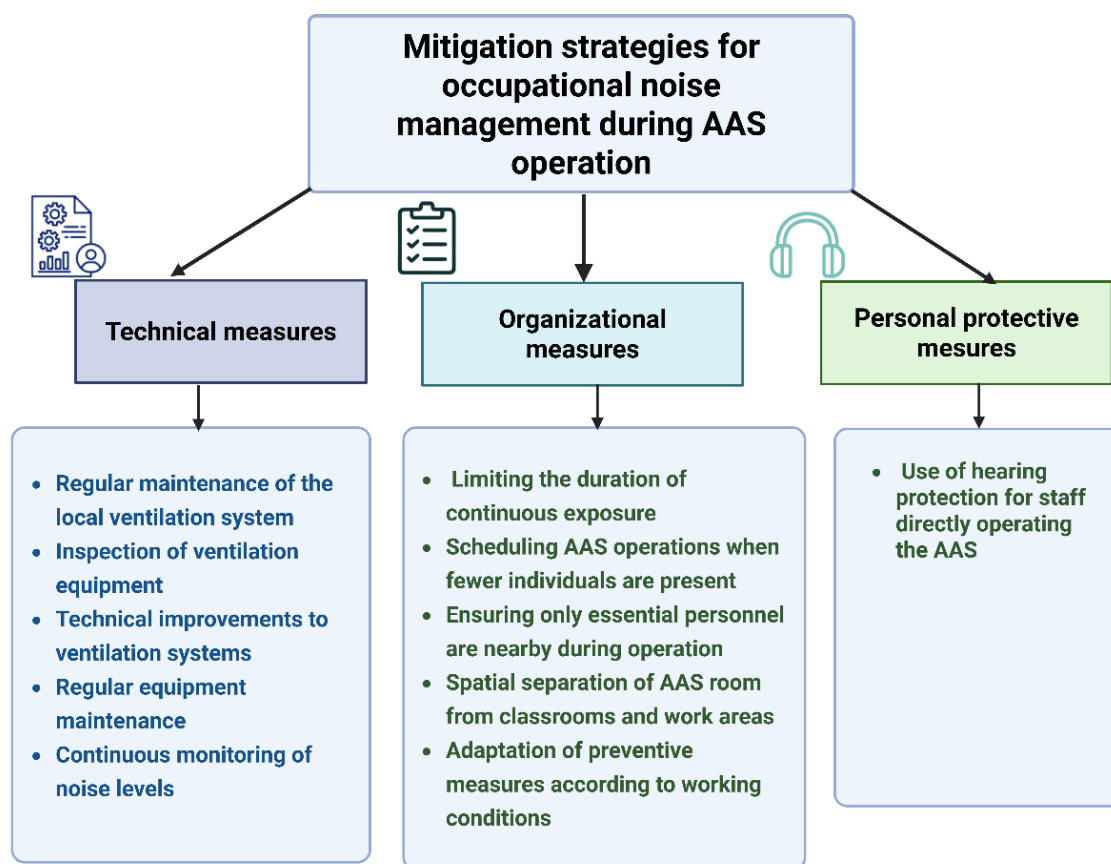


Figure 2. An overview of the proposed mitigation measures for occupational noise management during AAS operation

Additionally, organizational strategies, such as limiting the duration of continuous exposure, scheduling AAS operations when fewer individuals are present, and ensuring that only essential personnel are in the immediate vicinity during operation, can be advantageous. If necessary, the use of personal protective equipment, such as hearing protection, may be considered for staff directly operating the AAS, particularly during prolonged or repeated

measurements. Further improvements in laboratory noise control may be achieved through the implementation of advanced noise monitoring technologies, including smart systems such as wearable noise sensors and continuous real-time sound level monitoring. In this way, continuous monitoring and control of workers' exposure to laboratory noise can be achieved (Kanu et al., 2025) .

CONCLUSION

This study emphasizes the importance of systematic noise assessment in laboratory and provides a basis for improving working conditions through targeted noise management strategies. Continuous monitoring and adaptation of preventive measures are recommended to ensure long term protection of health and maintenance of optimal working performance.

Despite the limited nature of the identified risk, this study confirms that laboratory noise should not be neglected, particularly in laboratories where precision, concentration, and safety are essential. The implementation of preventive measures, including technical improvements to ventilation systems, regular equipment maintenance, and appropriate organizational practices can further minimize exposure. Additionally, the potential use of personal protective equipment should be considered for personnel directly involved in high-noise activities.

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PREVALENCE OF METABOLIC SYNDROME AMONG BANK EMPLOYEES AND THE IMPORTANCE OF WORKPLACE HEALTH PROMOTION

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Abstract: Workplace health promotion represents an important component of contemporary public health, particularly under conditions of increased exposure to stress and a sedentary lifestyle. Bank employees are especially vulnerable, as the specific conditions of their work—including prolonged sitting, a high level of responsibility, and time pressure—contribute to the development of chronic non-communicable diseases.

Metabolic syndrome (MS) is defined as a cluster of interrelated metabolic and haemodynamic disorders, including abdominal obesity, insulin resistance, dyslipidaemia, and arterial hypertension, which significantly increase the risk of developing type 2 diabetes mellitus and cardiovascular disease. Its prevalence is steadily rising, placing it among the leading public health problems of modern society.

Bank employees constitute a high-risk group owing to the combination of occupational stress and reduced physical activity, which favours the emergence of insulin resistance and abdominal obesity as key components of metabolic syndrome. Contemporary working conditions further contribute to an increased psychosocial burden and a reduction in overall work capacity.

Health promotion, grounded in the principles of the World Health Organization and the Ottawa Charter, entails integrated measures aimed at fostering healthy lifestyles, reducing risk factors, and improving the working environment. Interventions directed at increasing physical activity, promoting proper nutrition, and managing stress are of particular importance.

The application of these measures in the working environment can significantly contribute to the prevention of metabolic syndrome, a reduction in the incidence of chronic non-communicable diseases, and an improvement in employees' quality of life. At the same time, the positive effects are also reflected in increased productivity, reduced absenteeism, and overall socioeconomic progress.

Keywords: metabolic syndrome, workplace health promotion, bank employees, workplace, public health

INTRODUCTION

Work, as a fundamental human activity, has a significant impact on an individual's physical and mental health. Contemporary forms of work, particularly in the service sector, are characterized by reduced physical activity and increased mental strain, which gives rise to a

range of health disorders. Prolonged sitting, stress, and unhealthy lifestyle habits constitute significant risk factors for the development of chronic non-communicable diseases.

The banking sector is an example of a working environment in which the aforementioned risk factors are present. Employees are exposed to continuous mental strain, responsibility, and time constraints, which can adversely affect their health and work capacity.

MATERIALS AND METHODS

The study was conducted as an analytical cross-sectional study with the aim of determining the prevalence of metabolic syndrome among bank employees and assessing its association with risk factors related to the working environment and lifestyle. The study included employees in the banking sector who voluntarily agreed to participate.

The sample comprised respondents of both sexes, economically active, of varying age and length of service. Employees who had worked at their current position for at least one year were included, whereas those with a previously diagnosed serious chronic condition that could affect the results (e.g., malignancies or severe endocrine disorders) were excluded.

Data were collected using a combination of a survey questionnaire, clinical examination, and laboratory analyses. The questionnaire contained information on the respondents' demographic characteristics (sex, age, level of education), working conditions (length of working hours, nature of work, level of stress), and lifestyle habits (physical activity, dietary patterns, tobacco and alcohol consumption).

The clinical examination included measurement of anthropometric parameters, comprising body weight, body height, and waist circumference. On the basis of these data, the body mass index (BMI) was calculated. Blood pressure was measured using a standard method at rest, following at least five minutes of rest.

Laboratory analyses included determination of fasting blood glucose and lipid status (triglycerides and HDL cholesterol). Blood samples were drawn in the morning hours, following an overnight fast.

The diagnosis of metabolic syndrome was established on the basis of internationally accepted criteria, requiring the presence of at least three of the following five components: increased waist circumference, elevated triglyceride levels, reduced HDL cholesterol levels, elevated blood pressure, and elevated fasting glucose.

The data obtained were processed using appropriate statistical methods. Descriptive statistics were used to present the basic characteristics of the sample (arithmetic mean, standard deviation, percentage distribution), together with inferential methods to assess associations between variables. The results are presented in both tabular and textual form, with appropriate interpretation.

All research was conducted in accordance with the ethical principles of medical research. Participants were informed of the aim of the study and gave their consent to participate, with due respect for the anonymity and confidentiality of their data.

RESULTS

The study included a sample of respondents of both sexes and of varying age structure, with a predominant participation of middle-aged individuals. Women were more strongly represented than men in the total sample, and the largest proportion of respondents had a secondary level of education and were employed in administrative positions.

Analysis of the age structure showed that the largest number of respondents belonged to the 31–40 age category, while the fewest respondents were older than 50 years. The mean age of respondents indicated a predominantly economically active population, which is consistent with the aim of the study.

The results demonstrated a high prevalence of metabolic syndrome in the studied population. The prevalence of metabolic syndrome varied depending on the diagnostic criteria applied, but was significant in all cases. According to one of the applied definitions, metabolic syndrome was present in slightly fewer than one third of respondents (27.8%), which points to a serious public health problem in this population.

Differences in the prevalence of metabolic syndrome were found with respect to sex. Metabolic syndrome was registered more frequently in men than in women, which somewhat deviates from the findings of other studies. A clear association was also observed between age and the prevalence of metabolic syndrome, with its frequency increasing with age.

Analysis of the individual components of metabolic syndrome showed that reduced HDL cholesterol was the most frequently represented component in the total sample, as well as among women. In men, abdominal obesity was most frequently present. Elevated arterial blood pressure, blood triglycerides, and hyperglycaemia showed a statistically more significant frequency in men than in women, while hypertriglyceridaemia was the least frequently registered component of metabolic syndrome.

Regardless of the diagnostic criteria applied, abdominal obesity, arterial hypertension, hypertriglyceridaemia, and elevated glucose levels were more pronounced in men. Reduced HDL cholesterol was the only component of MS that was more frequent in the female sex. These results indicate different patterns of risk factor distribution between the sexes.

Among respondents already diagnosed with metabolic syndrome, combinations of several components were most frequently present, with abdominal obesity being the most common component and hyperglycaemia the least common. This pattern indicates the dominant role of lipid metabolism disorders in the pathogenesis of metabolic syndrome in the studied population.

Data analysis did not reveal an association between the level of education and the frequency of metabolic syndrome. The prevalence of MS was found to be lower among workers with a lower level of education. An association was, however, observed between employment status and the health condition of respondents. Employees in positions involving prolonged sitting and a high level of mental strain had a higher frequency of risk factors for the development of metabolic syndrome. A sedentary work pattern and exposure to stress were recognized as significant factors contributing to its development.

Overall, the results of the study indicate a high prevalence of metabolic syndrome and its components among bank employees, as well as a significant association with age, sex, and workplace characteristics, but not with the workers' level of education. These findings confirm the need for the implementation of preventive measures and health promotion programmes in the working environment.

DISCUSSION

The results of this study indicate a high prevalence of metabolic syndrome among bank employees, confirming the significance of this problem in contemporary working environments characterized by predominantly sedentary work. The findings obtained are consistent with numerous epidemiological studies that point to the rising prevalence of metabolic syndrome in the general population, as well as to an increased risk in occupations involving prolonged sitting, a high level of responsibility, and pronounced psychosocial stress.

One of the key findings of the study is the high prevalence of abdominal obesity, which was identified as the most common component of metabolic syndrome. This result is to be expected given the nature of banking work, which entails reduced physical activity and prolonged time spent in a sitting position. Abdominal obesity plays a central role in the pathophysiology of metabolic syndrome, as it is directly linked to the development of insulin resistance and lipid metabolism disorders.

Furthermore, the significant frequency of arterial hypertension and lipid status disorders indicates that cardiovascular risk factors are widespread in the studied population. Elevated triglyceride levels and reduced HDL cholesterol levels further confirm the presence of an unfavourable metabolic profile in a large number of respondents. Such findings indicate an increased risk of developing cardiovascular disease and type 2 diabetes mellitus.

The observed differences in the prevalence of metabolic syndrome with respect to sex stand in contrast to the findings of other studies. The higher frequency in men may be explained by the greater prevalence of abdominal obesity and hypertension, as well as by a greater tendency toward a sedentary lifestyle and greater exposure to stress among male workers. In women, by contrast, lipid status disorders are more pronounced, which points to different patterns of risk factor distribution.

Age proved to be a significant factor associated with the frequency of metabolic syndrome. The increase in prevalence with age can be explained by the cumulative effect of risk factors, including reduced physical activity, changes in metabolism, and an increased frequency of chronic diseases. This finding further emphasizes the need for early prevention and continuous monitoring of employees' health.

A significant association between a lower level of education and a higher frequency of metabolic syndrome would point to the role of socioeconomic factors in its emergence. Persons with a lower level of education often have less knowledge of healthy lifestyle habits, as well as limited access to preventive health programmes, which may contribute to increased risk. In the present study, however, no statistically significant difference in the frequency of MS was observed with respect to the level of education of bank employees.

The results of the study also point to the important role of the working environment in the emergence of metabolic syndrome. A sedentary work pattern and a high level of stress were identified as key risk factors. Chronic stress can lead to hormonal changes that affect metabolism, increasing the risk of obesity, hypertension, and blood glucose disorders. At the same time, a lack of physical activity further aggravates these effects.

The results obtained confirm the significance of workplace health promotion as an effective strategy in the prevention of metabolic syndrome. The implementation of programmes that include increased physical activity, education on proper nutrition, and stress management can significantly contribute to reducing risk factors. Such programmes not only improve employees' health but also have a positive impact on productivity and a reduction in absence from work.

In comparison with other studies, the results of this work show similar trends, but also highlight the specific features of the banking sector as a high-risk environment. The limitations of the study relate to its cross-sectional design, which does not permit the determination of cause-and-effect relationships, as well as to possible shortcomings in the collection of certain laboratory parameters.

Despite the aforementioned limitations, the results clearly indicate the need for a systematic approach to the prevention of metabolic syndrome in the working population. The integration of health promotion measures into the working environment represents a key step toward reducing the burden of chronic non-communicable diseases and improving the overall health status of employees.

CONCLUSION

The results of the conducted study indicate that metabolic syndrome represents a significant health problem among bank employees. The high prevalence of this syndrome in the studied population confirms that contemporary working conditions, marked by a sedentary lifestyle

and an increased level of psychosocial stress, play an important role in its emergence and development.

The most strongly represented components of metabolic syndrome were abdominal obesity, reduced HDL cholesterol, and arterial hypertension, while hypertriglyceridaemia and elevated glucose levels were also significantly present. The observed differences with respect to sex and age indicate the existence of specific risk patterns, whereby the frequency of metabolic syndrome increases with age.

The results, however, did not indicate an association between metabolic syndrome and the level of education of bank employees. Sedentary work and chronic stress stand out as key factors contributing to the development of metabolic disorders.

The findings of the study emphasize the importance of the early identification of persons at increased risk, as well as the need for continuous monitoring of employees' health. Particular emphasis should be placed on the application of preventive measures in the working environment, including the promotion of physical activity, the adoption of healthy dietary habits, and stress management programmes.

Workplace health promotion represents an effective and sustainable approach to reducing the frequency of metabolic syndrome and its complications. The implementation of such programmes can contribute not only to improving the health status of employees but also to increasing productivity, reducing absence from work, and improving overall quality of life.

Ultimately, metabolic syndrome requires a multidisciplinary approach involving cooperation among the health system, employers, and the employees themselves, in order to ensure effective prevention and control of this significant public health problem.

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ANALYSIS OF THE RISK OF ELECTRIC SHOCK IN PUBLIC AREAS DUE TO FAULTY ELECTRICAL INSTALLATIONS – EXAMPLES FROM PRACTICE

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Abstract: The condition of electrical installations in public areas, owing to unprofessional installation or inadequate maintenance, is in some situations such that it poses a danger to citizens' lives. The dangers are particularly pronounced in cases of atmospheric precipitation, and especially in winter, when salt is spread because of snow, further reducing the resistance of the current path through the human body. The aim of this paper is to present examples from practice that illustrate the dangers of electric shock resulting from inadequate installation and maintenance of electrical installations in public areas.

Keywords: *Electrical installations; Public areas; Electric shock; Touch voltage; Step voltage.*

INTRODUCTION

Street lighting, traffic lights, communication networks, and other consumers of electrical energy are present daily in the immediate vicinity of citizens. However, inadequate maintenance, unprofessional installation, and physical damage to installations can create conditions that directly endanger people's safety. Inadequate installation and maintenance of electrical installations in public areas significantly contributes to an increase in the number of electric shocks.

This paper examines specific cases from practice (documented with photographs taken in public areas) that demonstrate the improper execution of electrical installations. Particular attention is paid to winter conditions, when the presence of snow and road-spreading salt further increases the conductivity of the water located between the damaged cable insulation and metal structures.

DANGERS OF ELECTRIC SHOCK

Electric current usually travels in closed circuits and normally moves through conductors. Sometimes it also passes through the human body, which by mistake becomes part of the electrical circuit, causing an electric shock. When a person experiences an electric shock, electric current flows between parts of their body, or through the body in a circular path with the ground. The primary consequence of an electric shock is cardiac arrest, particularly at

frequencies of 50 Hz (IEC 60364-4-41:2005; SRPS HD 60364-4-41:2012). Figure 1 shows situations in which electric shock occurs due to indirect touch voltage (Mišković, 2020).

There is:

- Direct contact, when a person touches a bare (uninsulated) live conductor.
- Indirect voltage transfer – voltage is transmitted via a conductive medium (water, melted snow, salt water) to metal structures that are not galvanically connected to the phase conductor but are spatially close.

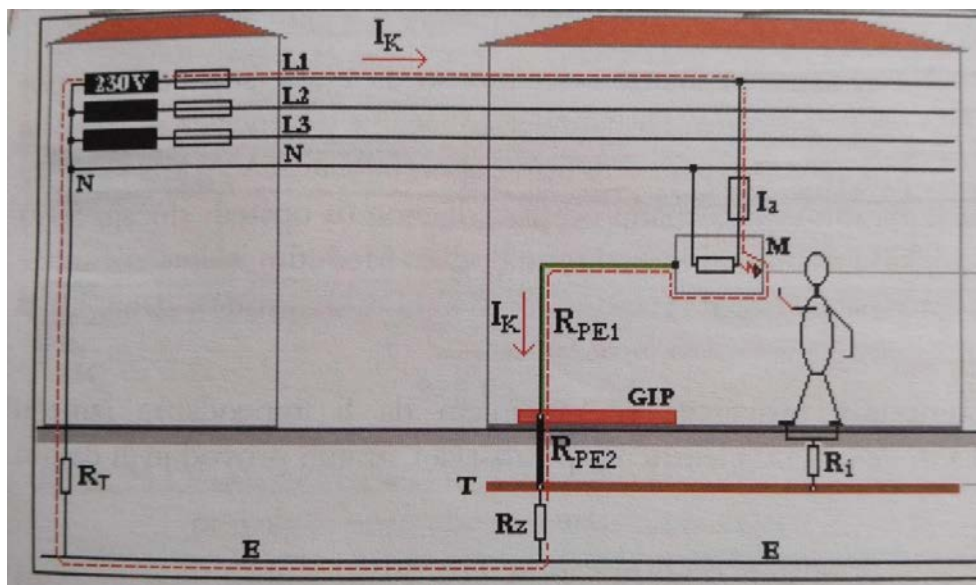


Figure 1. A situation in which electric shock occurs due to indirect touch voltage.

The consequences of an electric shock — that is, of cardiac arrest and the degree of burns — depend on:

- The magnitude of the current passing through the body.
- The path of the current through the body.
- The duration of the electric shock.
- The type of current (AC/DC).

The magnitude of the current passing through the body depends on the potential difference and the body's resistance. It is considered that even an alternating voltage of 24 V at a frequency of 50 Hz poses a risk of electric shock in certain situations (e.g., in swimming pools, bathtubs, etc.) and can cause fatal consequences (IEC 60479-1:2018: 1-72; IEC 61140 Edition 4.0 2016-01; Vesterman, 2008). As the voltage increases, so do the dangerous consequences of an electric shock. People are mostly harmed by alternating voltages up to 500 V. The degree of injury also depends on the duration of exposure to current flowing through the body. The effect of current flow through the human body ranges from a temporary

mild tingling to death. Currents through the human body of 50 mA are considered lethal. In addition to cardiac arrest and burns, an electric shock can also cause chemical reactions in the body that destroy tissue, primarily the nervous system and blood vessels (SRPS EN 60529; M. Kostić, 2014).

ANALYSIS OF CASES FROM PRACTICE

Case 1. – Removed covers on street-lighting poles at the points where the luminaires are connected, Figure 2. The Rulebook on Technical Standards for Low-Voltage Electrical Installations ("Official Gazette of the SFRY", Nos. 53/88 and 54/88 – corr., and "Official Gazette of the FRY", No. 28/95) does not apply to electric luminaires, but they fall under low-voltage consumers, and we can rely to some extent on the provisions of this rulebook. The protective covers on street-lighting poles are mostly removed by socially disadvantaged persons who trade in scrap (secondary raw materials). The protective cover is made of cast iron and, given its small mass (1–2 kg), has negligible financial value. However, removing this cover creates a risk of electric shock, because it is located in the lower part of the pole, which is easily accessible, especially to children. From an economic standpoint, it is logical for the connection to be as low as possible in order to save conductor material, since almost all street-lighting poles are of the loop-in (through) type — i.e., mechanically they are connected in cascade, while electrically all the luminaires are connected in parallel. What does this mean? The supply conductor is brought into the first pole up to the distribution terminal, and then from that distribution terminal a conductor continues to the next street-lighting pole. From the upper end of that same terminal, a lead is run to the luminaire. So it is logical for the connection to be as low as possible in order to save conductor: raising the distribution terminal by 0.5 m increases the conductor length by 1 m. Also, the part of the pole where the distribution terminal is located is wider than the part continuing toward the top of the pole — that is, toward the luminaire — which makes the pole cheaper, as less material is used. A pole without a protective cover poses a great risk of electric shock, especially for children, who can very easily touch live parts, since these are at a low height and within arm's reach. Also, during snowfall, the depth of the snow may exceed the height of the connection terminals, and since snow is a good conductor of electricity, the voltage from the terminals can be transferred to the street-lighting pole itself; if it is touched, a risk of electric shock arises. In addition, part of the current from the distribution terminal flows into the ground via the snow, causing considerable losses of electrical energy.



Figure 2. Removed covers on street-lighting poles.

Case 2. – A distribution cabinet made of cold-rolled (pickled) steel sheet, used for the distribution of electrical energy, damaged and knocked off its base onto the ground, Figure 3. The metal door is physically damaged and open, so that the interior is accessible to physical contact. The lower metal part of the cabinet has corroded, indicating poor maintenance. The cabinet is located on a ground surface next to the sidewalk curb. Protective black PVC pipes can be seen in the concrete base, from which thinner yellow underground cables emerge. The cables are exposed to atmospheric influences. Damaged metal distribution cabinets pose a risk of electric shock, especially for children, as they are located at low heights.



Figure 3. Damaged metal distribution cabinet.

Case 3. – Unprofessionally executed temporary electrical installations in public areas, e.g., for decorative lighting, advertisements, the connection of various devices, and the like. These installations are mostly not carried out according to a design, and building owners install them

on their own initiative. Most of the conductors they install themselves are not intended for outdoor use and are not of an adequate cross-section, nor are they properly mechanically protected, primarily against being stepped on. Because they are improperly installed, they are very often damaged, so it happens that uninsulated and unprotected conductors protrude from the concrete or the ground. Such a cable poses a great risk of electric shock, especially in atmospheric conditions with increased moisture (rain, snow, mist, dew, etc.). Several black power cables are wrapped around the base of a metal pole, lying on the sidewalk and extending in several directions, Figure 4. The cables are wrapped around the metal pole without any protective conduit; in the event of damaged insulation, they can cause direct contact of the phase conductor with the metal pole, so that the entire pole comes to a voltage of 230 V. Given the high frequency of people on the sidewalk, there is a great risk of electric shock.

Persons walking along the sidewalk may trip over one of the cables lying on it. In an attempt to steady themselves and prevent a fall, they will grab the nearest solid object with their hand — which is the pole that is, at that moment, at a voltage of 230 V. The current will cause muscle contraction, meaning the person will grip the pole even more tightly and be unable to release it, thereby prolonging the time of current flow through the body. Water present in the joints between the paving slabs significantly increases the conductivity of the surface (creating a lower-resistance path for the current). According to Ohm's law, lower resistance means that a stronger current passes through the human body, which significantly increases the risk of electric shock.



Figure 4. Several cables wrapped around a metal pole.

Case 4. – Near the base of a metal fence there is a power cable with bare (uninsulated) wires, Figure 5, giving rise to various dangers. There is a danger of direct touch voltage, especially

for children, who while playing may touch the phase wire and thus receive an electric shock. Moisture further worsens the condition of the cable insulation.

Because of the immediate proximity (only a few centimeters) of the cable to the metal pole, even if the conductor does not physically touch the metal pole, a connection between the phase conductor and the metal pole can occur via water, which is an excellent conductor of electricity. Thus the fence pole comes under voltage, which spreads along the entire metal structure. This means a person can suffer an electric shock by touching the fence tens of meters away from the damaged cable. Water (especially if road-spreading salt is present) drastically increases conductivity. A puddle of salt water located between the cable and the pole provides good electrical conductivity between the phase conductor and the pole of the metal fence.

When a metal fence comes under voltage due to a fault, a person does not even have to touch the fence — it is enough to step near the place where the current from the cable enters the wet ground. The potential difference between the two feet can be sufficient to cause muscle contraction and a fall, which then leads to even more dangerous contact with the ground, because in that case the circuit closes through the chest.



Figure 5. A power cable with uninsulated wires located near the base of a metal fence.

PROPOSED PROTECTIVE MEASURES

On the basis of the above, protective measures against electric shock in public areas are proposed, which can be divided into technical and organizational.

Technical protective measures include:

- Mandatory installation of residual current devices (RCDs) with 30 mA sensitivity in electrical installations in public areas, which instantly interrupt the circuit if a fault current greater than 30 mA occurs.
- Distribution boxes with an IP65 degree of protection, which prevents the ingress of water, should be used.
- Metal fences and poles should be connected to earth electrodes.
- Cables should be laid in protective metal conduits at a certain depth to protect them against mechanical damage.

Organizational measures include:

- Regular technical inspections of outdoor electrical installations should be carried out.
- Systems (applications, emergency telephone lines) should be implemented through which citizens can report faults to the competent institutions.

CONCLUSION

On the basis of the cases considered, we can conclude that the condition of electrical installations in public areas, owing to unprofessional installation or inadequate maintenance, is in some situations such that it poses a danger to citizens' lives. The dangers are more pronounced in cases of atmospheric precipitation, and especially in winter, when salt is spread because of snow, further reducing the resistance of the path that closes through the human body.

The magnitude of the current passing through the human body under unfavorable winter conditions can reach values above 50 mA, which is the threshold of a fatal outcome. The situation is particularly dangerous when the touch voltage is transmitted indirectly via salt water. Water enriched with minerals and salt is an extremely good conductor, which can bring metal fences and poles to almost the full phase voltage of 230 V, even when there is no direct physical contact of these structures with the phase conductor.

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CHRONIC PAIN AND ERGONOMIC INJURIES IN THE WORKPLACE

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Abstract: Apart from common colds, chronic pain is one of the most frequent reasons why the working-age population consults a primary care physician, and it represents one of the leading causes of both short-term and long-term sick leave. Among the most common causes of chronic pain are musculoskeletal disorders, including low back pain, neck pain, tendinopathies, nerve lesions and disc herniation. In addition to causing suffering for the worker and reducing work productivity, these conditions generate considerable economic losses for companies, health insurance systems and society as a whole.

According to data from the European Agency for Safety and Health at Work, low back pain is among the most common health problems associated with work. Since available pharmacological and physical therapies often provide only short-term relief, and symptoms frequently return after the worker resumes the same work process, it is necessary to consider whether the complaints may be the consequence of an ergonomic injury.

Ergonomic injuries at work result from a mismatch between the physical demands of the job and the physical capacities of the human body. They usually develop gradually through the repeated overuse of soft tissues, rather than as a consequence of a single acute event.

Ergonomics is a scientific discipline concerned with understanding interactions between humans and other elements of a system. It places the human being at the centre of its analysis. Occupational ergonomics is a specific branch of ergonomics whose task is to design work tasks and work processes in a way that does not exceed the worker's tolerance limits, meaning that the demands of the job should correspond to the worker's abilities at the workplace. Its main principles are to adapt the job to the person, to work smarter rather than harder, to make work more comfortable and to improve quality and safety.

The common goal of occupational safety and health professionals, primary care physicians and occupational medicine specialists is the prevention of injuries and diseases. Therefore, it is necessary to recognize ergonomic injuries and the importance of occupational ergonomics in the prevention and protection of workers' health. Occupational ergonomics should be acknowledged as an essential component in addressing work-related diseases and occupational diseases, together with closer and more effective cooperation between occupational safety professionals and occupational medicine specialists, as well as between occupational medicine and primary care physicians.

Keywords: chronic pain; musculoskeletal disorders; occupational ergonomics; ergonomic injuries; work-related musculoskeletal disorders; occupational medicine.

INTRODUCTION

Chronic pain represents a major clinical and occupational health problem, particularly among the working-age population. Pain is one of the most frequent reasons for seeking medical care in primary practice, while musculoskeletal pain accounts for a substantial proportion of pain-related consultations [1,2]. Although pain may initially appear as an isolated symptom, in many workers it reflects a broader functional disturbance related to repetitive physical strain, awkward postures, heavy physical work, psychosocial work demands, or an insufficient match between job demands and individual physical capacity [3].

Musculoskeletal disorders are among the leading contributors to disability worldwide. Global estimates based on the Global Burden of Disease Study indicate that musculoskeletal disorders represent the disease area with the highest contribution to rehabilitation needs, affecting approximately 1.71 billion people globally [4]. Low back pain remains the leading cause of years lived with disability worldwide, and its future burden is expected to increase mainly due to population growth and ageing, while part of its disability burden is attributable to modifiable factors such as occupational ergonomic factors, smoking and high body mass index [5].

In the working population, chronic pain involving the lower back, neck, shoulders, tendons, peripheral nerves and intervertebral discs can reduce work ability, contribute to sickness absence and impair work performance. Neck and low back pain have been associated with primary care consultations, sick leave and disability pension [6], while reduced productivity has also been documented among workers returning to full duty after sickness absence due to musculoskeletal disorders [7].

From the perspective of occupational medicine, chronic musculoskeletal pain should not be interpreted only as a condition requiring pharmacological or physical treatment. When symptoms recur after return to work, the workplace itself must be evaluated as a potential contributing factor. Work-related musculoskeletal disorders may develop through repeated exposure to biomechanical and organizational risk factors, including excessive repetition, awkward postures, heavy lifting and psychosocial work demands [3]. Therefore, recognizing work-related musculoskeletal disorders and identifying ergonomic risk factors are essential steps in preventing long-term disability, repeated sick leave and progression toward occupational disease.

WORK-RELATED MUSCULOSKELETAL DISORDERS AND CHRONIC PAIN

Work-related musculoskeletal disorders (WMSDs) are disorders of the musculoskeletal system that may be caused or aggravated by work conditions and work-related physical demands. They can involve muscles, tendons, ligaments, joints, nerves, cartilage and spinal structures, and most commonly affect the lower back, neck, shoulders, upper limbs and, less frequently, the lower limbs [8,9].

Unlike acute traumatic injuries, WMSDs usually develop gradually, as a result of repeated or prolonged mechanical load. Repetitive movements, awkward or static postures, excessive force, manual handling of loads, compression and mechanical vibration may progressively overload soft tissues and contribute to pain, fatigue, reduced range of motion and functional limitation [9]. In this context, chronic pain should be understood not only as a clinical symptom, but also as a possible indicator of an unresolved mismatch between the worker's physical capacity and the demands of the workplace.

The severity of WMSDs may vary from mild, transient discomfort to persistent pain that requires medical treatment, sickness absence, work modification or even withdrawal from work. Therefore, the identification of ergonomic risk factors is an essential component of occupational health practice and long-term prevention of chronic musculoskeletal pain.

ERGONOMIC RISK FACTORS

The risk of work-related musculoskeletal disorders is multifactorial and depends on the interaction between physical, organizational and psychosocial characteristics of work. Physical risk factors include repetitive movements, excessive force, awkward or static postures, manual handling of loads, mechanical compression and exposure to vibration. These exposures may increase tissue load, reduce recovery time and contribute to the gradual development of pain, fatigue and functional limitation [8,9].

Awkward postures and prolonged static positions are particularly important because even low-force tasks can become harmful when the same body position is maintained for a long period. Repetitive work is also relevant when the same muscle groups and joints are used continuously, especially in combination with force, high work pace or insufficient variation in tasks [9,10].

Organizational factors may further increase ergonomic risk by determining the duration, intensity and recovery pattern of exposure. High work pace, long working hours, monotonous tasks, insufficient task variation and inadequate opportunities for recovery can maintain cumulative mechanical load over time. Task rotation and regular breaks are therefore commonly considered preventive organizational measures, although evidence suggests that they should be combined with broader ergonomic redesign rather than used as isolated interventions [11,12].

Psychosocial factors also contribute to the development and persistence of musculoskeletal disorders. High job demands, low job control, poor workplace support and weak collaboration have been associated with the risk and progression of musculoskeletal disorders in longitudinal studies [13]. These factors may intensify muscle tension, increase perceived pain, reduce recovery and influence how workers respond to physical strain.

Therefore, ergonomic risk assessment should not focus only on posture or lifting technique. A comprehensive approach must include physical workload, work organization and

psychosocial working conditions, because these factors often act together and may reinforce each other in the development of chronic musculoskeletal pain.

ROLE OF ERGONOMICS AND OCCUPATIONAL MEDICINE

The management of chronic musculoskeletal pain in workers should not be limited to symptomatic treatment and temporary sickness absence. When pain recurs after return to work, the work process itself should be assessed as a possible factor that maintains or aggravates symptoms. Occupational health guidelines for low back pain emphasize diagnostic triage, identification of red flags and neurological problems, but also the assessment of psychosocial and workplace barriers to recovery. They also support remaining at work or an early gradual return to work, when medically appropriate, with modified duties if necessary [14].

Ergonomics has a central preventive role because it aims to adapt work demands to the physical capacities and limitations of the worker. The World Health Organization states that prevention of musculoskeletal disorders in the workplace should influence both the actions of employers and the behavior of workers, so that physical loads that are dangerous to health or unnecessarily fatiguing are avoided or reduced [15]. Therefore, ergonomic prevention should not be understood as a matter of comfort only, but as a structured occupational health strategy.

Effective prevention and management require cooperation between several actors. The primary care physician identifies symptoms, initiates diagnostic evaluation and recognizes when recurrent pain may be work-related. The occupational medicine specialist evaluates the worker's functional capacity in relation to job demands and proposes work restrictions, adaptations or gradual return-to-work measures. Occupational safety and health professionals identify ergonomic hazards at the workplace and participate in risk assessment. The employer enables technical and organizational modifications, while the worker contributes by reporting symptoms early, following preventive instructions and participating in safe work practices.

Evidence also supports the need for a multidomain approach. Workplace return-to-work interventions that combine health-focused measures, service coordination and work modification reduce the duration of work absence in workers with musculoskeletal and pain-related conditions more effectively than isolated measures [16]. Similarly, workplace-based rehabilitation for employees with physically demanding work commonly includes exercise, ergonomic training, participatory ergonomics and return-to-work interventions, although the strength of evidence varies between intervention types [17]. For this reason, occupational medicine should connect clinical care with workplace assessment, rather than treating chronic musculoskeletal pain as a purely individual medical problem.

PREVENTION AND CONCLUSION

Prevention of work-related musculoskeletal disorders requires early recognition of risk factors and timely modification of the work process. The aim is not only to reduce pain after it

appears, but to prevent repeated overload of muscles, tendons, joints, nerves and spinal structures. Preventive measures should include ergonomic assessment of the workplace, adaptation of tools and equipment, reduction of excessive force and repetitive movements, improvement of working posture, adequate task variation, planned recovery periods and education of workers and employers [15].

Chronic musculoskeletal pain cannot be managed successfully if the worker returns to the same work pattern that caused or maintained the symptoms. In such cases, pharmacological therapy, physical therapy and temporary sickness absence may provide short-term relief, but they do not remove the underlying occupational exposure. Therefore, prevention must connect clinical evaluation with workplace intervention. Multidomain return-to-work strategies, which combine healthcare measures, service coordination and work modification, are more appropriate than isolated interventions when the goal is to reduce work absence and restore functional capacity [16].

Ergonomics should therefore not be understood as a matter of comfort, but as an essential preventive tool in occupational medicine. Its purpose is to adapt work to the worker, reduce harmful physical load, preserve work ability and prevent the progression of reversible symptoms into chronic disability. Effective prevention requires cooperation between primary care physicians, occupational medicine specialists, occupational safety and health professionals, employers and workers. Only this coordinated approach can transform chronic pain from a repeated individual complaint into a signal for systematic workplace prevention.

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CHRONIC DISEASES AS A CAUSE OF WORK DISABILITY – NEW THERAPEUTIC POSSIBILITIES: A CASE REPORT

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Abstract: Chronic diseases, such as cardiovascular diseases, heart failure, chronic kidney disease and diabetes mellitus with complications, are, together with malignant diseases, among the most common causes of partial or complete loss of work ability. The high prevalence of chronic diseases results from population ageing and the influence of multiple risk factors. It is estimated that patients with diabetes mellitus have a twofold higher risk of developing cardiovascular disease and a markedly increased risk of developing chronic kidney disease. Cardiovascular mortality risk is also significantly increased in stage 3 chronic kidney disease, while a considerable proportion of patients with early stage 3 kidney impairment may progress to dialysis.

According to pension and disability insurance regulations, disability exists when changes in health status that cannot be eliminated by treatment result in partial or complete loss of work ability. Under the current Law on Pension and Disability Insurance, the right to a disability pension is acquired in the case of complete, 100% loss of work ability caused by injury or disease, whether work-related or non-work-related. Under previous regulations, this right could be acquired with a 75% loss of work ability. Consequently, a larger number of workers remain in the work process with varying degrees of work ability limitation.

Patient 1 was considered a candidate for disability pension in 2009 due to a sudden decrease in left ventricular ejection fraction below 35%. Since 2011, the patient has been treated with an SGLT2 inhibitor, followed later by ARNI therapy in combination with a beta-blocker and a mineralocorticoid receptor antagonist. Left ventricular ejection fraction increased to above 50% and remained stable until 2025. The therapeutic response was associated with preserved full work ability for an additional 16 years.

Patient 2 had markedly limited work ability in 2011 due to insulin-treated diabetes mellitus with multiple complications after myocardial infarction. At that time, SGLT2 inhibitor and GLP-1 receptor agonist therapy were introduced experimentally, resulting in significant body weight reduction, improved lipid profile, better glycaemic control, resolution of proteinuria and restoration of work ability. Although heavy physical work was contraindicated, the patient continued to perform physically demanding work. Work ability was lost in 2025, indicating that functional working capacity was preserved for an additional 14 years.

The development of new therapeutic options, including SGLT2 inhibitors and GLP-1 receptor agonists, together with the introduction of modern therapeutic procedures and screening for early detection of chronic kidney disease, enables better control of risk factors and prevention of complications. These advances may modify the course of chronic cardio-renal-metabolic diseases and significantly contribute to the preservation and prolongation of work ability.

Keywords: chronic disease; work disability; work ability; chronic kidney disease; SGLT2 inhibitors; occupational medicine.

INTRODUCTION

Cardiovascular disease, heart failure, chronic kidney disease and type 2 diabetes frequently coexist and should not be viewed as completely separate clinical entities. Contemporary literature increasingly describes their interaction through the concept of cardiovascular-kidney-metabolic disease, which reflects the close pathophysiological relationship between metabolic risk factors, chronic kidney disease and cardiovascular outcomes [1].

This connection is particularly important in occupational medicine, because chronic cardio-renal-metabolic diseases may gradually reduce functional capacity, limit physical tolerance and contribute to partial or complete loss of work ability. Modern treatment strategies therefore aim not only to improve glycaemic control, but also to reduce cardiovascular risk, slow kidney disease progression and preserve clinical stability. In patients with type 2 diabetes and chronic kidney disease, the ADA/KDIGO consensus recommends the use of an SGLT2 inhibitor with proven kidney or cardiovascular benefit when eGFR is ≥ 20 mL/min/1.73 m², while a GLP-1 receptor agonist with proven cardiovascular benefit is recommended when individualized glycaemic targets are not achieved with metformin and/or an SGLT2 inhibitor, or when these agents cannot be used [2]. This therapeutic shift is clinically relevant because better disease control may influence not only survival and hospitalization risk, but also the duration and quality of preserved work ability.

Legal and occupational medicine context

In the Republic of Serbia, disability in the pension and disability insurance system is legally defined as a complete loss of work ability caused by changes in health status due to occupational injury, occupational disease, non-occupational injury or disease, when such changes cannot be eliminated by treatment or medical rehabilitation [3]. The right to disability pension is therefore linked to complete loss of work ability, rather than to the diagnosis itself [3].

From the perspective of occupational medicine, the assessment of work ability should not be static. In workers with chronic cardio-renal-metabolic diseases, clinical diagnosis must be interpreted together with therapeutic response, functional capacity and the physical and organizational demands of the specific workplace. Serbian regulations on the assessment of work ability and the possibility of employment or maintaining employment include medical, social and other criteria, with the aim of determining the person's ability to perform specific work independently or with support [4]. This approach is particularly important when modern therapy stabilizes the disease, improves functional status and allows work continuation with appropriate restrictions or workplace adaptations.

CASE PRESENTATION

Patient 1: Heart failure with improved ejection fraction

The first patient was diagnosed with heart failure with reduced ejection fraction in 2009, when a sudden decrease in left ventricular ejection fraction below 35% was recorded. At that time, the patient had significantly reduced functional capacity and was considered a candidate for disability pension due to the severity of cardiac dysfunction and the expected limitation of work ability. Data on NYHA functional class and detailed occupational workload were not available for this report.

Pharmacological treatment included guideline-directed heart failure therapy, initially with a beta-blocker and a mineralocorticoid receptor antagonist, followed by the introduction of an SGLT2 inhibitor and later ARNI therapy. During follow-up, left ventricular ejection fraction increased to above 50%, indicating a transition from heart failure with reduced ejection fraction to heart failure with improved ejection fraction. This improvement remained stable until 2025.

From an occupational medicine perspective, the clinical improvement was associated with preserved full work ability for an additional 16 years. Although the patient had initially been considered for disability pension, stabilization of cardiac function and sustained therapeutic response allowed continued participation in the work process.

Patient 2: Type 2 diabetes mellitus with cardiovascular and renal complications

The second patient had insulin-treated type 2 diabetes mellitus complicated by cardiovascular and renal involvement. In 2011, after myocardial infarction, the patient had markedly limited work ability. The clinical picture included obesity, dyslipidaemia, impaired glycaemic control and proteinuria, indicating a high cardio-renal-metabolic risk profile. Due to the severity of complications, the patient was advised to avoid heavy physical work.

Therapy with an SGLT2 inhibitor and a GLP-1 receptor agonist was introduced, along with standard cardiometabolic treatment. During follow-up, significant body weight reduction, improvement of lipid status, better glycaemic control and resolution of proteinuria were observed. These clinical improvements were accompanied by restoration of work ability.

Despite medical restrictions, the patient continued to perform physically demanding work. Work ability was finally lost in 2025. From an occupational medicine perspective, the therapeutic response was temporally associated with preservation of functional working capacity for an additional 14 years, although continued exposure to heavy physical workload may have contributed to later functional deterioration.

DISCUSSION

The two presented cases illustrate the clinical and occupational relevance of modern cardio-renal-metabolic therapy. In both patients, chronic disease had already led to a significant

reduction in functional capacity and threatened long-term work ability. However, after the introduction of contemporary pharmacological treatment, clinical stabilization was followed by a prolonged period of preserved working capacity. These cases therefore suggest that, in occupational medicine, the assessment of work ability in chronic disease should consider not only diagnosis and current impairment, but also therapeutic response, functional recovery and the demands of the specific workplace.

Therapy for heart failure and cardio-renal-metabolic disease is no longer only symptomatic. In patients with heart failure with reduced ejection fraction, dapagliflozin reduced the risk of worsening heart failure or death from cardiovascular causes compared with placebo [5]. Sacubitril/valsartan was also superior to enalapril in reducing the risk of death and hospitalization for heart failure in patients with heart failure with reduced ejection fraction [6]. In the first presented patient, improvement of left ventricular ejection fraction to above 50% and long-term clinical stability are consistent with the modern concept of disease-modifying therapy in heart failure. From an occupational medicine perspective, this improvement was important because it was associated with preserved full work ability for an additional 16 years.

Renal protection is also essential for preserving functional prognosis in patients with chronic cardio-renal-metabolic disease. The KDIGO 2024 guideline emphasizes early detection, staging and treatment of chronic kidney disease based on glomerular filtration rate and albuminuria, because both parameters are used to estimate the risk of progression and adverse outcomes [7]. Contemporary interpretation of the KDIGO 2024 recommendations also highlights the role of SGLT2 inhibitors in proteinuric kidney disease, with or without diabetes [8]. In patients with type 2 diabetes and chronic kidney disease, the FLOW trial showed that semaglutide reduced the risk of clinically important kidney outcomes and death from cardiovascular causes [9]. These findings are relevant to the second presented patient, in whom improved glycaemic control, weight reduction, better lipid status and resolution of proteinuria were accompanied by restoration of work ability.

The most important occupational medicine aspect of these cases is the interpretation of work ability as a dynamic clinical and functional outcome. Most clinical studies focus on mortality, hospitalization, ejection fraction, estimated glomerular filtration rate, albuminuria, body weight, lipid status and glycaemic control. However, in daily practice, these outcomes also influence whether a patient can remain employed, return to work or continue working with restrictions. Work ability depends on the relationship between the worker's health condition, functional capacity and actual job demands [10]. Therefore, a diagnosis alone is not sufficient for assessing disability; the occupational physician must also evaluate functional limitations, treatment response, workplace risks and the possibility of job adaptation.

These two cases cannot prove a causal relationship between therapy and prolonged work ability, because this is a case-based observation. Nevertheless, they show a clinically

important temporal association between modern therapy, stabilization of chronic disease and preservation of work capacity. In this context, new therapeutic options should be viewed not only through their effect on laboratory and cardiovascular outcomes, but also through their potential contribution to maintaining functional independence and participation in the work process.

CONCLUSION

Chronic cardio-renal-metabolic diseases are important causes of reduced functional capacity and potential loss of work ability. The presented cases indicate that modern disease-modifying therapy may contribute to clinical stabilization and prolonged preservation of working capacity in selected patients. Improvement in left ventricular ejection fraction, better metabolic control, reduction of proteinuria and stabilization of renal and cardiovascular risk are not only clinical outcomes, but also factors that may influence the patient's ability to remain active in the work process.

From the perspective of occupational medicine, work ability should not be assessed only on the basis of diagnosis. It requires an integrated evaluation of disease severity, therapeutic response, functional capacity, occupational workload and the possibility of workplace restrictions or adaptations. These cases cannot establish a causal relationship between therapy and prolonged work ability, but they highlight an important practical message: timely and adequate treatment of chronic cardio-renal-metabolic disease may delay functional decline and support continued participation in work. Therefore, modern therapy should be viewed not only as a means of reducing morbidity and mortality, but also as a potential contributor to preserving independence, employability and quality of working life.

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BIOPHILIC DESIGN STRATEGIES AND USER PSYCHOLOGICAL RESPONSE IN CONTEMPORARY HOSPITALITY INTERIORS

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Abstract: Contemporary hospitality interiors increasingly emphasize user well-being, emotional comfort, and multisensory spatial experience. In response to the growing disconnection between humans and natural environments in urban contexts, biophilic design has emerged as an important architectural approach that integrates natural elements into interior spaces. This paper explores the application of biophilic design strategies in contemporary hospitality interiors, with a particular focus on restaurant environments and their influence on users' psychological responses.

The research analyzes how natural materials, vegetation, daylight, organic forms, water features, and spatial relationships inspired by nature contribute to stress reduction, emotional regulation, relaxation, and improved user satisfaction. Particular attention is given to the role of central natural elements, such as indoor trees and green focal points, in creating identity, atmosphere, and emotional attachment to space.

The study combines theoretical analysis of biophilic design principles with case-study evaluation of contemporary hospitality interiors. Furthermore, the paper examines the relationship between spatial perception and environmental psychology, emphasizing how nature-integrated environments can positively affect cognitive and emotional states of users.

The results indicate that biophilic strategies significantly improve perceived comfort, spatial quality, and overall user experience within hospitality environments. The findings suggest that biophilic interior architecture not only contributes to sustainability goals but also enhances psychological well-being and strengthens the human–nature connection in everyday urban life.

Keywords: biophilic design, hospitality interiors, environmental psychology, restaurant design, user experience, sustainable architecture, well-being

INTRODUCTION

Rapid urbanization and technological development have significantly transformed the relationship between humans and the natural environment. Contemporary lifestyles increasingly expose individuals to enclosed, artificial, and overstimulating spaces, often resulting in stress, anxiety, mental fatigue, and emotional disconnection. Within this context, architecture and interior design play an important role in improving psychological well-being and creating healthier environments for everyday life.

Biophilic design has emerged as a contemporary design approach that seeks to reconnect humans with nature through the integration of natural elements, materials, patterns, and spatial experiences into built environments. The concept is based on the theory of biophilia, introduced by Edward O. Wilson, which describes the innate human tendency to seek connections with nature and living systems.

In hospitality architecture, particularly in restaurant interior design, atmosphere and emotional experience strongly influence users' perception of space. Restaurants are no longer designed solely as functional spaces for dining; instead, they increasingly aim to create immersive experiences that stimulate comfort, relaxation, and social interaction. As a result, biophilic principles are becoming increasingly relevant within contemporary hospitality interiors.

This paper investigates how biophilic design strategies influence users' psychological responses in hospitality environments. The research focuses on the integration of natural materials, vegetation, daylight, organic forms, and central natural elements in restaurant interiors, examining their contribution to emotional comfort, stress reduction, and spatial identity.

THEORETICAL BACKGROUND OF BIOPHILIC DESIGN

Biophilic design represents an interdisciplinary approach that combines architecture, psychology, sustainability, and environmental science. Its primary objective is to strengthen the connection between humans and nature within built environments.

According to contemporary biophilic theory, natural integration in interiors can be achieved through three primary categories:

- direct experience of nature,
- indirect experience of nature,
- spatial and place-based experience.

Direct experiences include natural light, plants, water, airflow, and natural ecosystems within interiors. Indirect experiences involve the use of natural materials, colors, textures, biomorphic forms, and representations of nature. Spatial experiences focus on creating environments that evoke feelings of refuge, openness, mystery, and safety similar to those found in natural landscapes.

Research in environmental psychology suggests that exposure to natural elements can positively affect human cognitive functioning and emotional states. Natural environments are associated with reduced cortisol levels, improved concentration, emotional restoration, and decreased stress perception. Consequently, biophilic interiors are increasingly recognized as beneficial for mental health and overall well-being.

In hospitality spaces, these principles contribute not only to visual aesthetics but also to multisensory user experiences that shape emotional attachment and spatial memory.

BIOPHILIC STRATEGIES IN HOSPITALITY INTERIOR DESIGN

Contemporary restaurant interiors frequently apply biophilic strategies to create immersive and emotionally engaging environments. These strategies often include the use of natural materials such as wood and stone, integration of indoor vegetation, maximization of daylight, and implementation of organic spatial compositions.

Wood is particularly significant due to its tactile warmth, visual softness, and psychological associations with nature and comfort. Large central trees or green installations within restaurant interiors often function as focal spatial elements that organize circulation and create emotional identity within the space.

Vegetation contributes to improved air quality, acoustic comfort, and visual relaxation. Indoor plants soften architectural rigidity and introduce dynamic, living components into interior environments. Similarly, organic forms and curved geometries create more fluid and calming spatial experiences compared to rigid orthogonal compositions.

Natural lighting also plays a critical role in shaping psychological responses. Daylight improves mood, regulates circadian rhythms, and enhances users' perception of openness and comfort. Combined with natural textures and materials, lighting contributes to creating restorative environments within hospitality settings.

Additionally, sensory aspects such as natural scents, water sounds, and thermal comfort can further intensify the user's emotional connection with space.

PSYCHOLOGICAL RESPONSE AND USER EXPERIENCE

The psychological impact of biophilic interiors is closely connected to emotional perception and sensory processing. Users tend to perceive nature-integrated spaces as calmer, healthier, and more welcoming compared to conventional interiors dominated by artificial materials and enclosed atmospheres.

Several psychological effects are commonly associated with biophilic hospitality interiors:

- stress reduction,
- emotional relaxation,
- increased sense of comfort,
- improved social interaction,
- stronger spatial memory,
- enhanced user satisfaction.

Restaurant environments that integrate central natural elements often create feelings of refuge and intimacy while simultaneously encouraging social gathering and longer user retention within the space. Such environments can also strengthen brand identity and emotional attachment between users and hospitality spaces.

Environmental psychology studies further indicate that natural environments improve attention restoration and cognitive recovery. In highly urbanized societies, hospitality interiors designed through biophilic principles may therefore function as temporary restorative environments that counterbalance everyday psychological stress.

DISCUSSION

The increasing implementation of biophilic design in hospitality interiors reflects broader societal concerns regarding sustainability, mental health, and quality of life. While aesthetic value remains important, contemporary architecture increasingly recognizes emotional well-being as a central component of spatial design.

Biophilic restaurant interiors demonstrate that architecture can influence human emotions and behaviors through sensory and environmental qualities. The integration of vegetation, daylight, and natural materials not only improves environmental performance but also creates emotionally restorative spatial experiences.

However, successful biophilic design requires careful balance between aesthetics, functionality, maintenance, and sustainability. Superficial decorative use of plants without deeper spatial integration may fail to produce meaningful psychological benefits. Therefore, biophilic principles should be considered from the earliest conceptual stages of architectural design.

Future research may further investigate measurable physiological responses to biophilic interiors using biometric technologies, environmental sensors, and user behavioral analysis.

CONCLUSION

Biophilic design has become an important strategy in contemporary hospitality architecture due to its positive influence on psychological well-being, emotional comfort, and spatial experience. By integrating natural elements into restaurant interiors, architects and designers can create environments that support relaxation, social interaction, and emotional restoration.

The research confirms that biophilic hospitality interiors contribute to improved user satisfaction and strengthen the connection between humans and nature within urban environments. Natural materials, vegetation, daylight, and organic forms collectively shape healthier and more meaningful spatial experiences.

As cities continue to expand and human interaction with natural environments becomes increasingly limited, biophilic design may play a crucial role in developing sustainable and psychologically supportive architectural spaces for the future.

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HIGH-CAFFEINE STIMULANT BEVERAGES IN THE OCCUPATIONAL SETTING: ACUTE EFFECTS ON VIGILANCE AND IMPLICATIONS FOR RECOVERY AND OCCUPATIONAL RISK

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Abstract: High-caffeine stimulant beverages marketed as energy drinks are increasingly used in working populations as an acute counter-fatigue measure under conditions of shift work, extended duty hours, substantial physical load, and sustained cognitive demand. Despite their widespread occupational use, their actual contribution to preserving functional work capacity and operational safety remains insufficiently established. The aim of this paper was to critically appraise the available evidence on the effects of energy drinks and caffeine on occupationally relevant outcomes, with particular emphasis on vigilance, task errors, recovery sleep, and symptom profiles with potential implications for occupational risk. Current evidence indicates that caffeine and energy drinks may transiently improve selected domains of cognitive performance, particularly attention and certain indicators of task execution, yet without convincing evidence that such effects translate into a lower incidence of occupational injuries. In a systematic review comprising 13 studies in shift workers, none assessed injuries as an endpoint. In a randomized crossover model of a simulated night shift, administration of an energy drink was associated with a 29.1-minute reduction in subsequent daytime recovery sleep and a decline in sleep efficiency from 91.8% to 84.7%. In an industrial sample of factory workers, prevalence of consumption was 68%, while recent consumers reported thirst significantly more often than non-consumers, 35% versus 5%. Collectively, these findings suggest that high-caffeine stimulant beverages should not be regarded as a validated strategy for optimizing work performance, but rather as a short-lived stimulatory response of limited functional range, potentially accompanied by impaired recovery, dehydration-related symptom burden, and increased occupational risk.

Keywords: high-caffeine stimulant beverages; work capacity; shift work; recovery sleep; occupational risk

INTRODUCTION

High-caffeine stimulant beverages marketed as energy drinks have become increasingly visible in occupational settings characterized by shift work, extended duty hours, substantial physical demands, and sustained cognitive load. Their use is no longer confined to athletes or younger consumer groups, but is increasingly observed among workers exposed to fatigue, circadian misalignment, and prolonged performance requirements. From the perspective of occupational medicine, this topic is important because shift work and circadian disruption are associated with impaired alertness, reduced cognitive efficiency, increased sleepiness at work, and a higher risk of safety-critical events [1-3].

In such contexts, caffeine is often used as an alertness-promoting countermeasure. The rationale is straightforward: workers facing sleep restriction, night shifts, or prolonged tasks may seek a rapid and easily accessible means of maintaining vigilance and task execution. This pattern has also been documented in professional populations. In a large survey of U.S. Air Force personnel, energy drink consumption was highly prevalent, and adverse effects were commonly reported among users. Similarly, observational evidence from occupational groups suggests that these beverages are often consumed in direct response to operational demands rather than purely recreational motives [4-5].

At the same time, the actual contribution of these beverages to preserving functional work capacity remains insufficiently established. A Cochrane systematic review including 13 studies in shift workers found that caffeine may reduce certain types of errors and improve selected domains of cognitive performance; however, the review also highlighted that the available trials did not assess occupational injuries as an endpoint. This is a critical distinction, because transient enhancement of attention or task performance should not automatically be interpreted as improved overall occupational safety [6]. Moreover, the apparent short-term benefit may be accompanied by a measurable recovery cost. In a randomized crossover study simulating a first night shift, administration of an energy drink was associated with a 29.1-minute reduction in subsequent daytime recovery sleep and a decline in sleep efficiency from 91.8% to 84.7%. In another placebo-controlled study, energy drink consumption improved driving performance and reduced subjective sleepiness during prolonged highway driving, illustrating that acute benefits may indeed occur under fatigue-prone conditions. Nevertheless, such findings should be interpreted cautiously, because the preservation of wakefulness during a task does not necessarily imply preserved recovery, resilience, or sustained work capacity across repeated shifts [7,8].

Evidence from real occupational environments further supports the need for caution. In a factory-worker population, energy drink consumption was common, and recent consumers more frequently reported thirst and other adverse symptoms than non-consumers [4]. Taken together, the literature suggests that high-caffeine stimulant beverages should not be viewed simply as performance aids, but rather as occupationally relevant exposures situated at the intersection of fatigue, recovery, and professional risk. Accordingly, the aim of this paper is to critically examine the available evidence on the acute effects of high-caffeine stimulant beverages on vigilance and cognitive functioning, and to consider their implications for recovery and occupational risk within the framework of occupational medicine.

ACUTE EFFECTS ON VIGILANCE AND COGNITIVE FUNCTIONING

Available evidence indicates that high-caffeine stimulant beverages may acutely enhance selected aspects of vigilance and cognitive performance, although these effects are neither uniform across tasks nor sufficient to infer preserved overall work [9,10]. The most occupationally relevant synthesis remains the Cochrane systematic review, which included 13

studies in shift workers and found that caffeine was associated with reductions in certain types of errors and improvements in selected cognitive domains, particularly attention, orientation, and memory [6].

Importantly, these beneficial effects were demonstrated primarily on surrogate outcomes such as neuropsychological performance and task-related errors, rather than on broader indicators of sustained work capacity or occupational safety [6].

In a randomized crossover study simulating a first night shift, a caffeinated energy drink was considered effective as a short-term fatigue countermeasure during one night shift, supporting the view that these beverages may transiently sustain wakefulness under circadian [7]. Similarly, in a placebo-controlled study of prolonged highway driving, a 250 mL energy drink significantly improved driving performance during the third and fourth hour after ingestion and reduced subjective sleepiness relative to placebo [8]. Comparable findings were reported in professional truck drivers, in whom the combination of a short rest break and energy drink consumption was associated with lower lane deviation and reduced steering variability during the first 80 to 100 minutes of subsequent driving [11].

More recent experimental work also suggests that energy drinks may improve psychomotor vigilance and reaction time under controlled conditions, although these effects appear to be driven largely by caffeine itself rather than by additional ingredients contained in the beverage matrix [10,12]. Taken together, the available data support the existence of an acute stimulatory effect on vigilance and selected cognitive endpoints, but also indicate that this effect is transient, task-specific, and functionally limited [9,10].

RECOVERY AND ADVERSE EFFECTS

The acute alertness-promoting effect of high-caffeine stimulant beverages must be interpreted alongside their potential impact on recovery, symptom burden, and broader occupational risk, particularly in workers exposed to circadian disruption and repeated fatigue loading [13,14].

One of the most relevant findings for occupational medicine is that stimulation during a night shift may be followed by impaired post-shift recovery sleep rather than physiological restoration. In a randomized crossover simulation of a first night shift, administration of a caffeinated energy drink reduced subsequent daytime recovery sleep by 29.1 minutes and decreased sleep efficiency from 91.8% to 84.7%, despite maintaining wakefulness during the shift itself. This finding is particularly important because it suggests that the functional cost of stimulation may emerge not during task performance, but during the period when recovery should occur [7].

Evidence from real occupational environments further supports the presence of adverse effects. In a factory-worker population, energy drink consumption was reported by 68% of workers, and recent consumers reported thirst significantly more often than non-consumers, 35% versus 5%, while headache, insomnia, and anxiety were also more frequently reported

among users [4]. In military personnel, a large survey found that 76.7% had consumed energy drinks, 12.0% reported consuming at least one per day, and among users 60.0% reported at least one adverse effect, while 0.92% reported requiring physician or emergency department evaluation because of those effects [5]. Among shift-working nurses and midwives, the proportion of high caffeine consumers, defined as >400 mg/day, increased from 15% to 33% after starting shift work, and greater caffeine intake was associated with more sleep disturbance, psychological distress, abdominal pain, and weight gain [15]. These data suggest that the use of stimulant beverages in occupational settings should not be interpreted solely as a performance-related behaviour, but also as a marker of accumulating fatigue, impaired recovery, and adverse symptom load across different professional groups [5,15].

More recent broader reviews have also emphasized that energy drink consumption may be accompanied by cardiovascular, neuropsychiatric, renal, gastrointestinal, and sleep-related adverse effects, particularly when intake is frequent, excessive, or combined with other stressors [13]. Although case reports cannot be used to estimate frequency, they are useful for illustrating the possible severity of extreme patterns of intake in functionally demanding contexts.

A published case report described a 50-year-old construction worker who consumed 4–5 energy drinks daily for 3 weeks and was hospitalized with acute hepatitis, while a more recent report described a 54-year-old warehouse worker who consumed approximately 8 energy drinks per day and presented with hypertensive crisis and stroke [16,17]. Taken together, the available evidence indicates that any short-term gain in wakefulness or perceived functionality may be accompanied by impaired recovery, dehydration-related symptoms, neurovegetative complaints, and, in extreme cases, clinically serious outcomes relevant to occupational medicine [4,7,13].

WHY WORKERS TURN TO THESE BEVERAGES

Workers do not typically consume high-caffeine stimulant beverages in occupational settings as a matter of taste alone, but rather as a practical response to fatigue, sleepiness, and the need to maintain alertness under demanding work conditions [18,19]. In sectors characterized by shift work, night duty, extended work hours, and sustained operational pressure, these beverages are often used to prolong wakefulness, preserve perceived functionality, and maintain task performance until the end of the work period [18,20]. In construction settings, mixed-method evidence indicates that stress, pace of work, time pressure, and work intensity are among the main drivers of caffeine and energy drink use, suggesting that consumption is closely linked to the structure of the work process itself rather than to isolated lifestyle preference [21]. Similarly, studies in healthcare personnel show that energy drinks are frequently used during night shifts to sustain work performance and counteract circadian sleepiness, while recent occupational sleep research suggests that caffeine use in shift workers often functions as a behavioral countermeasure to stay awake when fatigue-management opportunities are limited [18,19]. Taken together, the literature supports the view that

consumption of these beverages should be interpreted not merely as an individual habit, but often as an adaptive response to work organization, fatigue burden, and circadian disruption.

IMPLICATIONS FOR OCCUPATIONAL MEDICINE AND BUSINESS

The occupational relevance of high-caffeine stimulant beverages should not be reduced to the beverage itself, but interpreted within the broader context of work organization, fatigue management, and recovery opportunities [4,21]. When workers repeatedly rely on stimulant beverages to maintain alertness and task execution, consumption may represent a marker of insufficient fatigue control rather than an effective solution to reduced work capacity [5,15]. Acute stimulation may temporarily mask sleepiness and perceived functional decline, but it does not address the underlying causes of fatigue, such as circadian misalignment, inadequate rest, prolonged duty hours, or excessive operational demands [7,15].

From the perspective of occupational medicine, preventive action should therefore prioritize organizational measures rather than individual stimulant use. These measures include adequate hydration, structured breaks, realistic workload distribution, recovery opportunities between shifts, and education of workers regarding the limitations and potential adverse effects of high-caffeine stimulant beverages. In high-demand sectors, particularly those involving shift work, heat exposure, physical strain, vigilance, precision, or safety-critical decisions, frequent consumption should prompt assessment of fatigue burden and work organization. In this sense, the central preventive question is not how to replace one stimulant strategy with another, but how to reduce the occupational conditions that make chemical compensation of fatigue functionally attractive.

CONCLUSION

High-caffeine stimulant beverages may provide a short-term effect on vigilance and selected domains of cognitive performance, but this effect is transient, task-specific, and functionally limited. Available evidence indicates that acute stimulation may be accompanied by impaired recovery, adverse symptom burden, and potential occupational risk. Their use in the workplace should therefore be interpreted not as a validated strategy for optimizing work performance, but as a possible marker of fatigue, circadian disruption, and organizational insufficiency. From an occupational medicine perspective, the key issue is not whether an energy drink can temporarily increase alertness, but why the work system requires stimulation to maintain the appearance of functionality.

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SMOKING AS A MODIFIABLE RISK FACTOR IN THE PREVENTION OF CHRONIC NON-COMMUNICABLE DISEASES - HARM REDUCTION IN FOCUS

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Abstract: Cardiovascular diseases remain a leading public health concern and are strongly associated with both modifiable and non-modifiable risk factors. Modifiable factors include smoking, harmful alcohol use, physical inactivity, poor diet, obesity, elevated cholesterol and blood glucose, while age, sex, genetic predisposition and family history cannot be changed. General practitioners have a central role in cardiovascular prevention through patient education, early identification of risk factors, regular health monitoring and individualized support. Among modifiable factors, smoking is particularly important because tobacco combustion generates numerous toxic substances associated with inflammatory processes, hypoxia, vascular damage and carcinogenesis. Complete cessation of tobacco and nicotine products remains the most effective strategy for reducing smoking-related health risks. Behavioural counselling and approved pharmacotherapy should therefore be prioritized and adapted to each patient. For smokers unable or unwilling to quit, harm-reduction approaches involving non-combustible products may be considered cautiously, temporarily and under medical supervision, while avoiding dual use. Effective prevention should emphasize understanding and motivation rather than fear alone. Electronic health records should also distinguish between different tobacco and nicotine product categories, enabling systematic monitoring of exposure, cessation outcomes and long-term health effects.

Keywords: cardiovascular disease; risk factors; primary prevention; smoking cessation; general practice.

INTRODUCTION

Risk factors that are recorded in the electronic record of the selected doctor are: smoking, alcohol, physical inactivity, high cholesterol, obesity, high glycemia, poor diet of fruits and vegetables, malnutrition. They are divided into variable and non-variable.

Variable risk factors are health conditions and lifestyle habits that can be influenced in order to prevent or delay the onset of many diseases. Immutable risk factors are health predispositions that a person cannot consciously influence by changing lifestyle habits.

General practitioners play a key role in the primary prevention of CVD through education, early diagnosis and continuous support for patients.

Key points:

- Patient education:

- o Information about risk factors such as improper diet, physical inactivity,

- smoking, excessive alcohol consumption and stress
 - o Promotion of healthy lifestyle habits.
- Early diagnosis:
 - o Regular examinations and monitoring of patients' health
 - o Identification of risk factors and timely response
- Continuous support:
 - o Individualized treatment and prevention plans
 - o Motivation and support for patients in maintaining healthy habits

By lowering the value of systolic pressure by 10 mmhg, we achieve a 13 percent lower mortality. By lowering the hba1c value by 1 percent, we achieve a 3 percent lower mortality., by lowering the LDL value by 1 percent, we achieve a 19-20 percent reduction in the number of major CV events, by reducing body weight by 5-6 kg, we achieve a 15 percent lower mortality, stopping smoking, a large drop in mortality, and the absence of burnout is significantly drastically less exposure to harmful combustion products.

Smoking is certainly the most powerful modifiable risk factor. Global data show that the prevalence of smoking is decreasing, however, the absolute number of smokers remains relatively stable. According to WHO data, one billion people in the world smoke, and according to forecasts, this number will not change significantly until 2025, despite all measures to ban and control the use of cigarettes.

Combustion of tobacco in a cigarette results in the release of tobacco smoke containing more than 6,000 ingredients, of which over 100 are classified as harmful and potentially harmful ingredients. Chronic exposure to these components activates a series of pathophysiological processes that are etiologically related to the development of a wide range of diseases.

The dominant harm from smoking comes practically from the process of burning tobacco at a high temperature. The process of burning tobacco, which takes place at temperatures above 400°C, plays a key role in the formation of smoke. Co binds to hemoglobin 200 times stronger than oxygen and thus leads to hypoxia.... Tar with solid carbon particles leads to the initiation of an inflammatory response.

During combustion, a complex mixture of harmful compounds is formed, among which polycyclic aromatic hydrocarbons, known for their carcinogenic potential, stand out. Experimental data show that an increase in combustion temperature significantly increases the concentration of these compounds. According to the classification of the International Agency for Research on Cancer (IARC) and the US Food and Drug Administration (FDA), nicotine is not classified as a carcinogen. Also, the US Food and Drug Administration does not classify nicotine as a cardiovascular toxin. Although nicotine acts on nicotinic acetylcholine receptors, activating the sympathetic nervous system, which can lead to a temporary increase in heart rate, myocardial contractility and vasoconstriction, these effects are acute and reversible, but nicotine itself is not a cause of chronic CVD.

The most important role of general medicine doctors is to promote healthy lifestyles and, in this connection, to prevent the initiation of smoking. However, in reality we often meet people who already smoke, and our work is reduced to trying to make them non-smokers. However, when all those who wanted to stop smoking what about those who at this moment do not want to give up this habit and for whom these approaches are not effective, which is confirmed by my practice so far. For this population, a harm reduction approach may represent an additional option. Harm reduction involves the use of less harmful alternatives that do not involve burning tobacco, with the aim of reducing exposure to toxins from tobacco smoke.

Cessation of all nicotine and tobacco products is the most effective approach to reducing the risk of smoking-related diseases. Quitting smoking requires an individualized approach, as there is no universal solution that fits all users. Different modalities of support are available, and a combination of them often gives the best results. It is crucial that interventions are tailored to the needs of the individual, with effects being monitored and evaluated.

In the 2024 ESC guidelines, there is a cautious and limited recommendation regarding the use of e-cigarettes as a transitional measure in the cessation process

This recommendation has a low level of evidence (IIb, C), meaning that it can be considered but is not strongly supported by clinical evidence.

WARNINGS AND LIMITATIONS

The ESC does not recommend the simultaneous use of e-cigarettes and traditional cigarettes, as this does not reduce the risk and may even increase the harm

The health risks of e-cigarettes remain, particularly related to vascular function and potential long-term effects

The ESC advocates strict regulation or even a ban on e-cigarettes, particularly due to their popularity among young people and the lack of clear evidence of long-term safety

Thus, we can conclude that ESC 2024 does not promote e-cigarettes as a routine strategy for smoking cessation, but allows them as a temporary option for people who fail to quit using other methods — with a clear recommendation that their use be limited and monitored.

According to American Heart Association guidelines, tobacco cessation is a key component in the management of patients with cardiovascular disease. Smoking cessation counseling is recommended at every contact, with a combination of behavioral interventions and approved pharmacotherapy. Also, according to these guidelines, electronic cigarettes with nicotine can be considered as a tool for quitting smoking, but only in the short term.

Public health campaigns often use intimidation as a tool to reduce the prevalence of a bad habit, e.g. Visually powerful messages showing the consequences of smoking - loss of life per cigarette, harmful effects on blood vessels, impact on the environment and family - are often

used in campaigns aimed at changing the behavior of smokers. In Serbia, there are warning text messages on cigarette packaging. However, the question arises:

Does this approach really change behavior – or just increase resistance?

Although fear-based campaigns are supposed to increase awareness of the risks, research shows the opposite.

According to research by behavioral psychologists published in JAMA Network Open, graphic warnings did not change smoking habits, there was no reduction in smoking during 12 months.

The bottom line is that Intimidation increases fear. Understanding and motivation change behavior.

The role of the general/family medicine doctor:

- Informing patients about the negative effects of tobacco smoke and possible complications.
- Support in the process of quitting smoking.

CONCLUSIONS FROM CLINICAL PRACTICE

The number of patients-users of alternative products is increasing

It is necessary to systematically monitor users of alternative products through the health record, with a clear differentiation of categories of tobacco and nicotine products for long-term monitoring of effects.

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