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INNOVATION MANAGEMENT AND SAFETY

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UNIVERSITY OF APPLIED SCIENCES IN SECURITY AND SAFETY

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**Banja Vrućica, hotel Kardial, Bosnia and Herzegovina
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Mile Vajkić, Biljana Vranješ, Tamara Miladinović, Vesna Nikolić

INNOVATIVE APPROACHES IN EDUCATION AND TRAINING IN THE FIELD OF OCCUPATIONAL SAFETY AND HEALTH

Abstract
Major changes in the world of work and efforts to build the profile of experts in the field of occupational safety and health who possess a wide range of knowledge and skills impose the need to introduce innovations in the forms of formal education in the field of occupational safety and health. In the field of formal education, this would refer to the innovation of curricula, the introduction of practical classes on a larger scale, the expansion and modernization of laboratory research, etc. A competent expert with formal education can easily upgrade his knowledge and skills through various forms of continuous lifelong education. In occupational safety and health training, the possibilities of applying an innovative approach include a wide range of activities. One of them is the application of modern technologies: virtual reality (VR), augmented reality (AR), artificial intelligence (AI) and others. The application of these technologies makes it possible to speed up the training process while maintaining the necessary quality, and enables the participants to acquire practical knowledge and experiences closest to real conditions in the working environment. Quality training for safe and healthy work is one of the fundamental preventive measures in the field of occupational safety and health.

Key words: education, training, occupational safety and health.

INTRODUCTION

The occupational safety and health (OSH) system represents a multidisciplinary field encompassing numerous dimensions of the modern world of work. The complex nature of risks and hazards in the workplace requires a holistic understanding of the human factor as a key component of safe and dignified work [13]. Most European Union countries have already integrated OSH principles into their political strategies, which clearly indicates the growing importance of this concept within public policy and social development. It is particularly important to emphasize the increasing insistence on systematically embedding OSH into educational programs, thereby fostering the development of a safety culture from the earliest age and ensuring the long-term transformation of institutional practices.
In this regard, the contribution of the European Agency for Safety and Health at Work (EU-OSHA) should be highlighted, as it promotes the concept of "Mainstreaming OSH into education"—the systematic inclusion of occupational safety and health in curricula with the aim of cultivating a safety culture [5]. Meanwhile, the European Network for Education and Training in Occupational Safety and Health (ENETOSH) collects examples of good practice, research, and international events, encouraging the exchange of experiences and the development of educational standards.

Numerous strategies, declarations, and international documents (ILO and other international organizations) also promote the importance of integrating OSH into both formal and non-formal education, laying the foundation for future policies and programs [8][9][13]. However, despite the evident need for OSH integration into school and extracurricular programs, as well as the necessity of continuity through lifelong learning, there is still a lack of comprehensive research on methods, opportunities, and approaches for implementing these tasks.

Occupational Safety and Health in the Formal Education System

Given the many challenges accompanying young people's entry into the world of work and career development, their aspirations for decent work and dignified living can be undermined by insufficient knowledge of rights and responsibilities regarding occupational safety and health. Risks in the world of work vary in nature and scope—from strictly professional hazards to discrimination, violence, and other psychosocial risks, as well as those arising from natural disasters, wars, and armed conflicts.
The transformative nature of the world of work requires a transformative approach to formal OSH education. This entails a reconceptualization of education, demanding a new curriculum paradigm that incorporates occupational safety and health as a fundamental dimension.
Within the European Union, cooperation among member states has resulted in the convergence of learning objectives related to OSH. According to a study published by the European Agency for Safety and Health at Work [5], OSH education involves integrating safety and health content into various teaching disciplines, thereby promoting awareness and strengthening the culture of prevention. Furthermore, teacher training in this field is essential, but even more important is the development of appropriate didactic and methodological competencies to ensure effective knowledge transfer. Teachers must be able to promote changes in how children perceive, act, and behave regarding their own safety and health—both in school and in their future workplaces [4].

The ENETOSH standard clearly emphasizes that teachers must be trained to act as promoters of a prevention culture, not merely as transmitters of knowledge. This requires the development of competencies aligned with the European Qualifications Framework, the application of innovative methodological approaches, and the systemic integration of OSH into education.
By the nature of their profession, teachers already possess didactic and methodological competencies in line with legal requirements and professional standards [Law on the Foundations of the Education System, Serbia]. In practice, however, this often translates into traditional teaching approaches such as frontal instruction, reproductive methods, and classical forms of knowledge assessment. While these approaches provide structure and systematization, their impact on developing critical thinking and lasting preventive behavior remains limited [4].

On the other hand, innovative methodological approaches in formal OSH education demonstrate significantly greater potential for enhancing learning effectiveness and building a sustainable prevention culture. The greatest impact is achieved through the whole-school approach, which entails systemic integration of OSH into all aspects of school life [ENETOSH Standard], as well as the use of modern technologies—virtual reality, digital platforms, and gamified learning content [9]. These approaches enable active participation of both teachers and students, foster practical competencies, and encourage interdisciplinary learning.
In conclusion, innovative methods not only contribute to better knowledge acquisition but also shape values and behaviors that form the foundation for responsible action in professional and social contexts. The optimal model for developing a prevention culture in formal OSH education lies in combining teachers' traditional didactic competencies with contemporary methodological innovations.

Training of Occupational Safety and Health

Training of employees for safety and health work represents a fundamental preventive approach within the Occupational Safety and Health (OSH) system at every workplace. Within this training, the worker should become familiar with all hazards and harmful factors present at the workplace, the existing safety risks, the established procedures for safe work, and the measures undertaken to reduce the identified risks to an acceptable level. The aim is to reduce the likelihood of occupational injuries and work-related health impairment and to maintain an adequate level of safety in the working environment. The goal of the training process is to equip workers with the necessary knowledge and skills that enable the safe performance of work tasks, while minimizing the risk of injuries and damage [13]. Through the training and educational process, workers should also become familiar with the rules and procedures for the safe use of work equipment, safe movement within the workplace, basic ergonomic principles, rules of workspace organisation, incident response procedures, and proper methods of manual handling of loads. Research shows that in working environments where effective safety training has been implemented, an increased ability of employees to identify hazards and risks has been observed, along with appropriate

responses in incident situations, a reduced number of workplace injuries, a lower frequency of unsafe behaviour, and an improved level of safe handling of tools and equipment. In order to enhance hazard recognition and response skills, employers often provide new hires and experienced workers with hazard identification and management training programs [3].
Systematic and continuous training and education of employees for Occupational Safety and Health (OSH) represents the foundation for building a safety culture within an organisation. Training for OSH requires a specific approach, as it involves adults who already possess a certain level of professional knowledge for a given occupation acquired through formal education. Therefore, this type of training also requires an andragogical approach. Such an approach implies adherence to the fundamental principles of training based on conscious engagement, active participation of trainees, and the integration of theory and practice. Training should be based on proactive learning in order to enhance knowledge retention, acquisition, and application. Legal regulations in most countries prescribe mandatory training for Occupational Safety and Health (OSH). The employer has the primary obligation and responsibility to organise occupational safety and health within the working environment. One of the fundamental principles in ensuring preventive measures implemented by the employer is the appropriate training of workers for OSH, as well as the issuance of instructions for safe work practices. This includes initial training prior to a worker's commencement of work at the workplace, as well as continuous training in all situations that may lead to changes in the level of occupational safety and health, such as changes in the workplace, the use of new work equipment, and similar circumstances. Training must be tailored to the specific characteristics of each workplace. The employer may delegate OSH training to a designated occupational safety and health officer within the organisation or to an authorised external organisation responsible for performing occupational safety and health activities.

The traditional form of training for Occupational Safety and Health (OSH) is a combination of theoretical and practical components. The theoretical component involves familiarisation with regulations, rules, and the organisation of occupational safety and health, while the practical component, which is conducted directly at the workplace under the supervision of a direct supervisor, focuses on familiarisation with and preparation for specific work tasks and the associated safety procedures. In the theoretical part of the training, the effectiveness of knowledge transfer and knowledge acquisition by trainees largely depends on the expertise, pedagogical competencies, and skills of the lecturer/instructor, and it involves the use of educational materials such as specialised literature, legal regulations, as well as audio and video resources. Practical training and demonstrations under real working conditions have proven to be particularly effective in conveying key safety principles, increasing hazard awareness, and developing safe working practices [18]. After each training session, an assessment of the participants' acquired competencies is conducted in both theoretical and practical aspects, followed by continuous further training at intervals defined by the risk assessment document (Risk Assessment Act).
Numerous changes in the world of work, dynamic working environments, and the increasing level of digitalisation and development of modern technologies have imposed the need to introduce innovative approaches to Occupational Safety and Health (OSH) training in the workplace. The emergence of new technologies is transforming approaches to education, leading to various forms and models of e-learning [16]. The application of virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) technologies provides opportunities to accelerate the training process while maintaining the required quality, enabling the acquisition of practical knowledge and work-related experience in controlled conditions that closely resemble real environments, as well as supporting a proactive approach within the training process.

Virtual reality (VR) and augmented reality (AR) in Occupational Safety and Health (OSH) training are used for practical training by "immersing workers" in simulated work environments, including incident and accident scenarios, thereby enabling the acquisition of "real practical experience". They can also be applied in fully interactive training settings, where users engage with virtual educational content and three-dimensional virtual representations, through which they acquire knowledge and develop competencies.
In recent years, artificial intelligence (AI)-based technologies have increasingly influenced education [1]. As a standard component of modern education systems, AI can also be significantly applied in Occupational Safety and Health (OSH) training, contributing to the modernisation and improvement of the educational process [15], as well as to the reduction of risks in practical instruction within dual vocational education systems.

The potential of AI lies in the analysis of large datasets, the prediction of hazardous situations [6], the personalisation of learning, and the support of preventive measures. Its application can enhance learner safety through increased accessibility and interactivity of educational content, while simultaneously strengthening safety culture and ensuring compliance with institutional legal obligations. AI solutions support Occupational Safety and Health (OSH) training through the monitoring of the training process, including compliance with safety procedures, recording of injuries and learner behaviour [7], the implementation of adaptive learning platforms, VR/AR simulations, and intelligent knowledge assessment systems [14], as well as the use of IoT technologies for monitoring working environment conditions and providing timely risk alerts.

METHODS

Aim of the paper

The aim of this paper is to present the possibilities and necessity of applying an innovative approach in the field of education and Occupational Safety and Health (OSH) training, which have emerged as a result of changes in the world of work and the increasing level of implementation of modern technologies.

Methods of work

A combination of scientific methods was used: the method of analysis and synthesis in collecting relevant information on education and Occupational Safety and Health (OSH) training, the analysis of relevant literature in this field, and the interpretation of available models of education and training in occupational safety and health. In addition, methods of implementing the fundamental provisions of legal regulations governing OSH training were applied.

For the purpose of investigating the state of implementation of modern technologies in OSH training, a specially designed survey research was conducted.

APPLICATION OF MODERN TECHNOLOGIES IN TRAINING FOR OCCUPATIONAL SAFETY AND HEALTH

From their initial application in the field of gaming, augmented reality (AR) and virtual reality (VR) technologies have increasingly been used in the healthcare sector, education, and workforce training in general, including Occupational Safety and Health (OSH) training. Guidelines for education based on augmented reality applications are more effective solutions for training [19]. Studies have shown that VR is a suitable tool for designing safety training systems and researching human behavior in emergencies [12]. VR is increasingly being embraced in both its immersive and non-immersive versions for providing safety training in various industries and for different types of disasters [10].

VR technologies are applied in Occupational Safety and Health (OSH) training across many sectors, with construction being one of the earliest fields of application. The most commonly used models in construction-related safety and health training include the application of Building Information Modeling (BIM) software (Figure 1) and serious games. Unlike other VR models used in training, BIM-based VR relies on a model for repeating construction processes and operations, integrating safety training into construction [2]. The best examples of using VR technology in game-based training are multi-user safety training systems for dismantling tower cranes at construction sites [11].

Figure 1. BIM Software [16]

The methodology for conducting Occupational Safety and Health (OSH) training using VR and AR technologies is based on the development of interactive simulations of real work environments, enabling hazard identification and the practice of correct procedures without exposure to actual risks. The process includes the analysis of work tasks, scenario design, the implementation of training through immersive experiences, and the evaluation of achieved outcomes with the aim of improving safety competencies.

VR simulations are particularly applicable for practical worker training, as they enable the imitation of real working environments and the integration of educational content with real-life situations that workers may encounter in the workplace. Through this form of training, workers acquire a more engaging and effective "work experience", with improved knowledge retention and increased confidence in responding to hazardous situations in accordance with safety procedures. The advantages of virtual reality lie in its ability to transfer tacit "experiential" knowledge. Realistic training scenarios can effectively demonstrate workplace hazards and risks, thereby enabling high-quality education through the use of VR and AR technologies. The adaptability of content to different educational methods and to the diverse needs of trainees is a key factor for the successful implementation of these advanced technologies in education [16]. The creation of educational content for VR and AR technologies can be achieved through several methods: 3D modelling and animation, interactive programming, 360° video, simulations, and the development of interactive scenarios. Figure 2 illustrates the training process of a CNC machine operator presented through a series of 360-degree images, enabling the worker to independently become familiar with all work operations and applicable safety procedures in a fully controlled immersive environment through the generation of three-dimensional representations.

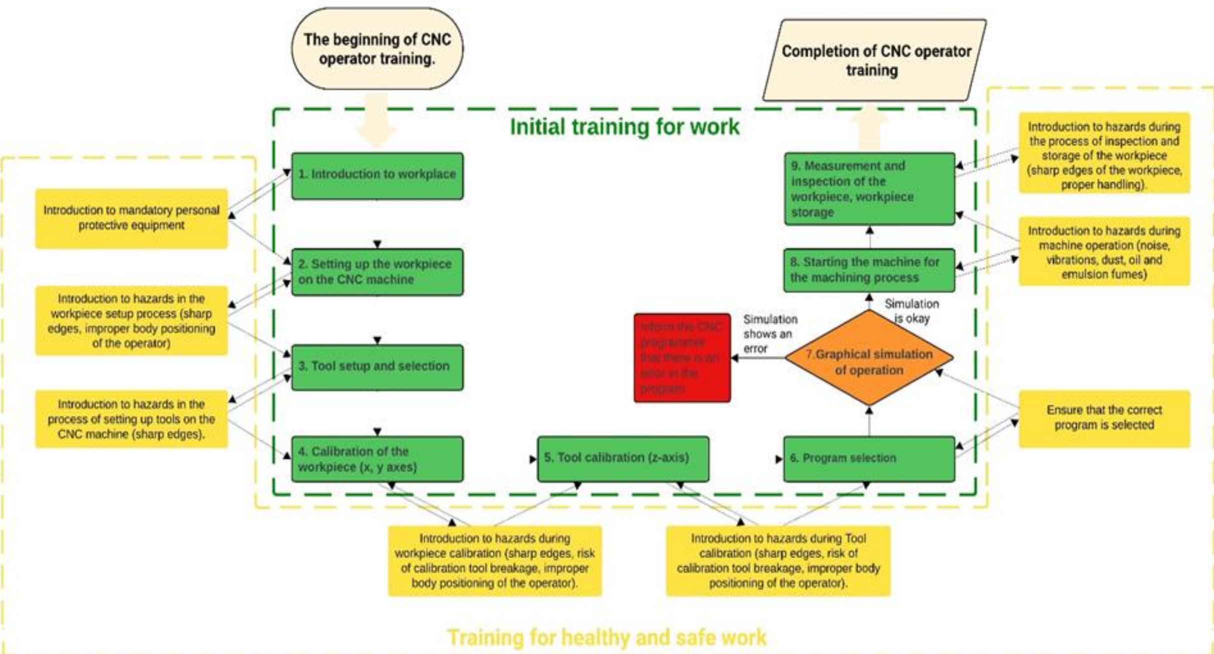


Figure 2. Developed OSH training model using VR360 technology for CNC operator [17]

RESULTS

Survey on the opinions of experts from authorised organisations for performing Occupational Safety and Health (OSH) activities in the Republic of Srpska - BIH

In order to obtain a comprehensive understanding of the application of modern technologies and approaches in Occupational Safety and Health (OSH) training, a survey was conducted among experts from licensed (authorised) organisations for occupational safety ain the Republic of Srpska. The survey was administered via Google Forms, and a total of 22 licensed organisations participated in the study, of which 16 provided completed responses.

The survey included questions related to the preparedness of educational materials for different workplaces, the use of materials that visually represent actual workplace hazards and harmful factors, as well as the accurate presentation of risks during OSH training. Additionally, respondents were asked about their familiarity with the concept of virtual reality (VR), prior experience in using VR technology, the possibilities of applying VR in the training process, the expected benefits of its use, and their willingness to implement this technology in future training activities.

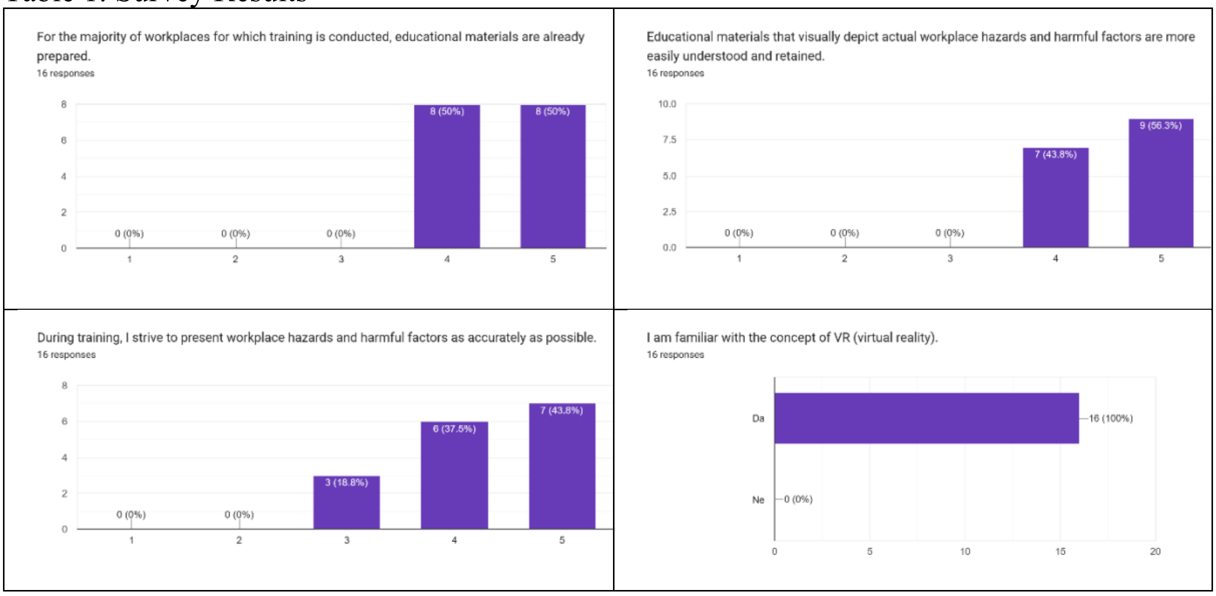
Respondents provided answers using a binary scale (Yes – No) and a five-point Likert scale (1 – Strongly disagree, …, 5 – Strongly agree).

The aim of the survey was to collect the professional attitudes and experiences of experts, with a particular focus on the effectiveness of different training methods, the opportunities and challenges associated with the application of modern technologies, and the identification of needs and potential improvements in Occupational Safety and Health (OSH) training programmes. The results provide insight into the perspectives and experiences of professionals, which may contribute to the development and enhancement of OSH training practices.

DISCUSSION

This section presents and analyses the results of the conducted survey, with the aim of examining the current state and possibilities for the application of modern technologies in Occupational Safety and Health (OSH) training. The obtained data are interpreted in the context of existing practices and theoretical insights in order to identify key trends, challenges, and potentials for improving the training process. The survey results are presented in Table 1.

Table 1. Survey Results



Source: Own source

Based on the obtained survey results, it can be concluded that all licensed organisations possess pre-prepared materials for Occupational Safety and Health (OSH) training for all workplaces, indicating the existence of a standardised approach to the implementation of this process. However, although the formal level of preparedness is satisfactory, the results point to the need for further improvement in the quality and methods of content presentation.

The obtained data also indicate that all respondents are familiar with the concept of virtual reality (VR); however, its practical application remains highly limited, as only 25% of respondents have used these technologies for any purpose. This points to a gap between theoretical awareness and the actual implementation of modern technologies in practice.

Furthermore, 62% of respondents believe that VR technologies can be used in the training process, indicating an awareness of their potential. However, when asked about the possibility of accelerating the training process and increasing the initial level of knowledge regarding hazards and harmful factors, the majority of respondents provided negative answers. This may indicate a certain level of scepticism or insufficient awareness of the specific benefits of these technologies.

Additionally, the results indicate that respondents are largely not prepared to attempt the implementation of VR technologies in Occupational Safety and Health (OSH) training processes in the near future, and that the majority believe these technologies will not significantly contribute to the improvement of this process even in the long term. Such attitudes may stem from technical, financial, and organisational constraints, as well as from a lack of practical experience and examples of good practice.

CONCLUSION

Within the European context, there is a well-established recognition of the necessity to systematically integrate Occupational Safety and Health (OSH) topics into formal education curricula across all levels of education, as well as into diverse forms of non-formal education and training implemented after the attainment of specific qualifications. The incorporation of OSH into educational processes requires a comprehensive and systematic approach, encompassing not only structured implementation but also continuous evaluation, revision, and innovation in alignment with the dynamic and evolving nature of

the contemporary labour market. Particular emphasis must be placed on teaching staff engaged in OSH education, whose competencies in knowledge transfer necessitate ongoing professional development. This development should be oriented toward the enhancement of pedagogical, methodological, and technological capacities, in accordance with emerging and innovative trends in education and training.
Furthermore, the application of innovative educational and training methodologies in the field of occupational safety and health is expected to facilitate more effective knowledge acquisition, while simultaneously contributing to the development of values, attitudes, and behavioral patterns that constitute a fundamental basis for responsible and proactive engagement in both professional and broader social contexts.
The development of contemporary technologies, including artificial intelligence, virtual reality, augmented reality, digital platforms, and gamified learning content, has enabled the introduction of new forms and modalities of delivering and acquiring educational and training content. This applies not only to the field of education and training in general, but also specifically to the domain of occupational safety and health.

The primary objective of any occupational safety and health training is to reduce the likelihood of risk occurrence in the workplace, thereby decreasing the incidence of occupational injuries and enhancing workers' well-being. In light of the rapid pace of technological advancement and the continuous need to improve occupational safety and health training, the potential offered by emerging technologies should not be overlooked.
However, the results of the conducted research indicate that, although there is a certain level of familiarity with contemporary technologies, their practical application remains insufficiently represented. A discrepancy has been observed between the recognition of the potential of these technologies and the readiness for their concrete implementation, which suggests the existence of specific barriers, both in terms of available resources and in terms of trust in their effectiveness.
In this regard, it can be concluded that the improvement of occupational safety and health training processes necessitates additional dissemination of information and targeted education of professionals regarding the possibilities of applying contemporary technologies, as well as the establishment of conditions for their gradual implementation in practice.
The integration of innovative approaches, while maintaining validated and established methods, may contribute to enhancing the overall effectiveness of training and fostering a more comprehensive understanding of workplace risks, ultimately leading to a higher level of safety and the protection of workers' health.

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IMPROVING DYNAMIC RISK ASSESSMENT THROUGH PHOTOACOUSTIC SENSING: FROM LAB TO FIELD

Abstract
Rapid technological development has introduced new challenges for occupational and environmental safety. Due to limited operational experience with evolving technologies, specific accident scenarios may remain unidentified until they occur for the first time. Since they deviate from conventional, expected, or previously recognized accident patterns, events can be classified as atypical. Traditional risk assessment, as static and nonflexible, generally is uncapable to predict and evaluate these uncommonly events. Dynamic risk assessment can overcome these limitations, by enabling continuous updating of risk levels as new data become available. At the same time, advances in detection techniques have improved the ability to monitor various accidents. Photoacoustic spectroscopy is a powerful tool for trace gas detection, capable of providing high-quality data, and support early warnings, and timely safety decisions. In this paper the potential usage of photoacoustic for dynamic risk assessment is discussed.

Key words: dynamic risk assessment, photoacoustic spectroscopy, trace gases detection.

INTRODUCTION

Rapid technological growth has introduced numerous benefits in modern life, including new methods, materials, devices, procedures, and systems. At the same time, innovations have created novel and unique safety challenges [2,30]. Hydrogen technologies, fusion energy, innovative nuclear technology (including small nuclear reactors and advanced nuclear reactors), carbon capture and storage, battery energy storage systems, advanced energy systems, nanomaterials, biotechnology, and other represent emerging or rapidly developing technologies with limited operational experience. Potential hazards may include leakage, corrosion, explosions, fires, toxic gas emissions, material degradation, and complex failure mechanisms. Accordingly, novel technology and processes may generate accident scenarios that deviate from conventional and previously recognized patterns. To predict such scenarios can be particularly difficult when hazardous gases are present in trace concentrations, fire propagation is unpredictable, or material characteristics under high temperatures and new condition are unknown. Owing to the limited operational experience associated with emerging technologies, certain types of accidents may remain unrecognized until they occur for the first time. Such events may be regarded as atypical when they deviate from conventional, expected, or previously identified accident patterns [43]. To prevent occupational risks, and possible accidents in high technology era, risk assessment and risk management must be developed in line with technology. Risk assessment includes identification, analysis, and evaluation of risk, to reduce and eliminate factors that can lead to injuries, accidents, or death. Since risks change over time, prediction must be focused on continuous and systematic hazards recognition, collection, and data analysis to timely prevent consequences.

Nowadays, in complex, high technology society, safety engineers often deal with uncertainty, incomplete or ill-defined data, which restrict their efforts to control and eliminate hazards from working environments. Traditional risk assessment, being largely static and strict, is often lacking in evaluation and prediction of atypical scenarios. To address these limitations, the concept of dynamic risk assessment (DRA) has been developed, enabling continuous risk updating as new data become available [24, 26, 44]. In the context of Industry 4.0 and Industry 5.0, digital transformation has significantly changed the way of monitoring and managed occupational and environmental risks. The use of sensor systems, the Internet of Things (IoT), artificial intelligence (AI), robotics, and automated data processing enables integration of numerous data that can be collected, analyzed, and exchanged in real time, to

advance early warnings, timely decision-making, and preventive action before incident arises [14]. The concept of Industry 5.0 further shifts the focus from competitiveness, efficiency, and productivity towards human well-being, sustainability, and system resilience [20]. Therefore, the implementation of advanced monitoring techniques and early warnings is essential for supporting DRA and improving timely recognition of atypical accident (current concentration of hazardous gases, temporal variation, exposure duration, and vicinity to toxic or explosive threshold). DRA represents an advanced approach in safety monitoring, where the level of risk is continuously updated according to real-time sensor data. Over the last decade, progressive development of low-cost sensors has significantly improved monitoring of airborne pollutants, environments, and industrial process control. Miniaturized, placeable and wearable low-cost sensors have enhanced long-term workplace surveillance, but they also raise challenges related to data reliability [15,31]. Low-cost sensors have limitations regarding sensitivity, interference, and calibration [31]. Current technological development supported by the growth of AI opens new possibilities for improving gas monitoring systems through automated signal correction, pattern recognition, and prediction. The rapid progress of science has also enabled development of detection techniques. Moreover, the need for more sensitive and selective detection methods creates significant opportunities for the implementation of modern and powerful techniques such as photoacoustic spectroscopy (PAS). PAS is a laser-based technique, suitable for environmental monitoring, industrial process control, the analysis of combustion processes and identification of toxic, flammable gases, and explosive. PAS has establish as a powerful technique with high sensitivity, selectivity, robustness, and wide dynamic range, which provides high quality measurement data [34, 35, 3, 5, 9]. It allows early warnings, continuous updating risk scenarios, and more timely decision in occupational, environmental, and fire-protection applications.
PAS may support sensor based DRA approaches, where real-time monitoring data are used to assess accident sources, and evolving risk conditions. In other words, PAS may transform gas monitoring from passive threshold based detection into proactive, data-driven DRA. In industrial process control, where various gases may release rapidly and simultaneously, continuous, approach is crucial for risk prevention and safety. According to the goals of Industry 5.0, integration of photoacoustic (PA) sensors into automated warning systems, may have significant role in effective workplace surveillance contributing to overall employee well-being.

FUNDAMENTAL PRINCIPLES AND PRACTICAL STRENGTHS OF PHOTOACOUSTIC SENSING

During the years PAS has established as reliable and successful technique for direct optical absorption measurements, providing real-time operation, in situ measurement, and multicomponent analysis, with no need for complex sample preparation [3, 5, 9, 34]. PA effect was discovered by Alexander Graham Bell almost 150 years ago. PAS is calorimetric method based on the generation of a PA signal after absorption of modulated or pulsed laser radiation by a gas sample. Excited molecules release energy through collisions with surrounding molecules (non-radiative relaxation). The most important relaxation process for PA signal generation in gases is transfer of absorbed optical energy into heat. Localized heating in a sample causes a periodic increase in temperature and pressure, producing acoustic waves. Acoustic wave (PA signal) is detected by a microphone or another pressure-sensitive detector. A typical PAS system for gas sensing consists of a laser source, a PA cell, and an acoustic detector (Figure 1). The amplitude of the PA signal, in the case of a gas mixture, can be calculate from [34, 35]:

$$S(\lambda) = C\langle P(\lambda)\rangle Nc\sigma(\lambda) \qquad (1)$$

where C is a cell constant, $P(\lambda)$ is the average power of the incident laser radiation at the wavelength λ, N is the molecular density, c is the concentration of absorber molecules and $\sigma(\lambda)$ is the absorption cross section at the wavelength of the incident laser radiation. PAS requires calibration, i.e., determination of relationship between energy absorbed by the sample and intensity of the PA signal. Sensitivity of PA systems increases with laser power. Energy absorbed by the sample is directly proportional to concentrations of absorbers (gas molecules), ensuring sensitive quantitative analysis [34]. To achieve high selectivity in trace gas detection, laser wavelength must match the absorption lines of the target molecules. This is particularly important in the infrared spectral region (fingerprint region), where numerous molecules absorb radiation through rotational and vibrational transitions. PA method is zero-background: if the sample does not absorb light, no acoustic signal is produced. PAS allows higher sensitivity and selectivity than conventional optical absorption spectroscopy. Sensitivity of a PAS system depends on several factors, including laser power, microphone sensitivity, PA cell design, background noise, and efficiency of absorbed optical energy conversion into heat. High-power lasers such as CO_2 and CO lasers provide high sensitivity and selectivity (reaching ppb to ppt detection limits)[1], but they are generally more complex and isn't suitable for in situ measurement. Successful PAS applications in industrial process control and environmental monitoring, along with sensitivity and selectivity, mostly depend on a wide dynamic range and good temporal resolution. The gas concentrations in the range of six orders of magnitude can be measure with the same device [35].

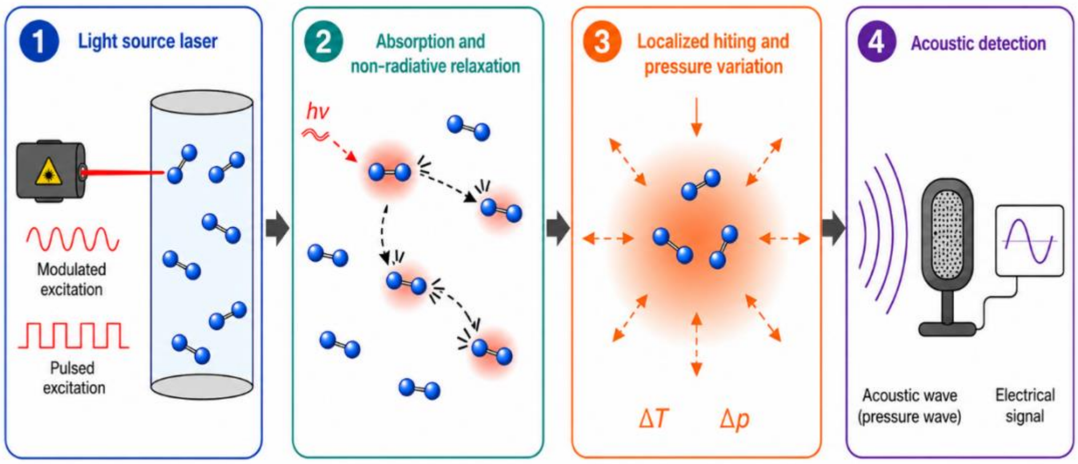

Fig. 1. Principal scheme of PA wave generation in a gas sample.

PAS characteristics that are crucial for successful application in detection and monitoring of toxic, flammable, hazardous, and trace gases are:

- high sensitivity,
- high selectivity,
- wide dynamic range,
- multicomponent analysis,
- simple and robust experimental setup,
- ease of use (suitability for field and in situ measurements);
- real-time signal analysis and continuous monitoring;
- reliability (calibration performed with certified gases and gas mixtures);
- no need for sample preparation;
- cost-effectiveness.

To enhance performance of PA detection and improve the portability and mobility of PA devices for practical use outside the laboratory, numerous adjustments of conventional PA configurations have been introduced [32]. These developments have mainly focused on three aspects: the use of higher laser power, optimization of PA cell geometry, and the implementation of more sensitive acoustic detectors [45]. However, development of tunable diode lasers has enabled the smaller size design, easy handling and lower price of PAS devices. Further, quantum cascade lasers, Nd:YAG lasers, and other compact laser sources are good alternatives to conventionally used measurement methods, due to long-term, automatic on-line monitoring [3]. Recently, more efficient acoustic transducers have developed: custom quartz tuning fork (QTF), cantilever, fiber-optic microphone, etc. Quartz-Enhanced Photoacoustic Spectroscopy (QEPAS) employs a resonant QTF as acoustic transducer instead of a conventional microphone [27, 29]. Current progress in QEPAS has significantly expanded the applicability of PA sensing in environmental, industrial, and safety monitoring. In the review by Shunda et al., QEPAS and light-induced thermoelastic spectroscopy (LITES) are identified as two major QTF-based techniques that provide high sensitivity, compact sensor design, and strong immunity to environmental noise [33]. LITES technology is vulnerable to damage from corrosive gases or harsh combustion environments

[1] ppm - parts per million (1 ppm = 10^{-6}), ppb - parts per billion (1 ppb = 10^{-9}), ppt - parts per trillion (1 ppt = 10^{-12}).

[33]. PA sensing approach, including QEPAS, and cantilever-enhanced photoacoustic spectroscopy (CEPAS), have shown strong potential for trace-gas analysis. In this method, the acoustic signal is detected by a miniature silicon or micromechanical cantilever that serves as the sensing element [46]. CEPAS offers higher sensitivity than many other PA methods. Compared with traditional PAS configurations, these techniques generally provide higher sensitivity and an improved signal-to-noise ratio. Also, to achieve a full sensor miniaturization and highly sensitive and cost-efficient PA device Strahl et al. proposed a MEMS microphone as PA cell [40]. PAS is particularly suitable for detection of atmospheric pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen monoxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and volatile organic compounds (VOCs). QEPAS and LITES have been reported highly sensitive detection of gases such as CO, N_2O, CH_4, CO_2, C_2H_2, NH_3, and H_2S, with very low detection limits [33]. De Palo et al. reported measurement of eight air pollutants CH_4, NO_2, CO_2, N_2O, CO, NO, SO_2 and NH_3 (with detection limits of 40, 13, 800, 230, 450, 78, 18, and 5.8 ppb) using a modular QEPAS setup, in which the same QTF acoustic detection was combined with interchangeable laser sources selected for each target molecule [4]. PAS has applied for online N_2O monitoring in the off-gas of wastewater treatment plants. In the study by Thaler et al., the PAS method was successfully implemented provided a detection limit below 1 ppm with a dynamic range exceeding four orders of magnitude, making it more suitable for practical wastewater off-gas monitoring [42]. Applying enrichment-enhanced PAS, a detection limit of 1.3 ppb for NO was achieved [8]. Ouma et al. developed a near-infrared diode-laser PA system for quasi-simultaneous detection of $^{14}NH_3$ and $^{15}NH_3$, with detection limits of 0.15 ppm for $^{14}NH_3$ and 0.73 ppm for $^{15}NH_3$, with a response time of 3.5 s [23]. Yin et al. developed a highly sensitive PAS system for ppb-level of SO_2 detection [38].

In industrial monitoring, QEPAS is relevant for real-time in situ gas analysis and process control. Important target gases include NH_3, CH_4, H_2S, CO, CO_2, NO, N_2O, SO_2, acetylene (C_2H_2), and other hydrocarbons. Shunda et al. highlighted several successful PA implementations [33]. NH_3 was detected at 14 ppb with 1 s integration time and at 1.5 ppb with 40 s integration time. H_2S was measured at 142 ppb with 67 s integration time, while simultaneous H_2S/NH_3 detection reached 17 ppb and 52 ppb, respectively. SO_2 was detected at 63 ppb, and H_2S at 492 ppb. NH_3 and H_2S detection are of grate importance due to their role in chemical plants, refineries, petrochemical facilities, and leak monitoring. Also, reliable detection of NH_3 is of particular importance in the chemical industry, allowing to reduce risk of fires and explosions. In the atmosphere, NH_3 levels may range from only a few ppb to several hundred ppb in polluted regions, while in industrial facilities they may increase from a few ppm to approximately one hundred ppm following leakage [36]. In this context, the wide dynamic range of PAS is important. Another significant pollutant is NO_2 representing a part of industrial exhaust gases, which significantly contributes to ozone formation. Through further optimization of QEPAS-based systems, detection limits of 54 ppt for NO_2 [37] and 2.41 ppm for CH_4 [39] have been reported. For industrial safety and environmental monitoring rapid hydrogen (H_2) detection is essential. A novel photoacoustic ringdown spectroscopy (PARS) technique enables fast and sensitive H_2 detection, achieving a response time of about 3.9 s and a detection limit of 8.68 ppm. This approach shows strong potential for leak detection and real-time monitoring in safety-critical environments [6]. Conductance–photoacoustic spectroscopy (ConPAS) has been proposed as a promising platform for simultaneous detection of hydrogen and hydrocarbon gases using a single QTF. Experimental results show detection limits of 0.69% for hydrogen, 40.26 ppm for propane and 133.7 ppm for methane, with excellent linearity and a response time below 1 ms. However, ConPAS should currently be regarded as an emerging laboratory-stage technique rather than a sensor technology already in regular industrial use. Further validation, long-term stability testing and industrial certification are required before practical deployment [49]. Zhang et al. developed a highly sensitive PA gas sensor for gas leakage detection, based on a micro-embedded acoustic resonator. The sensor was tested for acetylene (C_2H_2) detection in nitrogen and achieved a detection limit of 29 ppb with a 1 s integration time. Due to its compact design, small gas volume, and low cost, the proposed sensor is suitable for remote gas leakage monitoring, environmental sensing, and industrial process control [48].

A further challenge in industrial monitoring is simultaneous release of different pollutants. In those situations their absorption features may overlap, reducing the selectivity of the measurement. Serious consequences for both human health and the environment can occur under simultaneous emission of H_2S and CH_4 from oil and gas wells, petroleum refineries, and related sources. QEPAS measurements have provided minimum detection limits of 2.5 ppm for H_2S and 85 ppm for CH_4 in such applications

[22]. QEPAS-based sensor has been tested to continuously monitor the CO in air close to a traffic light [32]. Kinjalk et al. demonstrated a long-wavelength QEPAS sensor for selective detection of VOCs, including toluene, benzene and propane. The system achieved detection limits of 113 ppb for toluene, 3 ppb for benzene and 3 ppm for propane, showing strong potential for environmental and industrial monitoring. These compounds are released from transportation, engine exhaust, petrochemical refineries, and other sources, and represent health concern even when present at ppb concentrations [13]. It has been reported that CEPAS can reach a detection limit of 150 ppt for benzene, C_6H_6 [14].

For fire protection the main benefit of infrared PA gas detection is possibility to make low-cost detectors, especially in air-quality monitoring in ventilation systems, where PA sensors have long been used to measure CO_2 [21]. In fire safety monitoring, QEPAS has applied on early detection of combustion gases, leakage, and explosion hazards. CO is one of the most important fire-related gases, and using QEPAS minimum detection limit of 340 ppt of CO has reported. Yin et al. discussed the development and capabilities of PA sensors for detecting CO and CO_2. They conclude that current PAS-based systems for CO and CO_2 detection can achieve detection limits ranging from 1 ppm to 1 ppb [47]. CH_4 was detected at 13 ppb, while H_2S and NH_3 detection are relevant for toxic and explosive industrial atmospheres. Józsa et al. proposed External exhaust Photoacoustic Analyzer (ExPA) to monitor rapid changes in pollutant emissions during variable or unstable combustion. ExPA reacts faster and captures the real emission, helping researchers identify pollution peaks and develop cleaner combustion systems [10].

Development and various modification in PAS by improving the quality, reliability, and timeliness of gas-monitoring data can contribute to risk and safety management. Unlike conventional low-cost sensors, which may suffer from limited sensitivity, drift, cross-sensitivity, and calibration issues, PAS systems provide highly selective and sensitive measurements enabling detection of concentration changes before critical threshold values are reached.

FROM ADVANCED GAS SENSING TO INTELLIGENT SAFETY MANAGEMENT

Traditional risk assessment methods often do not provide a complete picture of how risk changes over time. Villa et al. advocate that a conventional techniques lack a “dynamic dimension,” i.e. ability to learn from new knowledge, experience, and early warnings [44]. Also, traditional assessments mostly rely on known scenarios, while events that seem unlikely may be neglected. Paltrinieri et al. [24,26,43] emphasize that accidents can occur in the process industry that were not covered by standard safety analyses. Such events they differ from usual expectations are called atypical [43]. The atypical scenarios are not necessarily completely “unknown.” In many cases, weak signals, similar incidents, near misses, technological changes, organizational weaknesses, or signs from literature and accident databases had already existed. Since, traditional methods often fail to include them due to low probability, Paltrinieri et al. are introduced – Dynamic Procedure for Atypical Scenarios Identification [43]. The DyPASI method upgrades existing techniques, by incorporating information from early warnings, previous accidents, databases, literature, and new knowledge. The main requirement is early recognition of small failures, deviations in process operation, near misses, repeated alarms, changes in equipment, weaknesses in communication and organization.

Accident occurrence is often preceded by a series of weak warning signals that are not taken seriously. DyPASI methodology based on early warnings is essential for identifying evolving risk. DRA doesn’t treat risk as fixed, but as a flexible category that fits to changes in processes, equipment, organization, and environment. DRA aims to consider evolving risks and early warning signs, to update systematically current risk estimation [44]. Implementation of new or developing technologies may generate new, unknown, unpredictable, atypical accidents and risks. The concept of DRA, [24], refers to risk as a time-dependent quantity that evolves with the changes in the system, learns from new information to timely update risk assessment. If risk is continuously monitored, management can react earlier: by changing procedures, adding maintenance, improving barriers, providing training, temporarily stopping the process, or carrying out additional analysis. It helps to detect atypical scenarios. It was obvious that commonly used definition of risk given by Kaplan and Garrick needs revision [11]. Aven and Krohn proposed new definition of risk (R), which includes continuous updated variable knowledge (k):

$$R = f(s, p, c, k), \qquad (2)$$

where s is a scenario (what can go wrong), p is a probability (what likelihood it will have) and c is a consequence [1]. There are various methods for updating knowledge variable k and risk R, such as iteration of dynamic hazard identification, frequency analysis and consequence analysis [24].

The main goal of DRA is to enable early hazard detection and timely response before the concentration of a hazardous gas reaches a critical level. It is not enough to know only information about the presence of gas, but: concentration trend, they proximity to safety limits, the potential formation of an explosive mixture, the level of worker exposure, and whether the overall situation is deteriorating or stabilizing. PAS transforms gas monitoring from passive threshold based detection into proactive, data-driven risk management [12]. Based on this DRA framework, the integration of PAS measurements can be described through the following steps. First, the sensing system continuously measures the concentrations of relevant gases by PAS sensors (QEPAS,CEPAS or other), which provide high sensitivity, selectivity, and real-time monitoring. In the second step measured concentrations are evaluated and compare with known safety thresholds (for examples occupational exposure limits for toxic gases, and lower explosive limit for flammable gases, or both for toxic and flammable gases simultaneously). The third step is the analysis of concentration changes over time, because the same concentration can be interpreted in different ways depending on the trend. The PAS system provides reliable real-time measurements, while the DRA algorithm can continuously evaluates risk (rate of change, or concentration trend) and calculates current risk level classifying into categories (normal, warning, hazardous, or critical) [17,41,44]. Finally, based on classification, system supports decisions such as alarm activation, ventilation control, process shutdown, or evacuation.

Therefore, the main PAS value for DRA relies on ability to convert high-quality gas measurements into actionable information for prevention, early warning, and continuous risk control. Hazardous gas scenarios are rarely static, and PAS usage should be focused on five main points: detection for prediction, move from static to dynamic risk management, informed decision-making, reduction of false alarms and operational interruptions, integration with AI and digital systems.

In the context of the Paltrinieri and Khan approach, PAS can be described as a proactive monitoring tool based on indicators, that is used not only to confirm that a hazardous threshold has already been reached, but also to identify early changes that may indicate the development of a hazardous scenario. For example, a gradual increase in CH_4 concentration may indicate the formation of a flammable atmosphere, an increase in CO may point to an early stage of fire or incomplete combustion, while an increase in H_2S or NH_3 may indicate a leakage. Instead of relying only on predefined alarm thresholds, the DRA system continuously learns from real-time measurements and manages of working conditions.

The implementation of machine learning (ML) can further advance PAS toward online, real-time analysis [18,19], particularly in complex environments where humidity variations, temperature changes, and background noise may affect measurement accuracy. ML can support the identification of pollutant sources, prediction of concentration trends and atypical scenarios. Furthermore, ML implementation can establish PAS as a more versatile, application oriented technique with self-correction capability. Improvement of PA detection by ML represents an important step toward intelligent gas sensing platforms capable of adaptive monitoring, and data-driven risk assessment. The approach proposed by Paltrinieri et al. supports the idea that risk assessment can be improved by using ML [25]. In this context, PAS can provide accurate real-time data as input for ML models used in DRA to support prediction, classification, and decision-making in hazardous gas scenarios. Such models could learn from data to recognize patterns and produce more adaptive and predictive safety response. PAS can serve as a tool for closing the loop in risk management by participating in the following steps.

a) **Hazard identification**. Conventional sensors often activate alarms after a threshold has already been reached. Due to high sensitivity and selectivity, PAS can detect small concentration changes at an earlier stage, allowing risk recognition in initial phase.
b) **Exposure assessment**. PAS provides real-time data on gas concentrations, as input in DRA models. In this way, risk is not assessed only in advance, but is continuously updated according to the current state of the system.

c) **Risk characterization**. Continuous monitoring and detection, and good temporal resolution of PAS provide concentration data, trend, rate of increase, and potential hazard, supporting more rational decisions, such as alarm activation, ventilation, process shutdown, evacuation.
d) **Risk treatment**. Due to high selectivity, PAS detection can reduce interferences among different molecules lines and uncertainties. False alarms in industry may lead to unnecessary process shutdowns, and additional costs. Also, the application of ML can enable PAS to become part of a smart DRA, rather than an isolated measuring tool.

CHALLENGES AND LIMITATIONS

PAS is a promising tool for DRA support, and for more proactive environmental, industrial, and fire-safety management. The risk level can be continuously updated according to concentration trends, exposure duration, threshold proximity, and operating conditions. Despite its potential, the integration of PAS requires reliable data processing, robust calibration, and proper interpretation of sensor outputs. In real environments, gas mixtures, humidity, temperature variations, pressure changes, and spectral overlap can affect measurement accuracy. For DRA application, measured concentrations must be translated into meaningful risk indicators, which requires suitable models, threshold values, and decision rules. Another challenge is the integration of PAS sensors with AI platforms. PAS systems are often more complex and expensive than conventional low-cost gas sensors, especially when advanced laser sources, or acoustic detectors are required.
Also, some PAS configurations may be sensitive to environmental noise, mechanical vibrations, or changes in the environment. If the sensor data are incomplete, ill-defined or incorrectly interpreted, the resulting risk assessment may be unreliable. For broader industrial implementation of novel PA sensors, further testing is needed to assess long-term stability, effects of humidity, temperature, dust, vibrations, interfering gases, and other. Therefore, PAS can be regarded as a highly promising and partially established technology for early warning and risk assessment, while the most advanced compact PA sensors are still being actively refined and adapted to meet the demands of real industrial environments.

CONCLUSION

PAS is a powerful and promising technique for early warning systems. It enables fast, selective and highly sensitive real-time gas detection. Current technological development has made PAS as a relevant and reliable method in many fields where precise, real-time, and continuous data are required. Modern PAS-based configurations enable sensor miniaturization and integration into portable or mobile monitoring systems. Commercial PAS analyzers are already available for industrial and environmental applications. In DRA framework, PAS represents an advanced gas sensing technique, capable to detect hazardous gases at an early stage, before critical threshold values are reached. This is particularly important for toxic, flammable, and environmentally relevant gases. DRA system can enable continuously update of current risk level according measured concentrations, concentration trends, exposure duration, and proximity to toxic or explosive limits.
Although challenges related to cost, calibration, field robustness, multi-gas interference, and model validation remain, PAS offers significant potential for intelligent safety management and continuous risk control. The integration of ML into PAS opens new possibilities for intelligent gas monitoring. Intelligent PA sensing can support more accurate, adaptive, and autonomous monitoring systems. Although PAS sensors show strong potential for industrial process monitoring and safety applications, the technology remains mainly at the research and prototype stage, and broader industrial adoption will require further improvements in robustness, cost-effectiveness, standardization, and long-term field stability.

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ARTIFICIAL INTELLIGENCE IN THE SAFETY OF GAS USE

Abstract
A big problem in the world is to ensure: a sufficient amount of energy, its transport from the source to the place of use, the highest degree of utilization, the lowest degree of risk during use, the lowest degree of impact on the environment, etc. It is a very complex process, and recently artificial intelligence methods have been introduced more and more in order to achieve optimal influence parameters in real time. In order to achieve this, the best effects are achieved by introducing modern methods of artificial intelligence, which is integrated from the source of energy to its final use. The paper discusses how to use the positive aspects of gas energy and minimize the negative impacts of its use. It is known that it is impossible to reduce negative impacts to zero, but we should strive for that goal. However, with the introduction of artificial intelligence methods, this impact can be maximally reduced compared to previously applied methods. Gas is transported from the source to the place of use in two known ways, using pipelines in the gaseous state and using mobile vessels (tanks, bottles) in the liquid state, so-called. of LPG. Both methods have their advantages and disadvantages in terms of use and impact on the environment. A big problem is its possible leakage, which can cause great dangers, and the harm can be noticed only after a long period of time.

Key words: gas, AI, transport, dangers and harms, LPG.

INTRODUCTION

It is a well-known fact that the driving force of all processes is energy. With greater development in the living and working environment, greater amounts of energy are also required. This process is unstoppable. A major problem is the available amount of energy, its location and its transport from its source to its use, with as little loss as possible, and in a safe manner for its transport and use. Losses are inevitable in every process, but methods and ways are proposed every day to minimize them, i.e. to increase the level of utilization of each system. The explosion in this field is contributed by new information technologies, especially the introduction and development of artificial intelligence [1, 2]. However, it can be said that if there are no problems, there are no new ideas and solutions. Almost all solutions in the human environment arise by solving identified problems. This paper refers to safety problems that arise in the production [3], transportation [4] and use of gas from natural and artificial sources [5, 6]. Natural gas is a mixture of methane (85%-95%) with a smaller percentage of ethane, propane and higher hydrocarbons, and some other impurities that are considered impurities. The processing of natural gas and oil produces a mixture of gases, propane-C_3H_8, butane-C_4H_{10}, small admixtures of impurities and intentionally added admixtures. The big problem of the modern world is the transportation of gas from the source (production) to the place of its use, i.e. of use. From the place of production and preparation of gas to the place of use, transport can be carried out continuously and discontinuously. Continuous transport is carried out by pipelines, and discontinuous transport by mobile tanks. Each of the aforementioned transport methods has its advantages and disadvantages.

The goal is to reduce the disadvantages to an acceptable level. Thanks to progress in the application and development of artificial intelligence (AI), which can significantly improve the processing of many parameters that occur in the zones around gas devices, i.e. by improving the sensitivity, selectivity and response time in traditional sensors through machine learning (ML) and deep learning algorithms, the intensity of the disadvantage is increasingly reduced. Here, AI is of particular importance, the application of neural networks, enabling the so-called "electronic noses" to recognize gas mixtures, gas leaks, etc. Artificial intelligence (AI), a subset of computer science that combines advanced computing and statistics, is the ability of a machine to take input and produce behavior or response similar to that of an intelligent human. AI uses complex instruction sets to approach human-level intelligence. AI operates on data and algorithms: sets of step-by-step computer instructions that can use data to construct models that make predictions based on data [7]. AI should extend to the point before decisions are made by humans, i.e. AI improves the quantity and quality of information available to human decision makers. To understand the logical functioning of AI, it is necessary to understand related terms in the field of data science. In data analysis, the logical flow is: data collection using a digital method, and descriptive-predictive-perspective analytics of this data. Data must be collected throughout the entire chain around the gas phenomenon. The first place where problems can occur is at the source and production of gas, they cannot be avoided, but efforts are made to keep these problems within the permissible level that does not cause serious consequences. A series of sensors created using different techniques with the help of artificial intelligence algorithms can increase safety in the production, distribution and use of gas [8]. Normally, in this chain, the reliability of the sensors is very important, which must be constantly controlled by reliable methods within AI.

PROBLEMS IN PRODUCTION, TRANSPORT AND USE OF GAS

Problems in gas production and the role of AI

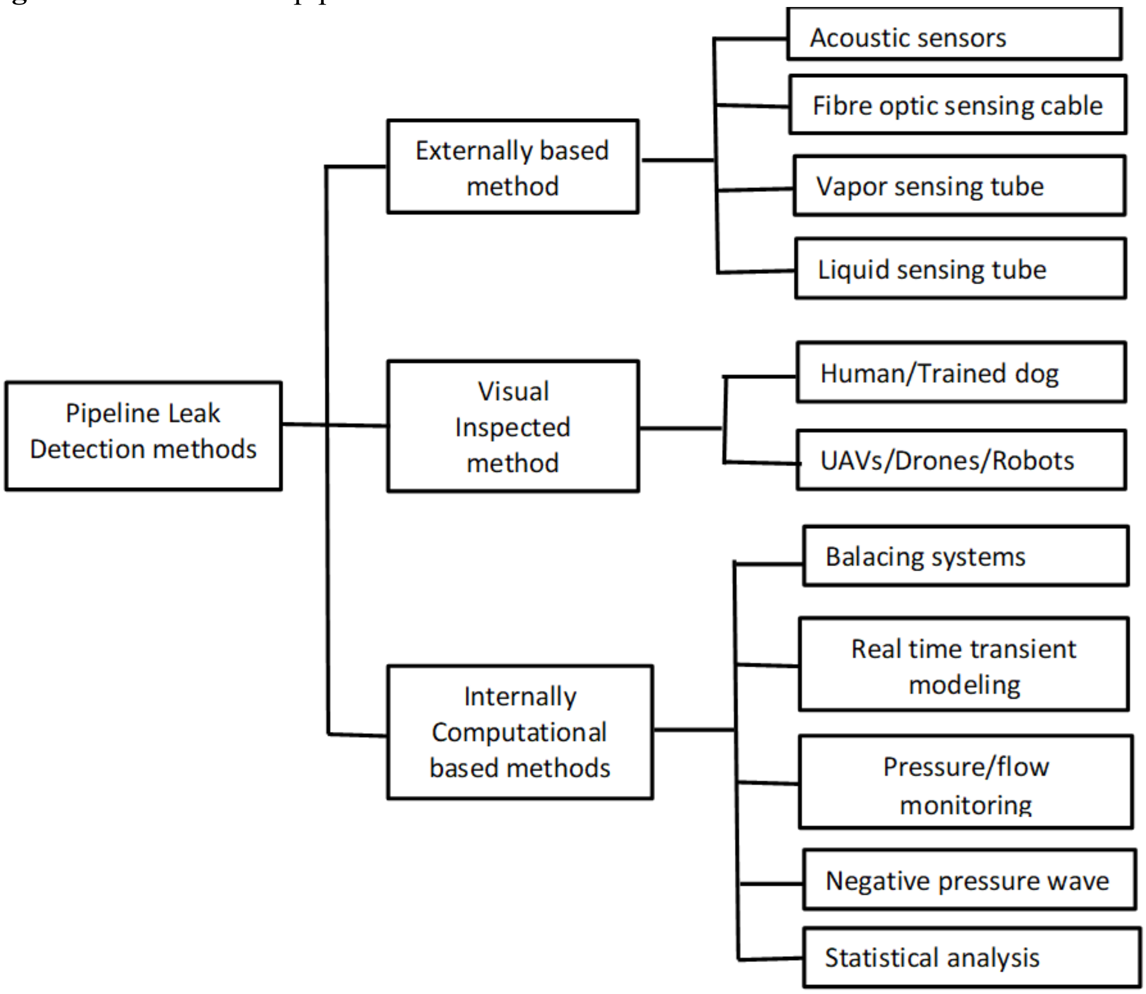
Artificial intelligence (AI) can play a very important role in the gas industry, i.e. its modernization, management, optimization, impact on risks of danger and harm. Through the application of predictive maintenance, robotics, downtime is reduced and reliability in risky operations is increased [9]. The application of neural networks leads to optimal procedures that, as part of AI, increase the reliability of decisions. However, problems arise during implementation, because implementation leads to costs, which reduces the speed of introducing AI methods. Introducing AI is a strategic need for competitiveness and increasing profits of gas producers and user safety.

However, if the risk of consequences that may arise in the event of possible accidents is assessed in a quality manner, these costs can be minor. The most optimal period for implementing AI segments is during the development of new production systems, reconstruction of existing systems by segments where accidents have been identified. Here, AI can again help us a lot if the problems are stored in databases. If we ask AI about the problem of accidents, we get the answer "Accidents in gas production often result from human error, inadequate maintenance and mechanical failures, resulting in explosions, fires and toxic releases. Major hazards include pipeline ruptures, well blowouts and tank failures, often caused by corrosion or improper safety protocols. These incidents cause fatalities, significant economic losses and enormous damage to the environment".

Problems in gas distribution and the role of AI

Gas users can be supplied in two basic ways: through main and local gas pipelines and through mobile cylinders (reservoirs). Each of the mentioned methods has advantages and disadvantages. If gas pipelines are used, the flow of gas to the user is constant, but the initial investment and maintenance of the pipeline requires higher financial costs. Pipeline transportation is the most optimal method for transporting large quantities of gas resources over larger and longer distances because the advantage is low operating costs, high reliability, and less sensitivity to severe weather conditions [15]. However, in this transport, the problem arises from possible gas leaks that cause accidents that are not negligible, [16]. According to that source, based on statistical sources, the biggest causes are corrosion and natural disasters (earthquakes, landslides, etc.). The biggest problem arises with the aging of pipelines, poor quality maintenance and marking of pipeline routes. There are various methods for gas leak detection, Figure 1. . They can be continuous or discontinuous. For the AI system, continuous methods are a priority and are easy to implement when designing a new gas pipeline system. Discontinuous methods on already installed pipelines can increase safety, are simpler and currently have lower costs.

Fig. 1. Classification of pipeline leak detection methods



Source:[10].

Problems in using gas from mobile cylinders

The optimal way to use gas for small consumers is mobile cylinders, where there is no gas pipeline or there is a small number of inhabitants per km^2, so the gas pipeline system is unprofitable, whose volume is about 25 liters with a gas quantity of 10 kg. Control of the safety of using gas from a cylinder depends on the user and the person filling the cylinders with gas. When filling the cylinders, the responsibility falls on the person filling the cylinders. He should check whether the cylinder has been tested according to the prescribed legal acts, and to check whether the valve on the cylinder does not leak gas when it is closed. The user of a gas cylinder should regularly change the flexible hose, the valve that regulates the gas flow and the final system where the gas is used. In addition, many countries have legal regulations that require the installation of a sensor in the area where gas is used that warns of gas concentrations that can cause fire and explosion. However, users in many countries are not educated about the dangers and harms that the gas they use can cause.
What they must check when replacing a cylinder and monitoring the age of the system in which the gas is used. Most users lack basic safety knowledge regarding the safe handling of gas. This is confirmed by research in the paper [11], 99.2% of users have never inspected and pressure tested their cylinders, and 98.0% did not know when the cylinders should be pressure tested. In order to avoid undesirable effects of gas use, many countries prescribe conditions under which gas from mobile cylinders can be used. Usually, the cylinder must be tested every 5 to 10 years. However, the percentage of cylinder malfunctions that lead to fires and explosions is small. However, the cause of a malfunction of the bottle that leads to a fire and explosion is a small percentage. The most common causes of fire, explosion and gas poisoning are malfunctions in the connection system of the bottle valve with the consumer and the gas consumer itself. The design and development of a smart and using IoT system for monitoring the

mass of LPG in the bottle in real time [12], the goal is to timely notify the logistics of gas delivery, i.e. stock management. The work [13] considers the application of AI in kitchens in which it monitors the cooking process and at the same time targets the safe use of LPG. Sensors monitor the occurrence of gas leaks, fires and smoke, and try to warn the user via IoT about these phenomena, close the valve on the bottle and inform the service (fire department) for extinguishing the fire. There is still much research on how to reduce the risk when using gas from mobile bottles. However, the problem is the commercial use of all new proposed solutions and legal regulations at the state level. The explosive development and application of AI in all areas of science and industry is also rapidly being considered in the area of safety of using gas from small bottles.

THE ROLE OF AI IN MINIMIZING ACCIDENTS

The role of AI in minimizing accidents in the gas production zone

A special level, AI can occupy based on monitoring all relevant parameters that occur in gas production, keeping them in optimal areas, warnings on parameters that deviate from defined and learned (adopted) values. By detecting values in the system that violate the optimal defined level and proposing predicative measures to resolve the deviation. Predictive analytics and monitoring systems based on artificial intelligence improve equipment reliability by detecting anomalies early enough to prevent unexpected accidents. They must implement systems with multiple layers of detection, in order to prevent small problems from escalating into large ones.

However, in order to improve the system, a quality analysis of small and large accidents in previous periods in the plant itself and similar plants is required. This is where problems arise because the causes of accidents are "hidden" for various reasons, so that the system can be improved mostly in its own zones where accidents occurred. In addition to the above, cybersecurity is very important, data manipulation can pose a significant risk to the integrity of the AI system and operational safety. Therefore, it is important that the final decision is made by an expert in that field who is informed in a timely manner about the problem and the proposed decision of the AI system.

The role of AI in minimizing accidents in the transportation and use of pipeline gas

The question arises, what level of costs for implementing AI can significantly reduce accidents. In the first case, by implementing AI segments for monitoring gas flow on the network based on machine learning, deep learning and IoT, the implemented system can detect the beginning of a gas leak on a certain part of the route. After this detection, the AI system warns of the problem, if it does not receive a message about what individual segments in the AI system should do, within a defined period of time, the corresponding AI segment blocks the gas flow on the detected part of the route. At a higher level, if multi-sensors are implemented to monitor parameters that are important for reliable gas transport and use, in that case AI gets a greater role in the reliability of the system's safety and the safety of users and the environment. Through multi-sensors, machine learning and deep learning, neural networks and IoT, dangers and harms tend to zero. Therefore, AI can warn in a timely manner what needs to be done to minimize or completely eliminate the danger.

The highest new is when AI can check the correctness of the sensors that are built into that system, i.e. if AI receives variable and unclear information from certain sensors that deviate from the standard (learned) information, it warns that it will block the gas flow. Then the possibility of accidents approaching zero. All sensors have their own technical service life, so it is important that as soon as the parameters of a sensor deviate from the learned value, the system must warn of the observed problem.

The role of artificial intelligence in minimizing accidents in the transport and use of bottled gas

The reliability of gas transport in tanks is highly debatable and there are many recommendations and regulations related to this area. Transport is carried out by special ships, railway and commercial road tankers. Mobile cylinders of smaller capacities are distributed to users again usually by commercial and luxury vehicles, each country has regulations on how these small cylinders can be transported and used. It is very difficult to predict risky situations during transport, i.e. for the AI system to warn in a timely manner of a high risk of an accident. The question arises, how many users are familiar with the transport regulations, e.g. a small number of cylinders (one, two) and how many comply with them. The result is the occurrence of frequent accidents with serious consequences. In this part of real life, the role of AI is currently miniature, everything comes down to research and recommendations. When using it, it is very important whether the cylinder is used indoors or outdoors. Education of gas users and their knowledge of AI is essential for AI to have a faster penetration in this area.

In order for AI to have a more significant implementation, it is necessary to: develop a system for labeling and monitoring the correctness of the cylinders, monitoring the solenoid valve, pressure and flow regulators, the hose connecting the regulator to the gas utilization system and the gas utilization device itself, and the IoT technology system. All this leads to financial costs, which makes the implementation of new technologies and the AI system more difficult. Further improvements must bring financial costs into an acceptable range, in this way AI will be more quickly acceptable to a wide range of users of gas from small cylinders.

Problems in gas usage and the role of AI

In order to use AI in the chain of production, transport and use of gas, it is necessary to invest significant financial resources, especially in already built systems. In the production and transport of gas, the AI system is already starting to occupy a significant segment, which can be seen in a large number of works related to this area. However, in the area of using gas from small cylinders, AI is in the experimental research and recommendation phase. The problems are related to: knowledge of the safety of using gas from these small tanks, financial resources, legal regulations and recommendations of distributors. In order to implement AI in the use of gas from small cylinders, legal regulations are needed that must be respected. This especially applies to the control of cylinders, intermediaries between gas use and cylinders and sensors in space. In addition, all sensors have their own technical lifespan. Reliability of the continuity of the energy provided for the AI system and its recommendations and reactions in the event of a cyber attack.

DISCUSSION

Accidents that are the consequences of causes in the production, transport and use of gas are the largest source for the database and the application of AI technologies, provided that quality analyses of the causes of accidents are carried out. Solutions are related to financial resources, legal regulations, knowledge and other parameters related to this area. It is necessary to find an optimally acceptable solution that would be easily implemented in real life in the gas-related system.

Smart elements must be implemented in all modules used in the gas utilization system that will react before accidents occur. They will warn the user about problems that have arisen and that may cause an accident in the next period of time. It is up to the user and the competent system for monitoring the recommendations of the AI system to make a timely decision that will lead to the minimization or prevention of accidents. Knowledge is the biggest problem in accepting new scientific achievements in practice. A new solution is condemned in advance without analyzing what it brings positively and what its negativity is if it is implemented. Thus, the implementation of AI will have its positive and negative impacts. The goal is to minimize negative impacts, i.e. to tend to zero.

CONCLUSION

Based on the research, it can be concluded that the introduction of AI systems in the production, transport and use of gas plays a major role in financial decisions, the introduction of a modular sensor system with IoT technologies. The return on investment time, for existing systems, is the basic problem for the decision to invest in the implementation of AI systems. The implementation of AI must offer its advantages over classic systems in terms of safety and reliability in the areas of gas production, transport and use management. This offer must move in steps.

Because only the positive effects of its implementation will affect the corridor of its application. The application of AI in the future will have a great importance in increasing the safety and reliability of systems related to gas. Continuous integration of AI solutions will improve automation, reliability, safety and contribute to a more sustainable and cost-effective gas sector. In the process of using LPG from bottles, there are major problems related to the knowledge, i.e. training of gas users about the causes that lead to accidents with serious consequences. In addition, legal regulations must define rules for the safe use of gas based on scientific achievements and recommendations. The production of financially acceptable and reliable modules that are implemented in the AI system must be ensured. In parallel, it is necessary to assess the risks of introducing AI by segments in the field of gas use, and the harm that may occur from the implementation of AI is currently difficult to predict. Time is the best judge that will influence the results of recommendations and the implementation of new solutions.

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Original scientific paper

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ASSESSMENT OF CRITICAL RAW MATERIALS DEVELOPMENT IN NORTH MACEDONIA: A PESTLE-BASED ANALYSIS OF REGULATORY, TECHNOLOGICAL, AND SUSTAINABILITY CONSTRAINTS

Abstract
Securing diversified supplies of Critical Raw Materials (CRMs) is a strategic priority for the European Union, increasing the relevance of EU candidate countries such as North Macedonia. This paper applies a PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) framework to assess structural constraints and development potential across the country's CRM value chain. The analysis integrates regulatory review, mineral production and infrastructure assessment, energy system characteristics, and socio-environmental factors. Results show that North Macedonia hosts significant primary and secondary CRM resources, particularly lead, zinc, copper, nickel, and gold, but development is constrained by regulatory fragmentation, prolonged permitting, outdated processing infrastructure, energy intensity, skills mismatches, and limited financing. Conversely, EU legislative alignment, circular economy opportunities, and low-carbon mining pathways provide strategic leverage. Regulatory streamlining, infrastructure modernization, improved geological data, and renewable energy integration are identified as key enablers for sustainable CRM development.

Keywords: Critical Raw Materials (CRM); PESTLE analysis; mining policy; EU supply chains; regulatory risk.

INTRODUCTION

Critical raw materials (CRMs) are indispensable to the European Union's economic competitiveness, industrial value chains, and societal well-being. They underpin all industrial sectors and stages of the supply chain and play a critical role in the EU's global position in technological development [5]. According to the EU's 2024 Critical Raw Materials Act (CRMA), the overall demand for CRMs is expected to increase six-fold by 2030 and seven-fold by 2050. For certain materials, growth projections are even steeper; for example, the demand for lithium batteries in the EU is projected to increase twelve-fold by 2030 and twenty-one-fold by 2050 [6]. More than 30 million jobs in the EU in key economic sectors such as automotive, aerospace, and renewable energy depend on a continued sustainable supply of CRMs [5].
The current geopolitical landscape has refocused attention on raw materials security. The financial crises, the pandemic, high inflation in Europe, global climate change, and the war in Ukraine have brought the crucial importance of commodities back to the fore [16]. Supply chains for critical minerals are notably concentrated, with the top three producing countries dominating between 73 and 98 percent of global output for each of the 18 critical minerals [10]. China is the primary processor for many materials, particularly rare earth elements and graphite, while much of the material mined in the EU is not refined domestically but exported to third countries for processing and then re-imported [5].

To reduce dependence on third countries, the EU has established ambitious 2030 objectives: 10 percent of annual consumption for domestic extraction, 40 percent for processing, and 25 percent for recycling, while ensuring that no more than 65 percent of any strategic raw material at any processing stage comes from a single third country [5]. These targets, embedded in the CRMA, have heightened the strategic relevance of resource-rich EU candidate and potential candidate countries.
The Western Balkans region stands out as a natural partner for the EU in this endeavor, given its close integration with EU markets and transport networks, its long mining tradition, and its legacy of old industrial sites and mine tailings [13]. North Macedonia, an EU candidate country since 2005, occupies

a particularly important position in this context. The country is rich in valuable and rare metallic primary raw materials (PRMs), with some included on the EU CRM list, including antimony at Lojane and Alšar, titanium-iron ore at Mitrašinci, and molybdenum at Strelci [6]. High copper mineralization potential of the porphyry type exists, with very large deposits totaling 734 million tonnes of proven and probable ore reserves [7]. The lead-zinc sector also presents high potential with large to very large deposits of 28 million tonnes of mostly proven ore reserves in five areas [7].
Despite this geological endowment, North Macedonia's CRM development remains substantially constrained by a complex web of regulatory, economic, technological, and environmental barriers. The purpose of this paper is to systematically examine these constraints and identify pathways for sustainable development through the application of the PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analytical framework. This approach enables a structured, multi-dimensional assessment of the macro-environmental factors that shape the country's CRM sector, while connecting national dynamics to broader European raw materials policy objectives.

THEORETICAL BACKGROUND AND LITERATURE REVIEW

The PESTLE framework in resource sector analysis

The PESTLE technique is a strategic management framework for assessing the impact of political, economic, social, technological, legal, and environmental factors on a project, industry, or market [4]. It categorizes environmental influences into six main types and provides a comprehensive list of influences on the possible success or failure of an organization, industry, or market. There are two types of factors influencing an organization: macro-environmental factors, which consist of broad environmental forces that impact organizations with less structured data available, and internal factors that are company- or project-specific [4]. The PESTLE framework has been successfully applied in the mining sector, notably by Kangwa and Mutambo [9] in their analysis of Zambia's potential for mining low-grade copper deposits, where they used PESTLE and SWOT tools because they offer broad and effective analyses of key areas of strategic planning and are suitable at the preliminary stage of the mining planning process.
Soares et al. [17] applied PESTLE analysis in the context of Mozambique's energy sector, finding that political and economic factors are typically the most important categories in developing countries, generally covering almost half (47 percent) of the collective weights attributed by experts. This finding has important implications for the analysis of North Macedonia's mineral sector, where EU accession dynamics introduce a unique political dimension. Dalirazar and Sabzi [4] used PESTLE to analyze barriers to sustainable building development across three countries, demonstrating the framework's versatility in capturing cross-national dynamics within structured analytical categories.

Critical raw materials: Global context and EU policy

The concept of raw material criticality was formalized by the European Commission through the Raw Materials Initiative (RMI) of 2008, with the first CRM list published in 2011 [6]. Since then, the list has been updated every three years, with the 2023 assessment including copper and nickel as strategic raw materials. The CRMA, adopted in May 2024, establishes a framework for ensuring secure and sustainable CRM supply, including measures for diversifying imports, reducing strategic dependencies, improving monitoring of supply risks, and enhancing sustainability and circularity [6]. The Act explicitly recognizes how old industrial sites and decommissioned mines could be a valuable complementary source of CRMs and includes provisions on recovering CRMs from closed extraction facilities [13].
The clean energy transition is a primary driver of CRM demand. The International Energy Agency predicts that if all countries fully implement their national energy and climate pledges, the demand for minerals for clean energy technologies would more than double by 2030 and triple by 2040, reaching nearly 35 million tonnes annually [5]. Kursunoglu [10] provides a comprehensive review of recent developments in tailings reprocessing, highlighting the potential for secondary resource recovery in response to rising global demand for critical metals such as rare earth elements, lithium, cobalt, and nickel. The integration of circular economy principles into tailings management not only enhances resource efficiency but also supports decarbonization and strengthens supply chains [10].

The Western Balkans mineral sector

The Western Balkans region has been identified by the European Commission as having significant mineral potential that could contribute to lowering Europe's dependence on imported mineral resources [14]. The EIT RawMaterials-funded RESEERVE project created a West Balkan Mineral Register covering primary and secondary raw materials for six Eastern and South-Eastern European countries: Albania, Bosnia and Herzegovina, Croatia, Montenegro, North Macedonia, and Serbia [7]. The SWOT and Gap analysis performed within the project identified key strengths including favorable geological settings, long mining traditions, and the availability of secondary raw materials, alongside challenges such as the lack of regional exploration campaigns, non-compliance with international codes and standards in resource estimation, and regulations not aligned with European legislation [2].
Borojević Šoštarić [3] analyzed the implications of the CRMA for the Adria region, noting that the region hosts significant primary geological potential of antimony, barite, borate, lithium, magnesium, and to some extent titanium, rare earth elements, and graphite among the 28 critical raw materials listed by the European Commission. However, implementation of the CRM Act in West Balkan candidate countries is expected to follow their negotiation and harmonization process, introducing additional temporal and institutional complexity.
A recent CEPS Policy Brief by Righetti, Tekin, and Rizos [13] explored the opportunities arising from recovering CRMs from decommissioned sites and mine tailings in the Western Balkans, identifying three priority areas: upgrading exploration and geological data, driving innovation and pilot projects, and advancing regulatory alignment. The authors emphasized that firms often lack the capital needed to upgrade operations, modernize equipment, and improve productivity, particularly smaller operators that struggle to access affordable, long-term finance.

METHODOLOGY

This paper employs a PESTLE analysis framework adapted for the resource extraction sector. The PESTLE framework is particularly suited to this analysis because it enables a systematic examination of the macro-environmental factors shaping the CRM sector in North Macedonia, while connecting national dynamics to the broader European policy context. Following the methodological approach established in the mining sector literature [9][17], the analysis draws on multiple data sources to construct a comprehensive picture of the enabling environment and constraints.
The data collection strategy integrates several streams. First, peer-reviewed academic literature on the mineral sector of the Western Balkans and North Macedonia was reviewed, including geological characterization studies, geochemical analyses of mining waste deposits, SWOT assessments of the regional mineral sector, and reviews of CRM recovery technologies. Second, EU policy documents and regulatory frameworks were analyzed, including the CRMA, the Green Agenda for the Western Balkans, and the EU accession framework. Third, project deliverables from EIT RawMaterials-funded initiatives, including the RESEERVE and RIS-RECOVER projects, provided primary data on mineral inventories, geological characterization, and technology assessment. Fourth, reports from international organizations, including the European Training Foundation (ETF), the Joint Research Centre (JRC), and the USGS, supplied production statistics and workforce data.

The PESTLE analysis is structured around the six conventional dimensions: Political factors encompass government policy, EU accession dynamics, geopolitical positioning, and international cooperation frameworks. Economic factors address mineral production capacity, investment flows, financing mechanisms, commodity markets, and infrastructure requirements. Social factors include workforce skills, community acceptance, health impacts, and demographic dynamics. Technological factors cover processing infrastructure, innovation capacity, research and development, and available recovery technologies. Legal factors examine the mining regulatory framework, permitting procedures, environmental compliance requirements, and alignment with EU directives. Environmental factors consider contamination legacies, waste management practices, biodiversity protection, and climate-related considerations.
For each PESTLE dimension, the analysis identifies both constraints (barriers to CRM development) and enablers (factors that provide strategic leverage or opportunities for advancement). The findings are then synthesized into an integrated assessment that highlights cross-cutting themes and prioritized recommendations.

RESULTS

This section presents the findings of the PESTLE analysis across all six dimensions, drawing on the data sources described in the methodology. Each subsection identifies the key constraints and enablers within the respective dimension.

Political factors

North Macedonia's political environment for CRM development is shaped by a unique confluence of EU accession dynamics, geopolitical positioning, and domestic governance challenges. The country has been an EU candidate since 2005, and its accession process requires gradual adoption of the EU acquis, notably including reforms under Chapter 20 (Enterprise and Industrial Policy) and Chapter 27 (Environment) [13]. Chapter 20 entails requirements centered on aligning industrial and business policies with the EU, with a focus on creating an industrial climate conducive to competitiveness, innovation, and sustainable growth. Chapter 27 requires strict technical and legally binding compliance with specific environmental laws, covering water and air quality, waste management, and biodiversity conservation [13]. These chapters directly shape the regulatory framework for mining and related areas including industrial pollution control, environmental permitting, and the modernization of industrial processes.

The CRMA's implementation at the national level of EU member states includes monitoring, data collection, guidelines development, and coordination of general exploration programmes; strategic national raw materials projects; permitting processes; and specification of which end-of-life products and waste streams contain relevant amounts of critical raw materials [3]. For West Balkan candidate countries, implementation is expected to follow the negotiation and harmonization process, creating a transitional period during which alignment can proceed incrementally.

The new Growth Plan for the Western Balkans explicitly envisions the development of strategic partnerships on sustainable raw materials value chains as a key element [13]. Regional leaders signed the Sofia Declaration on the Green Agenda for the Western Balkans in 2020, committing to action on climate, energy, circular economy, and depollution. Its implementation is being supported primarily through the Instrument for Pre-Accession Assistance (IPA III) and the Economic and Investment Plan (EIP), together allocating 9 billion euros in grants and aiming to mobilize up to 20 billion euros in investments via the Western Balkans Guarantee Facility [13].

A significant recent political development was the endorsement of the Krstov Dol antimony mine by the Minerals Security Partnership in April 2025, with operations planned to restart by the first quarter of 2027 [5]. This underscores the growing international strategic interest in North Macedonia's CRM deposits. However, progress on fundamental areas like the rule of law and judicial independence remains essential for building trust in raw materials-related projects [13]. Administrative bottlenecks, particularly slow and fragmented permitting procedures, create additional uncertainties that deter long-term investment.

In summary, the political environment presents a dual character: the EU accession framework, international partnerships, and growing strategic interest provide strong positive momentum, while governance challenges, institutional capacity gaps, and the complexity of multi-level administrative coordination remain significant constraints.

Economic factors

North Macedonia's mineral sector has historically made a substantial contribution to the national economy, with a long tradition of mining and metallurgical activity. The country's copper production ranged from 11,000 tonnes in 2015 to 7,231 tonnes in 2019, while lead production ranged from 37,920 tonnes to 43,490 tonnes over the same period, and zinc annual production remained stable at around 30,000 tonnes [7]. The country also produces gold and silver, with outputs of 593 kg and 17,780 kg respectively in 2019 [15]. Gold concentrations are mined from the operating Bučim porphyry copper mine, while silver comes from the large lead-zinc deposits at Toranica, Sasa, and Zletovo, as well as from the copper deposit at Bučim [15].

The general increase in global demand for raw materials and the interest of international mining companies in exploration and exploitation represent a significant opportunity for the mineral sector in North Macedonia [2]. However, economic instabilities in non-EU countries and underdeveloped local infrastructure, including transportation and energy infrastructure, are identified as weaknesses for the sector's growth [2]. The volatility of commodity prices on the world market and the underdeveloped downstream industry for certain raw materials are seen as threats to sustained development.
A particularly important economic dimension relates to the value embedded in secondary raw materials. Šajn, Ristović, and Ceplak [18] found that approximately 2.6 gigatons of mining and processing waste had been deposited at 1,650 sites across the West Balkans, covering almost 65 square kilometers. About 42 promising locations containing roughly 270 million tonnes of material could be selected for recovery. At March 2022 metal prices, the recovery potential was estimated at 18,100 million USD, a significant increase from the 10,600 million USD estimate at March 2020 prices [18]. For North Macedonia specifically, key secondary sources include the Veles Pb-Zn slag deposit (1.2 million tonnes with an average zinc content of 9.6 percent and an estimated 120,000 tonnes of recoverable zinc), the Sasa Pb-Zn tailings (multiple dams totaling approximately 20 million tonnes), the Probištip Pb-Zn tailings (approximately 30 million tonnes across three facilities), and the Bučim copper tailings (125 million tonnes covering 250 hectares) [19][20].

The financing landscape for CRM development in the region has been bolstered by several EU instruments. Under the Growth Plan for the Western Balkans, the Reform and Growth Facility (RGF) provides up to 6 billion euros in funding (2 billion in grants, 4 billion in soft loans) between 2024 and 2027, with disbursements conditional on reform agendas [13]. The European Critical Raw Materials Centre and CRM financing hub announced in the RESourceEU Action Plan are intended to coordinate de-risking tools such as InvestEU and the Innovation Fund towards a pipeline of viable projects, including recycling and secondary CRM projects in partner countries [13]. Involvement of the European Investment Bank and EBRD can serve as an additional lever to de-risk projects and draw in private investment.
Despite these opportunities, firms in the region, particularly smaller operators, often lack the capital needed to upgrade operations, modernize equipment, and improve productivity [13]. The competitiveness of the sector is recognized as a multi-faceted task requiring enhanced research and development activities, technology transfer for upgrading processing capacity, and vertical integration of the mineral sector [2]. Gross domestic expenditure on research and development as a percentage of GDP in Western Balkan countries ranged from approximately 0.2 percent in Bosnia and Herzegovina to 1 percent in Serbia, compared with an EU average of 2.2 percent [2].

Social factors

Social acceptance and workforce capacity constitute two critical social dimensions for CRM development in North Macedonia. The mineral sector in the Adria region faces challenges related to reduced social acceptance, which is compounded by past environmental damage and general low trust in institutions [13][2]. This means that resolving the technical, data, and infrastructure barriers alone will not be sufficient; wider social concerns call for more transparent decision-making, stronger community engagement, and broader social acceptance of CRM recovery initiatives.
The health impacts of historical mining and metallurgical activities provide important context for understanding public attitudes. The Veles Pb-Zn smelter, which operated from 1973 to 2002 and was the most polluting industrial facility in North Macedonia, left a significant legacy of contamination. Research showed that elevated concentrations of lead were found in the blood of Veles schoolchildren when the plant was operating [20]. Soil contaminated with arsenic, cadmium, copper, lead, antimony, and zinc exceeded target values in an area of 70 square kilometers, while the area with soil contaminated above intervention values was 14 square kilometers [20]. Cadmium levels in vegetables grown near the smelter were found to be 3.2 times higher than permissible values, while lead content was 1.6 to 10 times above permissible levels [20]. These documented health impacts contribute to deeply entrenched community skepticism about mining-related activities.

Workforce capacity presents another significant social constraint. The mineral sector faces a lack of skilled technical, scientific, and managerial personnel involved in the whole cycle of mineral activities [2]. Stakeholder discussions within the RESEERVE project identified capacity building programs as a

priority action for sustainable development of the mineral sector. The ETF [5] has noted that while the mining industry has embraced technological transformation including automation, robotics, and the Internet of Things, the skills profiles needed have changed accordingly. In-demand profiles are no longer traditional miners but specialists with vocational qualifications, creating a mismatch between available and required human capital.
Awareness-raising campaigns to obtain the required social license to operate and gain stakeholders' knowledge and consent have been proposed as a key action for the Adria region [2]. Progress on fundamental areas like rule of law and judicial independence is also essential for building trust in raw materials-related projects, and by linking cooperation on raw materials to tangible improvements in governance and environmental safeguards, both the EU and partner countries can reinforce public trust [13].

Technological factors

The technological dimension of North Macedonia's CRM sector encompasses three interrelated areas: the state of existing processing infrastructure, the availability of advanced recovery technologies for secondary resources, and the country's innovation and research capacity.
Industry stakeholders report a lack of investment in green technology and research infrastructure for mining and processing [2]. The existing processing plants operate with outdated technologies that limit both efficiency and environmental performance. External funding for innovation and technological development is expected from regional, national, and EU sources, but the overall investment in research and development remains well below EU averages. Among the Adria candidate and potential EU candidate countries, gross domestic expenditure on R&D as a percentage of GDP ranged from approximately 0.2 percent in Bosnia and Herzegovina to 1 percent in Serbia, compared with an EU average of 2.2 percent [2].

From a secondary resource recovery perspective, the available technologies span a wide spectrum. Pličanič et al. [11] describe a zero-waste approach to recycling mining waste that involves two phases: extraction of valuable metals and critical raw materials in the first phase, and recycling of residues for the construction sector in the second phase. The extraction methods available include pyrometallurgy (extraction and purification of metals by thermal processes), hydrometallurgy (using chemicals for the recovery of metals from mining waste), and bioleaching (using autotrophic or heterotrophic bacteria for extraction of metals) [11]. Before extraction methods are applied, beneficiation can be achieved through physical-mechanical treatments such as gravitational or magnetic separation of minerals crushed and milled to particles of different sizes.
Kursunoglu [10] provides a comprehensive review of recent advances in the recovery of critical metals from mine tailings, noting that advances in technologies such as hydrometallurgy, bioleaching, and advanced flotation systems have improved the recovery of valuable minerals, including rare earth elements and lithium, making tailings reprocessing an economically attractive alternative. Hydrometallurgical advancements that optimize extraction processes, minimize energy consumption, and reduce secondary waste generation are central to achieving sustainability goals. However, many promising CRM recovery approaches from extractive waste remain at the laboratory or pilot stage [13], and secondary CRM recovery can be energy-intensive depending on the technologies applied and the energy mix.
The RIS-RECOVER project, coordinated by the Slovenian Civil Engineering Institute with partners including the Geological Survey of Slovenia, the Construction Institute of North Macedonia, Goce Delčev University, Montanuniversität Leoben, and VITO, specifically evaluated and selected the most promising technologies for mineral and metallurgical extraction of elements from metallurgical slag in North Macedonia [20]. The detailed geochemical characterization of the Veles slag deposit identified not only base metals (Zn, Pb) but also precious metals (Ag, Au), critical metals (In, Pd, Se, Te, Tl), and rare earth elements, providing the foundation for targeted technology selection.

The RESEERVE project's West Balkan Mineral Register represents a significant technological advancement in data infrastructure. The Register was created in compliance with the INSPIRE Directive guidelines for mineral resources, organizing and making accessible data on primary and secondary raw materials across the six ESEE countries [14]. However, for ore reserves classification, no international standard is applied in North Macedonia, representing a significant gap that affects investor confidence and international comparability [7].

Legal factors

The legal framework governing North Macedonia's mineral sector encompasses mining legislation, environmental regulations, spatial planning requirements, and EU alignment obligations. In all the Adria countries, mineral resources are protected by the Constitution and the existing legal framework includes regulations for exploration, mining, and mine waste treatment [2]. However, the SWOT and Gap analysis conducted within the RESEERVE project identified several critical legal deficiencies.
Methods for estimating reserves are not aligned with international standards such as PERC, JORC, UNFC, or CIM [2]. Concession and exploration licensing procedures are reported as lengthy and in need of significant simplification, with institutional quality affecting investment activities [2]. The analysis identified five priority areas for legislative intervention: mineral policy and strategy of the state, licensing and permit procedures for exploration and exploitation activities, royalties, fees, and compensatory benefits, harmonization of spatial plans and alignment with EU environmental legislation, and codification and simplification of mining regulations [2].
A recent JRC assessment suggests that while there has been progress in adopting green legislation across the region, implementation remains uneven and still at an early stage [13]. Many governments have adopted provisions including on energy and climate, but the overall framework remains incomplete and in parts outdated, and many measures are yet to be enforced. This implementation gap creates legal uncertainty for investors and operators.

The legislative framework for circular economy approaches to mining waste is particularly relevant. Pličanič et al. [11] provide a holistic overview of technological as well as administrative and legislative aspects of recycling secondary raw materials from tailings and heaps in North Macedonia. Key open questions include compliance with environmental legislation, especially regarding end-of-waste status, construction legislation that governs the use of recycled materials, and circular economy policies that encourage the use of secondary raw materials. North Macedonia has developed a national circular economy roadmap that specifically mentions the opportunities of recovering mining waste, acknowledging that circularity solutions can contribute to environmental sustainability goals while providing valuable commodities [13].
Regulatory alignment with the EU acquis requires adopting recognized international standards and certification schemes for sustainable sourcing and due diligence [13]. This is increasingly relevant as EU market access rules evolve under the Batteries Regulation and the CRMA, including reporting requirements for extractive-waste sites. The CRMA's Article 27 introduces obligations on Member States to collect information about extractive facilities and make this information available to the public by 2026 in the form of a database [13]. While this requirement applies to Member States, candidate countries preparing for accession will need to develop equivalent capabilities.

Environmental factors

Environmental factors in North Macedonia's CRM sector are characterized by a tension between historical contamination legacies and the environmental remediation potential embedded in circular economy approaches to mining waste. The country has one of the greatest potentials to establish a zero-waste model due to its geological, historical, and socio-economic characteristics. As a consequence of its long mining tradition and abundant ore resources, there are many mining and metallurgical tailings, and on the other hand, a vivid economy with numerous sinks for the use of recycled materials in the construction sector [11].
The environmental contamination from historical mining activities is extensive and well-documented. The Veles slag deposit covers a surface area of 33,000 square meters and contains approximately 1.2 million tonnes of slag with 7 percent zinc, 1 percent lead, and 2 to 4,000 mg/kg of other potentially toxic elements including manganese, copper, nickel, and arsenic [20]. The slag was only partially covered and dust emissions were obvious, affecting the Vardar river as well. Very high levels of cadmium, lead, zinc, and other potentially toxic elements were found in the air, with average cadmium content of 240 mg/kg in attic dust and 19 mg/kg in house dust samples [20]. Lead content was found to be 6,300 mg/kg in attic dust and 460 mg/kg in household dust.

At the Lojane mine, a former arsenic, antimony, and chromium mine that operated from 1923 to 1979, the completely unprotected tailings hold 3.5 million tonnes of which 15,000 tonnes are 50 percent arsenic concentrate [19]. Currently, the acid mine drainage potential is low, but the waste material is distributed by wind, surface water, and groundwater. The Lojane site has been identified as a significant environmental hotspot by the United Nations Environmental Programme [1].

Steiner et al. [19] conducted a preliminary chemical and mineralogical characterization of tailings from base metal sulfide deposits in Serbia and North Macedonia, identifying the presence of EU-critical metals including germanium and indium at Sasa, indium at Probištip, and antimony and cobalt at Lojane. This dual character of mining waste sites as both environmental liabilities and potential secondary CRM sources creates a powerful rationale for integrated remediation-recovery approaches.

The energy intensity of mining and mineral processing operations represents another important environmental factor. The extraction and processing of CRMs is energy-intensive, raising concerns about sustainability and environmental impact [5]. North Macedonia's energy system, which relies significantly on domestic lignite-fired power generation and imported natural gas, contributes to a high carbon footprint for mineral processing operations. However, the country's renewable energy potential, particularly in solar and wind resources, offers a pathway toward decarbonizing the energy supply for mining operations.

Mining activities generate vast quantities of waste that pose serious environmental risks, including soil contamination that reduces fertility, water pollution affecting ecosystems and human water supplies, biodiversity loss due to toxic discharges, and greenhouse gas emissions from waste management processes [10]. Effective mine waste management reduces the environmental footprint while securing raw material supplies and aligning with carbon neutrality targets.

DISCUSSION

Synthesis of PESTLE findings

The PESTLE analysis reveals a complex but ultimately promising landscape for CRM development in North Macedonia. The country possesses significant geological potential in both primary and secondary resources, supported by growing international strategic interest and an evolving EU policy framework that explicitly prioritizes supply chain diversification through partnerships with candidate countries. However, this potential is substantially constrained by a mutually reinforcing set of barriers across all six PESTLE dimensions.

The most critical cross-cutting constraint is the gap between policy adoption and implementation. While North Macedonia has taken steps to align its legislative framework with the EU acquis and has developed national strategies including a circular economy roadmap, the actual implementation of these frameworks remains uneven. This implementation deficit manifests across dimensions: permitting procedures remain lengthy and fragmented (political and legal), investment in green technology and R&D is insufficient (economic and technological), environmental monitoring and ESG enforcement are weak (environmental and legal), and workforce skills do not match the requirements of modern mining operations (social and technological).

Priority recommendations

Based on the PESTLE analysis, four strategic priority areas are identified for enabling sustainable CRM development in North Macedonia.

First, regulatory streamlining and institutional capacity building should focus on simplifying and codifying mining regulations, accelerating permitting procedures, and building administrative and technical expertise within public institutions. The targeted use of EU technical-assistance initiatives such as TAIEX and Twinning programs can support the development of modern, transparent permitting systems [13]. Aligning reserve classification with internationally recognized codes such as JORC, PERC, or UNFC is essential for attracting international investment [7][2].

Second, infrastructure modernization and technology transfer should prioritize upgrading processing facilities, establishing pilot projects for secondary CRM recovery, and linking local actors more closely to EU instruments such as Horizon Europe, EIT RawMaterials, and relevant industrial alliances. The Veles slag deposit, with its documented high concentrations of zinc (120,000 tonnes), indium (4.1

tonnes), and rare earth elements, represents an ideal candidate for a pilot zero-waste recovery project [20]. A centralized raw material processing facility realized through regional collaboration could help achieve economies of scale, retain value in the region, and facilitate integration into EU value chains [13].

Third, improved geological data and systematic exploration should involve upgrading the quality of geological potential data, conducting new exploration campaigns, and integrating national datasets into the pan-European Minerals Intelligence Network. The RESEERVE West Balkan Mineral Register provides a foundation, but further development is needed to include data on all commodities in the deposits, particularly CRMs, and to increase the confidence level of existing geological data [7][14]. The CRMA's requirements for extractive waste databases present both an obligation and an opportunity to systematically catalogue and assess secondary CRM potential.

Fourth, renewable energy integration and environmental remediation should be pursued as complementary objectives. Decarbonizing the energy supply for mining operations through solar and wind energy development would reduce the environmental footprint and improve the competitiveness of North Macedonian mineral products in an EU market increasingly sensitive to carbon intensity. Simultaneously, framing secondary CRM recovery as environmental remediation rather than new mining can help overcome social acceptance barriers by demonstrating tangible health and environmental benefits for affected communities.

PESTLE summary

Table 1 summarizes the key constraints and enablers identified across all six PESTLE dimensions.

Table 1. PESTLE summary of key constraints and enablers for CRM development in North Macedonia

PESTLE Dimension	Key Constraints	Key Enablers
Political	Fragmented permitting; slow institutional reform; governance gaps; multi-level coordination complexity	EU accession framework (Chapters 20, 27); Minerals Security Partnership endorsement; Sofia Declaration; IPA III/EIP funding
Economic	Underdeveloped local infrastructure; limited domestic financing; commodity price volatility; low R&D spending	High secondary resource value (est. 18.1 bn USD regionally); RGF/WBIF financing; EBRD/EIB de-risking; growing global CRM demand
Social	Low social acceptance; health legacy of past mining; skills mismatch; demographic decline in mining regions	Awareness-raising programs; capacity building through EIT RawMaterials; university partnerships (UGD, UKIM)
Technological	Outdated processing plants; no international reserve standards; lab-stage recovery technologies; low R&D investment	RIS-RECOVER/RESEERVE results; zero-waste sequential model; INSPIRE-compliant Mineral Register; hydrometallurgy advances
Legal	Non-aligned reserve classification; lengthy licensing; incomplete environmental regulations; weak enforcement	National circular economy roadmap; CRMA alignment roadmap; end-of-waste criteria development; EU technical assistance
Environmental	Extensive contamination at Veles, Lojane; unprotected tailings; energy-intensive processing; Vardar river pollution	Remediation-recovery synergies; renewable energy potential; zero-waste construction sector use; carbon footprint reduction

CONCLUSIONS

This paper has presented a comprehensive PESTLE-based analysis of the macro-environmental factors shaping the development of critical raw materials in North Macedonia. The analysis demonstrates that the country possesses significant geological potential in both primary deposits and secondary waste resources, with documented occurrences of EU-listed critical raw materials including antimony, arsenic, cobalt, germanium, indium, and rare earth elements across active mines, abandoned sites, and metallurgical waste deposits.
The PESTLE framework has proven effective for revealing the interconnected nature of constraints facing the sector. Regulatory fragmentation and prolonged permitting cannot be addressed independently of institutional capacity gaps, outdated processing infrastructure cannot be modernized without access to financing and technology transfer, and social acceptance cannot be built without tangible improvements in environmental governance and community health outcomes. These interdependencies underscore the need for integrated, cross-cutting policy interventions rather than piecemeal reforms.

The EU's evolving policy framework, particularly the CRMA and the associated strategic partnerships, provides unprecedented leverage for North Macedonia to transform its CRM sector. The country's position as an EU candidate, combined with the growing geopolitical urgency of supply chain diversification, creates a window of opportunity that should be actively pursued. The key strategic priorities identified by this analysis are regulatory streamlining and institutional capacity building, infrastructure modernization and technology transfer, improved geological data and systematic exploration, and renewable energy integration combined with environmental remediation.
The findings of this paper carry implications for both national policymakers and EU-level decision-makers. For North Macedonia, the analysis highlights the urgent need to accelerate legislative reform, invest in human capital development for the mining sector, and establish pilot projects that demonstrate the viability of circular economy approaches to mining waste. For the EU, the analysis underscores the importance of embedding CRM cooperation with candidate countries into the accession framework in a binding, monitored manner, rather than relying solely on non-binding memoranda of understanding.

Future research should focus on detailed techno-economic assessments of specific recovery scenarios at priority sites, particularly the Veles slag deposit and the Sasa, Probištip, and Lojane tailings. Quantitative PESTLE analyses employing stakeholder surveys, as demonstrated in the Zambian and Mozambican contexts, could provide weighted factor assessments that further refine the prioritization of interventions. Additionally, comparative PESTLE analyses across Western Balkan countries could identify regional synergies and inform the design of centralized processing facilities serving multiple national markets.

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DEVELOPMENT OF A MODEL FOR EFFECTIVE WORKER PARTICIPATION IN THE SAFETY SYSTEM BASED ON STANDARDIZATION AND MULTI-CRITERIA DECISION-MAKING

Abstract
The participation of workers in the functioning of an organizational system is a significant activity enabling employees to take part of the decision-making processes affecting the how work activities are performed and the conditions under which work processes operate. In this way, employees directly contribute to the development of organizational knowledge, express their views on the current state of the organizational system or production process, and influence relevant decision-makers. In the field of safety management, this participation implies, in addition to the standard monitoring of rules and work procedures, the sharing of control over decisions critical to the safety system, such as hazard identification, selection of appropriate measures, assessment of real risks, performance monitoring, interpretation of safety outcomes, and development of a safety culture. This approach both reduces the likelihood of adverse events and ensures proper system functioning. Supported by system standards and multi-criteria decision-making methods, employee participation enables the development of an efficient and effective safety system, as presented in this paper.

Key words: Safety management, worker participation, standardization, multi-criteria decision-making.

INTRODUCTION

In the last 40 years, techniques for identifying and analyzing risks in complex systems, as well as the basic concepts on which occupational safety systems are built, have been significantly improved. The developments of the safety lifecycle model and standardization have contributed to better safety management and integration with other business processes. However, numerous studies still indicate a high number of accidents resulting in fatalities or injuries of varying severity, and only a slight decrease in workplace-related illnesses, as well as an increase in disorders related with psychological burden and stress [1],[2],[3].

Efficient and effective management of safety systems, especially in complex organizational and production systems requires appropriate data for decision-making [4],[5],[6]. The volume of such data often necessitates expert selection of key indicators related to both states and activities. Although direct indicators have traditionally been considered the primary basis for decision-making because they describe outcomes within the safety system, indirect indicators are becoming increasingly important due to their ability to reflect the current state of the safety system, that is, the activities contributing to it [7].

The development of modern technologies facilitates the monitoring of conditions in the working environment, enabling the development of monitoring systems that are gradually evolving from IoT (Internet of Things) to IoW (Internet of Workers). However, employees remain the basis of the safety system, and their participation in the decision-making related to safety is invaluable. The active participation of employees in safety systems, together with their perceptions of the effectiveness of safety measures, is indispensable in the development of a successful safety system.

LITERATURE REVIEW

Numerous authors emphasize the importance of employee participation in OHS management systems, considering it a critical component [8],[9],[10]. It affects the success of the implementation and functioning of the OHS system at different organizational levels, as well as the improvement of safety performance [11].

There are two key dimensions of participation, relating to its extent and depth. These are basically based on the requirements defined by standardized management systems, which allow for different levels of participation. These levels range from basic information sharing, through a consultative function, to active participation in decision-making related to safety. Comprehensive participation of employees is desirable from the very beginning of the establishing the safety system and defining of the safety policy, through the development of trainings and the definition of the necessary competencies of employees, to the implementation of risk reporting mechanisms and the analysis of the effectiveness of the applied safety measures.

A large number of indicators within the safety system aim to enable a better understanding of its functioning [4],[12]. However, not infrequently, the effect may be the opposite of what is intended. Indirect indicators describe organizational activities, while direct indicators describe the outcomes of the safety system. Employee participation is of particular importance, along with other management mechanisms that enable the selection of key indicators. Multi-criteria analysis (MCDA) or multi-criteria decision-making (MCDM) has proven to be a useful tool for selection, even in situations involving multiple participants and where it is necessary to account for uncertainty in the process. ISO 31010 itself identifies multi-criteria methods as useful tools in risk management.

Different MCDM methods can be applied in the realization of participation in OHS management systems. Some of the classic approaches are presented in [13]. AHP-like methods are used to determine criteria weights, while their fuzzy extensions incorporate uncertainty into decision-making processes. The ranking of alternative solutions is effectively carried out using TOPSIS methods, while the relationships between factors or variables can be analyzed using DEMATEL and ANP methods, respectively. The VIKOR method can be used to identify compromise solutions between management and employees, while the comparisons of several alternative solutions can be conducted using one of the methods from the PROMETHEE family.

METHOD

The paper employs an analytical-synthetic research approach to examine the properties and importance of employee participation in OHS management systems. This specific research approach involves dividing a complex research subject into its component parts during the analytical phase, followed by identifying the connections among those parts in the synthesis phase to determine their interdependence and mutual influences. This cyclical process is applied in the analysis of both relationships and data, serving as a means of integrating deductive and inductive approaches.

The analytical component refers to the decomposition of a system into its basic elements to identify the nature and causes of specific phenomena and their consequences. The synthetic component primarily focuses on connecting these building elements to form a comprehensive view of the system and identify specific relationships, bearing in mind that certain properties are characteristic only of the system as a whole and not of its individual elements. Understanding these interactions provides the basis for a more complete understanding of the system functioning and for the development of more complex models or theories. This is particularly important in the analysis of complex phenomena and in forming new insights aimed at introducing innovations, while taking into account both individual elements and the system as a whole.

For the purposes of decision-making related to the subject system, data from manuscripts available in the KobSON and Google Scholar databases were used. Representative references were selected through searches based on keywords and specific phrases, and the PRISMA guidelines for systematic reviews were applied to ensure greater objectivity and focus.

Efficient and effective management of the safety system cannot be reduced to the use of a single criterion, whether it is the cost of implementing or maintaining the system, or a qualitative assessment of success in reducing risks to an acceptable level. Rather, it is necessary to consider a large number of indicators that describe both the outcomes of applied safety measures and the organizational activities

aimed at improving the existing system. Since the number of indicators can be very large, selecting the most influential indicators at a given point is of great importance for adequate decision-making.
There is a need to link employee participation in OHS systems supported by ISO 45001 and related standards, with appropriate MCDM methods. These methods represent a means of improving participation by enabling the entire process to become well structured, based on clearly defined rules, and supported by evidence-based decision-making involving multiple stakeholders. They make it possible to resolve conflicting demands and respect different opinions, while the application of fuzzy logic also incorporates uncertainty. In addition, technical, human and organizational factors are analyzed at the same time, including the influence of the dynamic environment in which the system operates. Activities such as risk evaluation and the determination of priority measures can be effectively carried out by applying MCDM methods because they allow to simultaneously analysis of several criteria and to reduce the subjectivity of individual views on a problem by taking into account the consistent opinions, knowledge, and experience of different stakeholders (employees and managers). Thus, MCDM methods actually represent means of operationalizing participation.

RESULTS

History

The historical development of employee participation in OHS management systems demonstrates a gradual evaluation from informal consultation to the application of formalized standard requirements aimed at improving the efficiency of employee safety and health protection. Employee participation has developed in several stages from the initial, elementary forms to today's more advanced approaches. Table 1 shows the historical development of different participation approaches.

Table 1. Development of worker participation in OHS systems

Safety	**Participation**	**Worker**	**Outcomes**
Protective	Informal	Passive object	Accident reduction
Representative	Consultative	Represented participant	Legal compliance
Participative	Involved	Operational contributor	Improved risk control
Systems	Collaborative	System stakeholder	System effectiveness
Empowerment	Autonomous	Safety co-owner	High reliability

Source: Literature review and own source

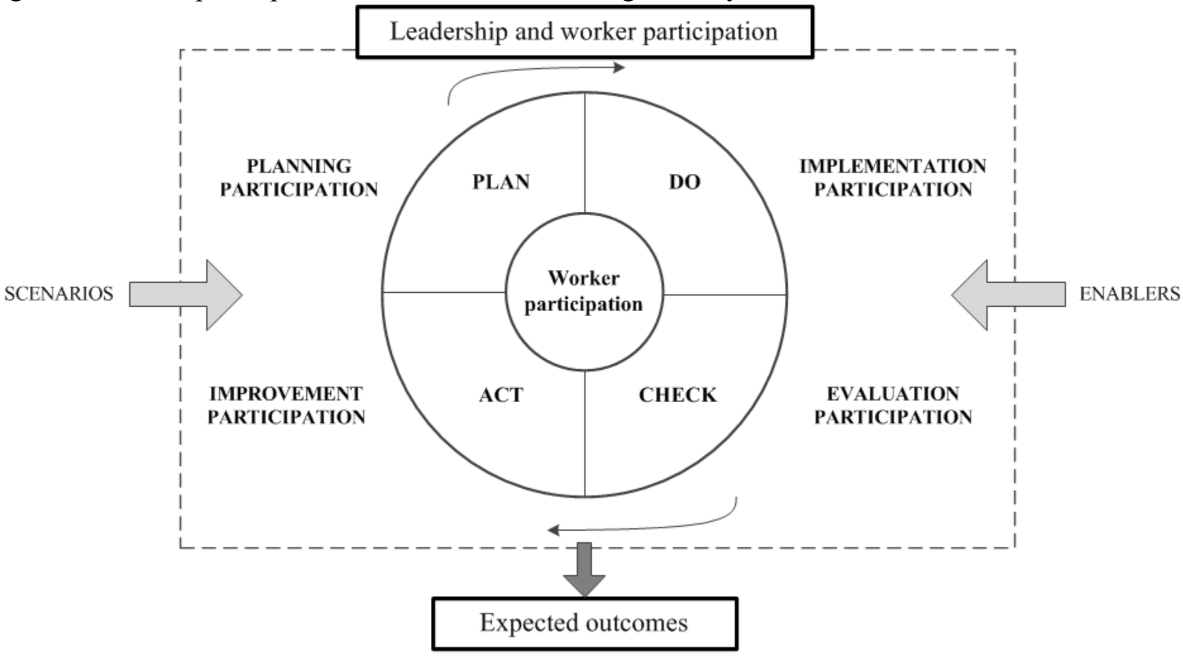
The standard approach, based on the command-and-control mechanisms and characteristic of management practices until the 1970s, implied the passive role of employees, top-down management, and strict adherence to defined work procedures, with minimal opportunity of changing existing rules. Early initiatives by labor unions and the introduction of employee representatives played a significant role in advocating for the rights of employees to a healthy and safe working environment. This has remained an important form of participation through employee representatives, who are often also OHS specialists, operating either at the organizational or local level. This approach was later improved primarily through the introduction of employee representatives, who served in consultations during the implementation of procedures and after the occurrence of adverse events, when compliance was required [14],[15].
However, only with the introduction of the management system, defined by the ISO 18000 series and later ISO 45000 series of standards was a modern approach based on integration and proactive action fully established. In this approach, employees become active stakeholders, involved both in the process of planning and defining policies, as well as in continuous consultation related to risk management and the evaluation of the effectiveness of applied safety measures. Several requirements within OHS management systems (OHSAS 18001, and later ISO 45001, as well as national equivalents of these standards) define and promote employee participation in at least three levels: participation in decision-making, consultation, and access to information. ISO 45001 identifies participation, alongside leadership, as a central requirement. In accordance with the recommendations of the World Health Organization (WHO) and the International Labour Organization (ILO), employees are recognized as key participants in management systems. Accordingly, ISO 45001 requires the implementation of strategies that give workers a leading role in the process of reviewing and approving OHS systems as a means of reducing adverse events and preventing adverse outcomes [16],[17],[18].

Model

The participation of employees in occupational health and safety (OHS) management systems is a significant building block, because regardless of management's vision, employees are exposed to workplace risks every day and have the most recent direct experience of them. Their experience and feedback is one of the most important and useful requirements in the ISO 45000 series of standards, because they describe the system as it actually operates, including all potential technical and organizational deficiencies that may not be easily visible at the management level. Participation in the development and improvement of work procedures enables employees to more easily accept and follow the requirements that they have partly helped define themselves. The ultimate goal of this is to improve the performance of the safety system, most often described by reducing the value of direct indicators such as accident rates and, therefore, fewer process disruptions and higher productivity.

An important aspect of the participation is how it is implemented in practice. Figure 1 presents different participation areas in the OHS system, based on the ISO 45001 standard. Avoiding a top-down approach can be achieved through joint forms involving management and employees for the exchange of ideas, analysis of incidents and audits, safety committees that maintain communication with management, various forms of direct consultation before and after work activities or in specially defined terms, and the existence of a reporting system through which employees can express attitudes about near-miss events and hazards in work processes.

Figure 1. Worker participation areas in the OHS management system



Source: Based on ISO 45001 standard and own source

The model is based on the standard PDCA cycle of the OHS management system, as defined in the ISO 45001:2018 standard. It integrates employee participation in all elements of the system based on the requirements of the standard, with special emphasis on Clause 5.4 relating to participation.

An important aspect of evaluating the success of participation is the introduction of specific indicators. The quality of participation is difficult to assess because of its predominantly qualitative nature. One useful indicator is employees' involvement in identifying near-miss events, which reflects a positive attitude to the culture of reporting and freedom of employees to express their views on potential problems in the safety system. Another important indicator is the active participation of employees in trainings or safety workshops, rather than just their simple attendance, bearing in mind the expression of opinions and the identification of possible difficulties in implementation. Additional indicators of engagement in the safety system may also be useful, such as the number of safety interactions conducted within a given period (week or month), the percentage of proposals for improving the safety system that were implemented by management, and the perception of employees of how management responds to their suggestions regarding improvements to the OHS system and, what is even more important, how fast those proposals are implemented in practice.

A comprehensive analysis of participation should include different phases in OHS management, from policy development and safety communication to participation in analyses and inspections, risk assessment, evaluation of safety measures, and reporting on incidents and accidents, as well as analysis of adverse outcomes. Various authors emphasize the importance of participation for the successful implementation of the OHS management systems [5]. Evaluation of participation effectiveness should include both qualitative and quantitative evaluation approaches, so that results can be presented through numerical values, frequencies, percentages, as well as qualitative statements and scale-based assessments.

The quality of participation can be described using the composite index Q, which includes different types of employee participation in OHS systems. It can be defined as follows:

$$Q = f\left(a_1,\ldots,a_n\right) = \sum_{i=1}^{n} \chi_i \cdot \omega_i, \tag{1}$$

where χ_i represents the normalized score for the i-th criterion, n is the number of criteria, ω_i is the weight of the i-th criterion ($\Sigma\omega_i$=1), while a_i represents different types of worker participation, including, but not limited to, sharing information, consultation, active participation and empowerment, with the aim of improving the effectiveness of the OHS system. The values can be crisp or fuzzy, depending on whether uncertainty is incorporated into the decision-making process. Care should also be taken regarding the minimum share and importance of individual forms of participation, since they are not mutually exclusive. On the contrary, different forms of participation complement one another and contribute to making the OHS system more functional.

DISCUSSION

During the analysis of employee participation in OHS management systems, various principles were identified, depending on the levels at which employees are able to make decisions or provide suggestions regarding safety. The basic level of participation is passive in nature, where employees receive information and participate in scheduled trainings in accordance with legal obligations and organizational recommendations. A higher level is consultative in nature, where management communicates with employees regarding safety and independently makes final decisions based on the information collected. The highest level of participation implies the active involvement of employees in decision-making related to safety measures and preventive actions. Various methods are used to implement such participation, ranging from joint committees, which facilitate the exchange and mutual understanding of information between employees and management, to different forms of involvement at different organizational levels in accordance with the PDCA (Plan-Do-Check-Act) cycle, as well as in different phases of risk management, the development of safety programs and policies, and the development of training programs and continuous education of employees.

The modern approach to participation implies employee leadership of and empowerment. The high priority that the ISO standard assigns to participation, together with the top management's commitment to providing the conditions and resources necessary for active involvement in various stages of system development, forms the basis for the success of an OHS management system. This approach ensures a leadership role for employees, while their sense of responsibility is strengthened through appropriate training and consistent, positive management responses to employee initiatives and requests.

Organizations can monitor the success of participation by introducing performance indicators [11], [20]. Although different indicators may be used, numerous authors emphasize the importance of leading indicators and their relationship to OHS system outcomes, such as accident rates or absenteeism levels. In the context of activity indicators, participation metrics related to meetings are particularly significant, as they reflect employee involvement in various OHS teams, goal setting, and the development of OHS training programs. In addition, the number of employee suggestions implemented in practice is also important indicator, as it reflects both employee contribution and organizational recognition of their suggestions. The importance of employees in the decision-making process can also be assessed through the number of employees involved in decision-making on OHS issues, as well as through employees' awareness of appropriate safety measures.

The primary contributions of employees in OHS systems relate to the identification of priority hazards and the selection of appropriate safety measures. Employees identify hazards, but the organizational management must decide which of them are the most critical and to which available resources should be directed as a priority. It is desirable to consult employees regarding the effectiveness of measures for

risk control in order to assess their acceptability and ensure their successful implementation [21], [22]. For analyzing the quality of participation, a suitable quality index can be developed, multidimensional in nature, using several different criteria weighted by appropriate coefficients.
A large number of indicators leads to the need for adequate data management. The selection and more detailed analysis of key indicators, determined through the application of MDCM methods, have proven to be a good solution in numerous situations involving complex safety systems and have also been shown to be effective in measuring the success of employee participation in OHS management systems.
The importance of employee involvement and the potential application of MCDM in real systems are increasing, particularly in the context of standardization, with the aim of enhancing participation from the level of informal exchange of opinions to the level of structural participative decision-making based on evidence. In modern OHS systems, decisions related to safety are based on the analysis of objectives, with the participation of multiple stakeholders under conditions of uncertainty, as well as consideration of human, organizational and technical factors in a dynamic environment characterized by constant changes. MCDM helps in situations involving numerous, often conflicting criteria. When multiple stakeholders are involved, their personalized opinions can be aggregated to obtain a single group decision.
Employee participation implies various forms of contribution to the functioning of the organization, primarily through improving knowledge and identifying risks, providing feedback on the success of applied safety measures, and influencing the selection of priority actions and safety-related decision-making. MCDM serves as a tool for the operationalization of employee participation and is very suitable for application in safety systems, from defining priority hazards, through selecting optimal safety measures, to evaluating and monitoring the effects of implemented innovations.

CONCLUSION

The foundation of the development of safety systems, their efficient and effective management, is reflected in the modern approach to safety based on resilience engineering. A safety system, viewed as a complex system in continuous interaction with other systems in its environment, is supported by the knowledge and experience of employees in the field of safety, who represent an immeasurable source of solutions rather than merely an outcome that should be controlled in the simplest way. In this paper, the principles of employee participation in occupational health and safety (OHS) management systems are examined, taking into consideration the systems approach, the ISO 45000 series of standards, the evolution of participation over time, and the ways in which the effectiveness of such participation were analyzed.
Traditionally, decisions in OHS systems are made by experts based on qualitative indicators and are often subjective in nature. The application of MCDM methods enables the verification of decision consistency, the involvement of multiple stakeholders, and greater transparency in the decision-making process. In this way, structured participation is achieved instead of symbolic, purely consultative employee participation. Using MCDM methods in the context of employee participation in OHS management systems helps determine the most important criteria and identify the best alternative solutions. It is possible to analyze different participation scenarios with the aim of selecting the optimal solution for achieving the best safety outcomes, as well as determining the priority forms of participation. All this is done with the aim of improving safety and building consensus on priorities in improving the existing system. At the same time, MCDM methods do not replace employees in any way. They enable employee participation to be transparent, based on a clearly defined procedure, and associated with measurable results, in accordance with the requirements of relevant system standards.

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Standards

- IEC 31010:2019, Risk management — Risk assessment techniques
- ISO 45001:2018, Occupational health and safety management systems—Requirements with guidance for use

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DEVELOPMENT OF LEAN SIX SIGMA BASED INNOVATIVE TRAINING FOR ENHANCING OCCUPATIONAL SAFETY AND HEALTH AWARENESS AMONG EMPLOYEES

Abstract
Lean Six Sigma is increasingly recognized in academic and professional literature as an innovative management approach for occupational health and safety field, facilitating a shift from reactive, compliance-oriented practices toward proactive, prevention-based, and data-driven safety management. Desktop research findings indicate that the integration of Lean principles focused on incident elimination with Six Sigma methodologies aimed at reducing process variability provides a structured framework for systematically identifying hazards, mitigating safety risks, and lowering incident rates, while simultaneously enhancing operational efficiency and organizational performance. By embedding continuous improvement and evidence-based decision-making into daily operations, Lean Six Sigma contributes to the development of a sustainable safety culture across organizational levels. A notable advancement in this context is the evolution of the traditional 5S methodology into the 6S framework, which explicitly incorporates safety as a core element. This extension strengthens the linkage between workplace organization, standardization, visual management, and risk reduction, including improvements in ergonomics and emergency accessibility. However, desktop analyses also emphasize that the effective implementation of Lean Six Sigma in health and safety management is highly dependent on strong leadership commitment and robust change management practices. In particular, aligning productivity and efficiency objectives with employee well-being is essential to prevent unintended consequences such as increased work-related stress or ergonomic risks. Consequently, Lean Six Sigma represents a promising integrative framework for advancing holistic and resilient safety management systems.

Key words: Lean Six Sigma, 6S, Innovative Management, Health and Safety.

INTRODUCTION

Occupational Health and Safety constitute fundamental determinants exerting a substantial influence on the sustainable growth and overall success of any organization. The commitment to ensuring workplace safety is not only mandated by prevailing legal frameworks but is also justified by economic considerations and upheld as an essential component of professional ethics. Consequently, the continuous enhancement of occupational safety within enterprises remains a persistently relevant and critical area of focus. Within the framework of the Occupational Health and Safety Management System, the enterprises systematically receive, evaluate, and respond to observations, suggestions, and information about occupational health and safety submitted by employees and their representatives. The principles and procedures governing internal communication in this domain are formally established through a designated procedural document. The primary objective of this procedure is to enhance the effectiveness and efficiency of information exchange across the organization in matters related to Occupational Health and Safety [1].

Enterprises frequently realize substantial gains during the initial stages of lean implementation through the application of tools such as Kanban, 5S, SMED, and FIFO. However, these improvements often plateau over time. This stagnation may be attributed to an exclusive emphasis on inefficiency (or "waste") elimination and the associated methodologies. While waste reduction constitutes a critical component of lean philosophy, it is insufficient, in isolation, to cultivate a genuinely lean-oriented organization or to sustain a Continuous Improvement Process (CIP). Indeed, CIP extends well beyond mechanisms such as employee suggestion schemes or periodic improvement workshops; rather, it emerges from a deeply embedded culture of continuous enhancement. In this context, lean leadership may represent the critical missing link between isolated waste reduction efforts and the development of a truly continuously improving lean organization [2].

The formulation and implementation of an effective Quality Improvement (QI) or Continuous Improvement (CI) strategy constitute a critical determinant of the long-term sustainability and competitiveness of modern organizations. In recent years, Lean Six Sigma has emerged as one of the most widely recognized and empirically validated methodologies for business process improvement.

Rooted in the principles of the Toyota Production System, lean thinking emphasizes the systematic identification of value within processes by distinguishing between value-adding and non-value-adding activities, and subsequently eliminating waste to ensure that each process step contributes meaningfully to value creation. In this context, lean prioritizes operational efficiency, with the objective of delivering products and services at minimal cost and within the shortest possible time.

Six Sigma, originally developed at Motorola in the mid-1980s by engineer Bill Smith, represents a structured, data-driven approach to process improvement aimed at identifying and eliminating the root causes of defects and errors. It focuses on process outputs that are critical to customer satisfaction, employing statistical methods to shift process performance, enhance robustness, and reduce variability that leads to quality deficiencies.

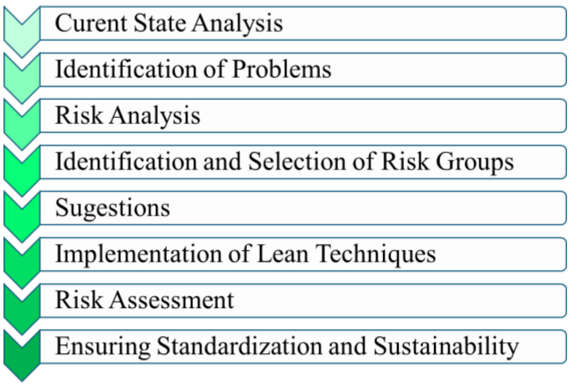
The integration of these complementary approaches within the Lean Six Sigma framework seeks to enhance organizational capability, minimize production costs, and maximize shareholder value through sustained improvements in quality and process performance [3].

The primary objective of this research is to examine the influence of production processes and human behavior on innovation-driven change, with particular emphasis on the application of the 6S method—within the frameworks of Lean management and Six Sigma—as a means of preventing workplace injuries. The study adopts a methodological approach involving the systematic collection and analysis of information derived from planned theoretical research, integrating and sequencing relevant sources to ensure coherence. Core concepts are examined through a critical review of selected scientific literature. Key constructs, including the working environment, 6S, risks, and opportunities, are investigated using document analysis and content analysis methods. Furthermore, the research employs a combination of deductive and inductive reasoning to classify, synthesize, and consolidate the theoretical foundations underpinning the study. Implementation of each 6S phase was guided by the PDCA (Plan-Do-Check-Act) cycle. Detailed planning sheets were developed for each phase, specifying the assigned tasks for individual team members along with scheduled deadlines for their completion, ensuring a structured and accountable execution of the methodology.

METHODS

A model for the development of an effective occupational health and safety (OHS) system, aligned with lean methodologies, is presented in Figure 1. This model is designed to enhance worker protection through the systematic reduction of potential hazards, the promotion of process standardization, and the assurance of long-term sustainability.

Figure 1. Lean Occupational Health and Safety (Lean-OHS) Model



Source: A case study on lean occupational safety [4]

The model exhibits a cyclical structure designed to facilitate continuous improvement. Beyond the immediate benefits associated with the implementation of the Lean-OHS model, it is anticipated that progressively greater outcomes will be realized over time as a lean-oriented culture becomes embedded within the organization.
The 6S methodology establishes an optimized working environment within the manufacturing sector. Its implementation enhances employee productivity and operational efficiency, while simultaneously cultivating a more disciplined and structured workplace culture across industrial settings.
Six phases of 6S technique are shown in Table 1.

Table 1. Six phases of 6S implementation

6S phases	Phase characteristics	Advantages
Sorting Seiri	Fundamental for workspace optimization. Removal of unnecessary items enhances spatial availability.	Improves material handling processes and enables employees to perform tasks with greater efficiency and ease.
Set in Order Seiton	Entails the systematic arrangement of tools, equipment, and materials in predefined locations.	Structured organization enables quicker access, decrease material handling time, and eliminates inefficiencies associated with searching for tools or raw materials.
Shine Seiso	Focus on maintaining all workplace elements (equipment, tools, and floors) in a clean, orderly, and well-maintained condition.	A clean and organized environment improves worker performance and reduces the risk of workplace accidents.
Safety Anzei Sei	Structured approach to establishing a secure work environment and enhancing employee working conditions.	Reduce the likelihood of workplace accidents and hazards.
Standardization Siketsu	Clearly defined standards are essential for systematically monitoring and preserving performance improvements.	Compliance enables continuous workplace monitoring and supports the attainment of both individual and team performance objectives.
Sustain Shitsuke	Ensure the continuity of all previously implemented 6S practices.	Disciplined work habits and organizational consistency. It secures the durability of improvements, enabling sustained efficiency, organization, and workplace safety.

Source. Own source and [3, 4, 8, 10]

The research design is primarily based on the DMAIC methodology (Define–Measure–Analyze–Improve–Control) framework, enabling a systematic, data-driven investigation within a real organizational context, as shown in Table 2.

Table 2. Six Sigma DMAIC methodology

D	Define	Understanding and mapping the process that generates the product or service to gain comprehensive familiarity with its workflow
M	Measure	Focus is placed on critical quality parameters—those with the greatest impact on the outcome, to ensure measurement efforts capture the most influential aspects of the process
A	Analyze	Identify performance gaps, defined as the difference between current operations and the process's potential performance
I	Improve (Inovate)	Proposed solutions to address process deficiencies are validated by the project team, and the capability of the optimized process is evaluated to confirm their effectiveness
C	Control (Check)	Focuses on sustaining process improvements and ensuring that the desired quality levels are maintained over time

Source. Own source

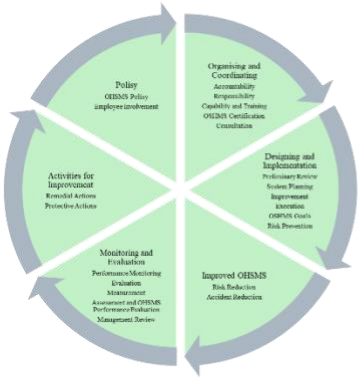
Overall, this methodological approach integrates statistical rigor with practical intervention, ensuring that the research not only analyzes safety challenges but also contributes to measurable and sustainable improvements in workplace safety performance.
Six Sigma advocates a structured problem-solving methodology to guide project execution. This approach follows a systematic five-step process, encapsulated in the DMAIC acronym: Define,

Measure, Analyze, Improve (or Innovate), and Control. The DMAIC framework, supported by a comprehensive set of analytical and operational tools, serves as a mechanism to transform complex problems characterized by numerous uncontrolled variables into scenarios where process quality is effectively managed and controlled [5, 6]

RESULTS

Incidents are unplanned or unforeseen events that deviate from established standard operating procedures or expected conditions of safety [7]. Occupational health is defined as the promotion and maintenance of employees' physical, psychological, and social well-being across all occupational sectors. Over time, advancements in this field have substantially enhanced workplace safety, strengthened health promotion initiatives, and improved the prevention of work-related illnesses. Contemporary developments in both technological innovations and occupational health practices continue to play a pivotal role in advancing worker safety and overall well-being [8]. Phases of implementation are shown in Figure 2.

Figure 2. Phases for OHSMS implementation in the field of sustainable building construction



Source: Advancements in Occupational Health: Enhancing Workplace Safety and Well-being [8]

Advanced risk assessment methodologies are employed to identify, evaluate, and mitigate hazards, utilizing approaches such as probabilistic risk assessment and bowtie analysis. The integration of predictive analytics with real-time monitoring technologies enables the proactive detection of potential safety issues, thereby preventing workplace incidents. Furthermore, the implementation of safety climate surveys and safety culture assessments cultivates a safety-oriented organizational environment, providing critical insights into the factors that influence overall safety performance. Virtual reality and augmented reality technologies are increasingly employed for safety training, hazard recognition, and emergency response simulations. Virtual reality simulations allow employees to engage in high-risk scenarios, enhancing their situational awareness and response capabilities. These digital platforms provide comprehensive training resources, employee support services, and occupational health information [8].

The organization seeks to cultivate a robust safety culture, elevate employee morale, and improve productivity through the adoption of emerging technologies, ergonomic interventions, mental health support, and advanced risk assessment strategies. Recognizing occupational health as a critical determinant of employee well-being, specifically examines how a manufacturing enterprise leverages these innovations to strengthen workplace safety and promote overall employee health [8].

The provision of a healthy and safe working environment by employers, the protection of employees from occupational accidents and diseases, and the implementation of necessary preventive measures constitute fundamental priorities of working life and a shared responsibility among all relevant social stakeholders. In the contemporary context, countries characterized by low rates of occupational accidents and diseases are regarded as well-structured and secure, demonstrating advanced levels of development through their ability to ensure optimal working conditions in alignment with modern standards [9].

Lean Business Management is a strategic approach that links organizational performance, measured in terms of productivity and quality, with operational flexibility, guiding enterprises to optimize and sustain all of their processes. Lean stakeholders prioritize performance enhancement through the principle of

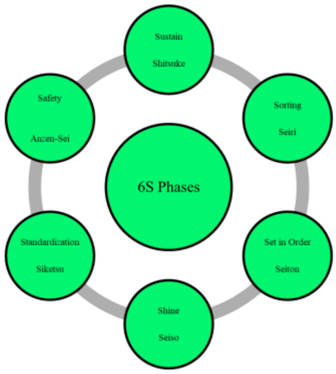
continuous improvement, which is achieved by systematically identifying and eliminating waste throughout organizational operations [6].
Lean transformation begins with the systematic elimination of the seven wastes: overproduction, waiting, transportation, over-processing, excess inventory, unnecessary motion, and defects. Central to this transformation is the implementation of the 5S methodology: Seiri (organization), Seiton (neatness), Seiso (cleaning), Seiketsu (standardization), and Shitsuke (discipline). The 5S approach is intuitive and relatively simple to apply, providing tangible improvements on its own while also establishing the foundational elements of process-oriented thinking and value stream mapping, which are critical for supporting broader system enhancements. Contemporary Lean practices emphasize the continuous identification and elimination of non-value-adding activities within the value stream, while simultaneously promoting value-adding processes. To achieve these objectives, Lean methodology employs a range of tools, including Value Stream Mapping, 5S, Kanban, Total Productive Maintenance (TPM), Visual Factory, Poka-Yoke, quick changeover techniques, Just-in-Time (JIT) production, Six Sigma, Kanban, Kaizen, Standardization, and process mapping techniques all of which reinforce operational efficiency and quality [10], [11], [12].

The Six Sigma methodology has emerged as a widely adopted industrial approach due to its effectiveness in identifying risks, measuring performance, and optimizing processes. Organizations employ Six Sigma to meet international quality standards, integrate advanced technologies, and drive continuous improvement within their manufacturing operations. By systematically eliminating waste and implementing high-impact solutions with minimal effort, Six Sigma seeks to establish well-controlled processes and effectively reduce defects. The methodology also emphasizes process integration, utilizing the five-step DMAIC cycle: Define, Measure, Analyze, Improve, and Control, alongside robust statistical tools. Key components include supporting organizational leadership, engaging personnel at all levels, sharing measurable performance metrics, and applying rigorous statistical analyses. Recently, Six Sigma has gained prominence as a holistic framework for enhancing the quality, safety, and efficiency of manufacturing, logistics, and technical maintenance processes [9]. Consequently, in recent years, the framework has evolved into 6S with the inclusion of “Safety” as an explicit component, further reinforcing its focus on protecting employees while maintaining operational excellence [11].
Safety refers to the systematic process of ensuring a secure and healthy workplace by creating optimal working conditions for employees. This is achieved through the proper use of tools, the application of personal protective equipment (such as gloves, goggles, masks, and helmets), the maintenance of clear access pathways, and the organized storage of safety equipment in designated, easily accessible locations.
The 6S methodology extends beyond mere cleanliness, encompassing workplace organization, safety, clear marking and labeling, optimized process flows, and the promotion of a healthy work environment. It also involves regular auditing to monitor progress and sustain improvements. By integrating these practices, 6S serves as a powerful mechanism for continuous enhancement of operational performance and efficiency across industries. Ultimately, the technique establishes a clean, organized, and safe work environment, thereby improving employee performance and contributing to overall organizational productivity [11].

One of the fundamental tools of Lean Manufacturing is the 6S methodology, which plays a critical role in enhancing productivity. Beyond serving as the foundation for continuous improvement, the 6S approach fosters positive employee motivation, promotes a pleasant and organized work environment, and reduces the occurrence of quality-related issues. Additionally, it significantly enhances the overall corporate image [11].
The 6S methodology is a widely adopted approach in the manufacturing industry aimed at enhancing operational performance. It represents an advanced evolution of the 5S concept originally developed in Japan. The 6S approach focuses on minimizing defects and optimizing the utilization of available resources to achieve maximum productivity. A primary objective of this methodology is to reduce workplace accidents and improve safety at industrial workstations.
Comprising six structured phases, the 6S framework can be implemented across organizations to achieve measurable benefits. Additionally, the 6S approach serves as an effective tool for analyzing and improving workstation processes. Its implementation reduces operational time, including activities such

as material handling and tool changeovers, while enhancing process control and ensuring more efficient and streamlined production systems [13].
The 5S methodology is implemented through a structured procedure that emphasizes careful planning, systematic execution, performance monitoring, and subsequent refinement. Similarly, the 5S + Safety (6S) approach demands a high level of discipline and precision to ensure effective application. Implementing 6S necessitates the development of a tailored process framework to integrate safety considerations alongside traditional 5S practices [14].
The 6S methodology fosters an organized and conducive work environment within the manufacturing sector. Its implementation enhances employee efficiency by streamlining workflows and optimizing operational practices. Additionally, the 6S approach promotes a disciplined workplace culture, reinforcing systematic processes and adherence to standards throughout the organization [15].
The 6S methodology is structured around six sequential phases introduced in Figure 3.

Figure 3: Phases of 6S Technology



Source: Application of 6S Approach in Manufacturing Industry - A Case Study [15]

To facilitate this objective, a set of documents was developed to establish systematic controls and audit procedures for evaluating the performance of the pilot area. These controls enable verification of whether the implemented changes and improvements have been effective. The audits assess process performance across the six phases, functioning as structured checklists to monitor and evaluate the condition and compliance of all elements within each phase [14].
Training in the field of Occupational Safety and Health (OSH) is essential for reducing workplace hazards and safeguarding employee well-being. The rapid advancement of digital technologies introduces both new opportunities and challenges within OSH. In this evolving context, emerging risks and unforeseen contingencies stem from the complex interactions among human factors, machinery, technological systems, and the surrounding environment [16].
An additional learning objective is to reduce exposure to workplace hazards and enable individuals to acquire and apply appropriate safety procedures. Further contributions focus on enhancing the effective use of Personal Protective Equipment (PPE) and promoting adherence to established safety regulations, guidelines, and procedures. The design of the training tool also integrates essential components for knowledge evaluation, particularly through the development of key performance indicators (KPIs) and clearly defined learning objectives.

Moreover, the development of immersive learning experiences should carefully consider the range of sensory inputs engaged during training. Effective learning extends beyond visual stimuli, incorporating auditory, tactile, and even olfactory elements to enhance realism. Engaging multiple senses contributes to a more immersive and memorable learning experience, thereby improving knowledge retention and facilitating the transfer of acquired skills to real-world contexts [16].
In a broader context, sustainability has become increasingly significant and encompasses three primary dimensions: social, environmental, and economic. Evaluating sustainability across these domains highlights areas requiring continuous improvement and long-term maintenance. The Lean Six Sigma framework provides an effective mechanism for identifying, implementing, and sustaining such improvements across these interconnected dimensions [3].
Workplace accidents negatively impact process efficiency by introducing non-value-adding activities within production systems. Given that Lean principles are inherently focused on waste reduction, it can

be reasonably inferred that minimizing occupational hazards is a natural outcome of implementing Lean practices. Establishing a Lean work environment requires strong managerial commitment and active employee engagement. All organizational levels must consistently collaborate and contribute to continuous improvement efforts, which ultimately lead to enhanced productivity, quality, and safety performance.
The shift from conventional safety practices to technology-driven solutions is reshaping occupational safety in the construction industry. Traditional methods, including safety manuals and scheduled inspections, frequently prove insufficient for managing real-time hazards on dynamic construction sites. In contrast, emerging technologies provide a more proactive and efficient approach to identifying and mitigating workplace risks [17].
Wearable technologies, including smart helmets and vests, are transforming occupational safety by enabling real-time monitoring of workers' physiological states and environmental conditions. These devices can detect fatigue, track exposure to hazardous substances, and provide alerts when personnel enter restricted or high-risk areas. Similarly, drones offer a significant innovation by allowing site managers to perform aerial inspections and identify unsafe conditions without endangering workers. Furthermore, smart sensors integrated into machinery and infrastructure continuously monitor factors such as structural integrity, gas concentrations, and equipment performance, thereby improving preventive maintenance and overall risk management [17].

The incorporation of these technologies into construction safety protocols not only reduces workplace risks but also promotes a culture of innovation and responsibility. By utilizing data-driven insights, organizations can implement more effective safety measures and ensure compliance with evolving regulatory standards.
The successful adoption of safety technologies depends on comprehensive workforce training, ensuring that both employees and managers are proficient in using these tools effectively. A lack of familiarity with wearable devices, drones, or sensor systems can result in underutilization or incorrect application. Therefore, training programs should emphasize practical, hands-on demonstrations, enabling workers to gain direct experience and build confidence in operating the technologies safely and efficiently.
Upskilling employees involves training them to interpret data generated by safety technologies and respond appropriately to alerts. For instance, training can demonstrate how to conduct site inspections using drones or how to analyze sensor readings to detect potential hazards. Such programs enhance worker competence while minimizing the risk of errors in utilizing these tools. Equally important is addressing resistance to technological adoption. Transparent communication regarding the benefits of these innovations, such as improved safety and reduced workload can alleviate employee concerns. Additionally, incentivizing participation through certifications or formal recognition for completing training programs fosters greater acceptance, engagement, and commitment to effective technology use [17], [18].
Within organizations, safety culture emphasizes the integration of health as a core component. Consequently, it is frequently referred to in the literature as the "Health and Safety (H&S) culture" [19]. Employee awareness of safety is critical for maintaining organizational safety standards. Low safety awareness reflects a weak safety climate, compromising employee health and safety. Behavioral-Based Safety is a structured process that engages employees in adhering to safety procedures, fostering the recognition of safe versus unsafe behaviors, and promoting behavioral and attitudinal transformation. This approach aims to prevent workplace hazards, injuries, loss of life, and associated time and financial losses [19].

Integrating Lean Manufacturing with Safety Management Systems highlights the importance of the "6th S"—Safety—added to the traditional 5S framework. The 6S approach enhances workplace organization, reduces waste and non-value-added activities, and simultaneously improves efficiency, quality, and safety, making it a critical component for achieving world-class competitiveness.
Six Sigma Aligned with Safety Management Systems - Safety management can also be enhanced through the Six Sigma methodology. The DMAIC (Define, Measure, Analyze, Improve, Control) framework has proven effective in reducing workplace hazards and quantifying safety performance through Sigma level assessments. Additionally, tools such as Failure Mode and Effects Analysis (FMEA) and Risk Priority Number (RPN) calculations provide structured approaches to identify, evaluate, and prioritize risks across different organizational departments [19].

DISCUSSION

Lean Manufacturing is a business philosophy focused on minimizing processing time, resource use, and non-value-added activities to achieve operational excellence and sustainability. The 5S methodology: Sort, Set in Order, Shine, Standardize, and Sustain, forms the foundation of effective Lean implementation, providing a structured framework to ensure organization, cleanliness, standardization, and discipline in the workplace. Lean Manufacturing emphasizes worker safety by empowering employees with knowledge, skills, and opportunities to act safely, thereby reducing hazards and accident risks [19].

The primary objective of Lean Six Sigma Safety is to establish a workplace that is entirely free from injuries, ensuring the well-being of both the organization and its employees. Achieving this goal requires a robust foundation built upon a culture that prioritizes safety, making an injury-free environment a core component of the company's vision. The framework is structured around three key elements: People, Internal Systems, and Performance Management, each comprising three defining attributes. The People element emphasizes leadership, innovation, and ethical conduct; the Internal Systems element focuses on processes and procedures, planning and risk management, and the implementation of innovative solutions with flawless execution; and the Performance Management element centers on metrics, data and information, as well as clearly defined goals and objectives. This integrated approach ensures that safety is systematically embedded into organizational practices, processes, and performance evaluation [12].

The 6S methodology is widely recognized as an effective approach for enhancing both efficiency and safety within organizations. It is applicable across all types of industries, including small-, medium-, and large-scale enterprises. By systematically organizing the workplace and integrating safety as a core component, the 6S method strongly supports organizational objectives, fostering continuous improvement and driving higher levels of performance in terms of quality and safety. Safety constitutes a fundamental component of the 6S methodology. It refers to the condition of being protected from harm and maintaining a work environment free from potential hazards. Ensuring safety involves implementing policies, procedures, and protective measures designed to prevent workplace accidents and injuries. Essential safety equipment, including helmets, safety jackets, protective footwear, fire extinguishers, and first aid kits, must be readily available and properly maintained. Regular inspection and upkeep of all safety equipment are critical to guarantee their effectiveness and to sustain a safe and secure working environment [20].

The development of training programs grounded in Lean Six Sigma principles offers a structured and systematic approach to improving occupational safety and health awareness among employees. By integrating Lean methodologies, which emphasize the elimination of waste and optimization of processes, with Six Sigma's focus on data-driven performance improvement, organizations can create training interventions that are both efficient and highly effective. Such programs not only equip employees with practical knowledge about workplace hazards but also foster a culture of continuous improvement, proactive risk management, and accountability.

Innovative training frameworks leverage modern technologies, such as virtual reality simulations, wearable safety devices, and interactive learning platforms to enhance engagement and provide experiential learning opportunities. This approach allows employees to practice hazard recognition, emergency response, and safe operational procedures in realistic, controlled environments, improving retention and the application of safety principles in real-world contexts.

Moreover, Lean Six Sigma–based training emphasizes measurable outcomes, linking employee learning to key performance indicators (KPIs) and organizational safety objectives. By systematically analyzing performance gaps, monitoring behavioral adherence to safety protocols, and promoting continuous feedback, the training ensures sustained improvements in both individual and organizational safety performance. Consequently, the integration of Lean Six Sigma into Occupational Safety and Health training not only strengthens employee competence but also contributes to broader organizational goals, including higher productivity, reduced incidents, and compliance with regulatory standards.

CONCLUSION

The development of Lean Six Sigma based innovative training for Occupational Safety and Health (OSH) focuses on shifting from a reactive "accident-results" mindset to a proactive "process-driven" approach. By integrating Lean Six Sigma tools like DMAIC (Define, Measure, Analyze, Improve, Control) with safety management, organizations can systematically identify hazards and reduce workplace incidents.

Innovation management and safety are deeply intertwined: innovation drives new ways to prevent harm, while effective safety culture *enables* innovation by providing psychological and operational security for experimentation, turning safety into a competitive advantage through proactive risk reduction and sustainable, resilient practices, requiring leaders to integrate both into strategy and daily operations.

Lean Six Sigma is increasingly recognized as an innovative management approach for Health, Safety, and Environment, as it reorients safety management from a reactive, compliance-focused activity to a proactive, data-driven core organizational function. By integrating Lean principles of waste elimination with Six Sigma methodologies for defect reduction, organizations can systematically mitigate safety incidents, enhance operational efficiency, and foster a sustained culture of continuous improvement.

To be effective, Lean Six Sigma training must be supported by management to ensure safety culture becomes a permanent part of the organization. Using a combination of e-learning, in-person workshops, and on-the-job training allows for maximum retention.

Effective implementation necessitates strong leadership commitment to address resistance to change and to ensure that productivity and efficiency initiatives do not inadvertently exacerbate employee stress or ergonomic risk factors.

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DRIVERS OF MODERN SUSTAINABILITY: INTEGRATING GREEN INNOVATION AND DIGITAL TRANSFORMATION WITHIN THE MRW FRAMEWORK

Abstract
Global development and shifting market demands have created unprecedented environmental challenges, compelling corporations to prioritize sustainability for competitiveness. Tackling these issues requires balancing regulatory frameworks, technology, and market dynamics. Amid rising anti-globalization, digital transformation and green innovation offer a path toward coordinated growth. This paper provides a theoretical foundation for sustainability, focusing on EU legislative efforts to safeguard public health through climate and air quality policies. Despite the Green Deal's impact, achieving 2050 carbon neutrality necessitates more assertive investments in clean technologies. Supporting this transition, the circular economy and the Mankiw-Romer-Weil (MRW) framework demonstrate that recycling and eco-innovation drive modern sustainability. Our contribution analyzes these themes through existing research, proving the MRW framework is instrumental for sustainable development. By synthesizing theoretical and empirical evidence, we illustrate how integrating human capital and technological progress enables long-term growth aligned with ecological boundaries and contemporary market demands.

Key words: Circular Economy, European Green Deal, Green Innovation, Human Capital, Mankiw-Romer-Weil (MRW) model, Sustainability.

INTRODUCTION

The exponential growth of the global population has been accompanied by a greater demand for goods and services, which is closely related to the globalization of the market. However, such an increase in needs has resulted in a negative impact on the regenerative capacities of the Earth. Earlier analyses based on a linear economic model are no longer applicable due to the critical turning point in the relationship between anthropogenic impacts and the stability of the biosphere. According to the concept of planetary boundaries [14, 15], humanity has already crossed the limits [11], suggesting that we have reached the maximum carrying capacity of the planet.

It is clear from the above that globalization has had an impact not only on the economy and states, but also on the environment over a number of years. Although theoretically founded in the name of trade to increase profits and foster unity among nations and ethnic groups, globalization has damaged the environment in many ways. It has been proven in the literature that pollution released into the atmosphere through globalization processes has an irreversible impact on the Earth in all components of the environment [17].

The Green Economy as a Survival Imperative

The green economy is a policy framework for sustainable growth and development, where one does not exclude the other. It is important and useful because, in addition to focusing on improving human lives and the environment, it ensures that ecological and economic sustainability are not excluded [17]. Transitioning through economic modeling, the Green Solow Model [2] illustrates how technological adaptation can reduce the environmental impact of growth.

Currently, the environment is burdened by numerous challenges, including environmental degradation, global warming, ocean acidification, shrinking polar ice caps, the increasing occurrence of extreme weather conditions, etc. Climate change is a threat that can endanger health, safety and livelihoods, and (in)directly damaging agricultural production and industry [3]. Economic sustainability is based on all phases of a product's life cycle (LCA), in a way that takes into account the reduced consumption and greater utilization of that product.

Digital Transformation and Green Innovation through the MRW Lens

Seeking a solution, this paper utilizes the Mankiw-Romer-Weil (MRW) framework [10], which extends the traditional production function by incorporating human capital (H). Within this model, sustainability is not viewed as a constraint on growth, but as a result of strategic investment in specific forms of capital (K) and technological progress (A), as supported by broader growth empirics [1, 6]:

Human Capital (H) and Digital Skills - the MRW model emphasizes that growth depends on knowledge [10]. If the focus is on green innovations through digital transformation, then it is important to take care that digital literacy is at a sufficiently high level.

According to the data available in the reports for the digital economy [4], it is clear that without ensuring a workforce that is educated and trained to manage AI and IoT networks, the technological potential cannot be exploited. Investments in the creation of digital infrastructure and the acquisition of energy-efficient technology achieve the accumulation of capital needed to reduce resource consumption [12]. Digitization is seen in this model as a multiplier of total factor productivity. Namely, existing tools such as big data and blockchain accelerate green solutions [5], due to less use of materials and the realization of a circular economy through digitally enabled business models [8, 13].

Transition Mechanisms and Challenges

The green economy strives for a balance between the requirements of production processes and the impact on the environment in all phases of the product's life cycle [3]. However, the application of the MRW model indicates the need to make an important compromise. First of all, digital transformation requires capital investments and increases the need for energy consumption [9], which can have a negative impact if it is not accompanied by an adequate increase in available green energy sources. Although it seems intuitive, it is important to emphasize that strategic digital and green innovations are not exclusively technological issues, but a matter of adjustments within the MRW model in a way to ensure long-term stability [7]. Climate change has a negative impact on production, and in addition to the impact on the health of the workforce, it also manifests itself in problems with the supply of (natural) resources.

The aim of this paper is to analyze how digital transformation and green innovations together change the variables within the Mankiw-Romer-Weil model. Resource efficiency, stakeholder collaboration and conditions are important processes for realizing modern sustainability, in order to reconcile differences in the needs for economic growth and environmental constraints.

METHODS

For the purposes of this paper, the Mankiw-Romer-Weil (MRW) model [10] was used, in order to analyze the effects of digital transformation and green innovations on economic development. The methodological approach is based on a modification of the standard aggregate production function (1):

$$Y(t) = K(t)^{\alpha} H(t)^{\beta} [A(t)L(t)]^{1-\alpha-\beta} \; . \tag{1}$$

Human capital (H), as one of the variables, is given exclusively in the domain of digital competences and environmental literacy [5, 13]. Green innovations are selected as variables that track the share of technological progress (A), while digital transformation is seen as a catalyst for reducing resource intensity per unit of production [8]. The research employs a qualitative analysis of existing literature and secondary data to deconstruct the mechanisms through which these factors influence capital accumulation and the long-term steady-state [1, 6]. Particular emphasis is placed on the causal links between technological "lock-in" and the costs of energy transition, aiming to quantify the impact of ecological constraints on the trajectory of economic growth within the MRW framework [2, 9].

Empirical Validation and Data Sources

For the empirical validation of the established hypotheses, the research is conducted at two levels: a comparative analysis of the EU27 member states and an in-depth analysis of Croatia as a country in the process of technological catching-up. The theoretical MRW framework is operationalized using high-quality secondary data obtained from the Eurostat database.

Human Capital (*H*): To measure this variable within the context of digital transformation, the Digital Economy and Society Index (DESI) is utilized, allowing for the quantification of digital skills and the integration of digital technologies into business operations [4].

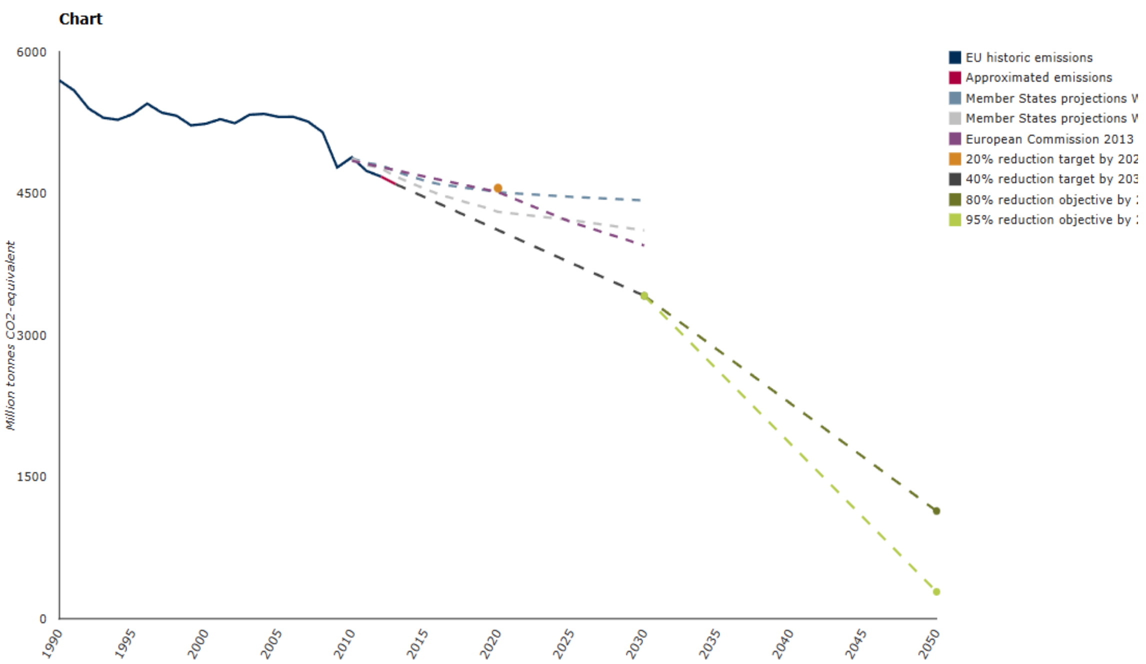
Technological Progress (*A*): The parameter relating to green innovations is monitored via the Eco-Innovation Scoreboard, which evaluates environmental efficiency and the outcomes of eco-friendly innovations.

A special focus of the analysis is placed on energy efficiency as a significant growth factor. In this sense, the paper draws on the research of Vlahinić-Dizdarević and Žiković [16], which highlighted that energy efficiency plays a role in the economic growth of South-Eastern European countries. The results show that through the MRW model, the reduction of energy intensity is inversely proportional to the growth of productivity. This is important for Croatia, but also for all other countries that are trying to align their economic growth with EU environmental standards. The paper will provide insight into the results of statistical data for the EU27 and an analysis for Croatia to show the actual impact of the digital transformation into a green economy through selected and defined growth variables.

RESULTS

The available quantitative data indicate a discrepancy between the achieved emission trends and the ambitious goals set by the European Green Plan. As shown in Figure 1, although there has been a continuous reduction in total greenhouse gas (GHG) emissions since 1990, extrapolation of current values can show that this is not enough to achieve climate neutrality. Although documented reductions have averaged around 46 Mt CO_2 per year, the pace of reductions would need to almost double to 81 Mt CO_2 to meet the 2030 targets and more than triple for the 2050 targets. This suggests that the targets set are quite ambitious, but that efforts so far have not achieved significant success and that the measures currently implemented need to be revised. Extrapolating from existing measures (WEM) and even additional planned measures (WAM), it follows that under current socio-economic and technological parameters, the EU is unlikely to achieve the primary target of a reduction of -55%. This discrepancy suggests that the Green Deal targets may be overambitious. The data emphasize that the current approach is not sustainable, and that it is necessary to increase the processes of digital transformation in order to separate economic growth from the consumption of resources.

Figure 1. Greenhouse Gas Emissions Trends and Projections vs. EU Climate Target



Source:European Environment Agency, https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse_gas_trends_and_projections

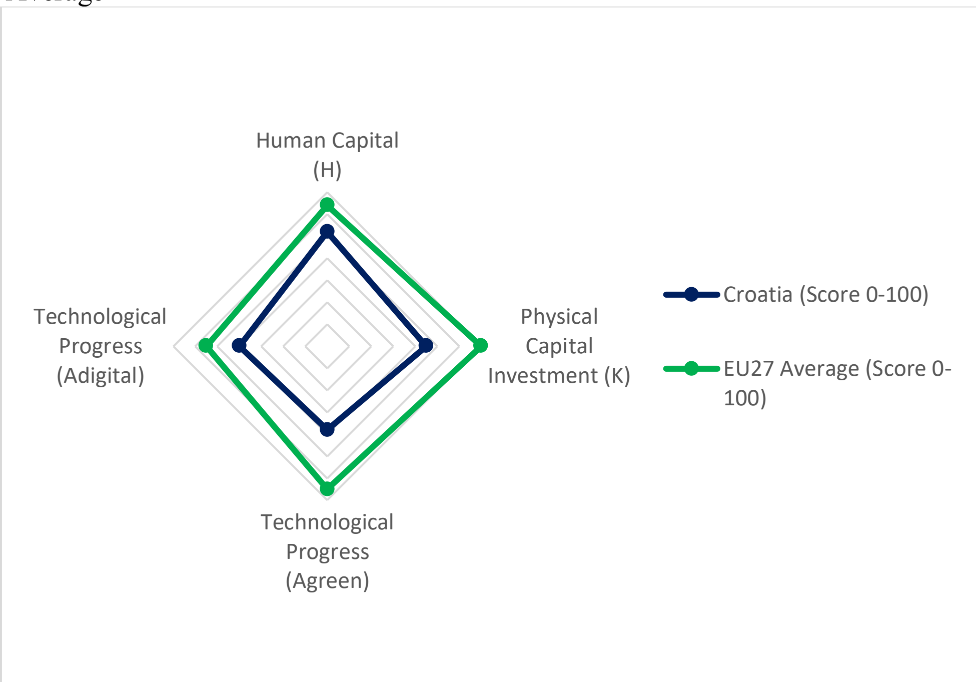
Integration of the Twin Transition into the MRW Framework

Within the analysis of data for the EU27 and Croatia, the Mankiw-Romer-Weil (MRW) model provides a quantification of differences in economic growth rates through the prism of systematic investment in

technological progress and human capital. At the European Union level, this framework is applicable to examine technological convergence through the "twin transitions" (green and digital transitions), where synchronized policy actions aim to increase the parameter of technological progress in all Member States. In parallel, the Digital Compass 2030 sets quantitative targets, such as requiring 75% of enterprises to adopt advanced technologies such as cloud computing, big data and artificial intelligence (AI). These advances directly optimize supply chains and improve total factor productivity.

The synergy between these policies - as evidenced by the NextGenerationEU mechanism, which mandates the allocation of at least 37% of funds to climate objectives and 20% to digital transformation - acts as a multiplier within the MRW model. Empirical indicators, such as the correlation between the Digital Economy and Society Index (DESI) and the Eco-Innovation Index, confirm that countries that lead in both segments show faster convergence towards a stable level of development.

Figure 2. Radar Chart of Expanded MRW Variables: Comparative Structural Analysis of Croatia and the EU27 Average



Source: Prepared by the author

The diagram in Figure 2 clearly shows the difference between Croatia and the EU27 average. EU27 reflects a relatively balanced growth boundary, the Croatian profile shows a certain decrease in a couple of dimensions of the extended Mankiw-Romer-Weil model.

The most prominent difference is found in green technological progress. According to what is shown, this existing transition is currently not synchronized because at the same time we have a relative resistance in the context of digital adoption, but also a lag in eco-innovations, which in turn suggests that technological progress was achieved through digital services, and not "greening" of the industrial sector. This discrepancy is manifested through the accumulation of capital, where the narrowing of the axes shown on the graph is the result of actually reduced investments in research and development. Within this framework, this reduction contributes to the slowing of the convergence towards sustainability.

It is interesting that the gap in human capital (digital skills) is the smallest among the observed variables. This implies that Croatia has the basic knowledge, but lacks adequate support in terms of physical capital and technology to fully exploit the potential for sustainable growth. From a strategic perspective, the analysis shows that in order to achieve economic convergence with the EU27, it would be necessary to prioritize green investments and eco-innovations. Without an increase in green technology, digital transformation alone will not be sufficient to achieve these goals, that is, the separation of further economic growth from (harmful) environmental impacts and resource consumption.

The Evolution of Human Capital

Within this model, investments in human capital can no longer be understood through the prism of traditional educational metrics. Data from the 2022 Digital Economy and Society Index highlight large disparities within the European Union member states: while Scandinavian countries such as Finland and Denmark have a share of around 70 % of the population with advanced digital skills, southern member states such as Greece and Romania often have a share of less than 50%. Reducing these disparities is important for a more even technological transition that benefits all member states.

The human capital gap just mentioned is much more than just a learning curve that directly reduces the return on investment in new technologies. While in Northern Europe, a digitally-savvy workforce has a high "absorptive capacity",

Southern Europe, however, faces a "digital wall". While they may be installing, for example, solar panels (hardware), they often lack the digital literacy to manage advanced data systems. This is one explanation why EU funding alone is not achieving its goals. Without specialized skills, financial assistance is just buying tools that no one knows how to use to their full potential.

Croatia is in a tricky situation. We actually have decent human capital compared to our neighbors, but we don't see that talent being used. We also face the "brain drain" trap: if we train people but don't provide them with a high-tech environment to work in, they simply leave. When our best talents move to technology leaders like Sweden or Germany, Croatia loses its investments and our green transition stalls.

The following Table 1 provides a strategic categorization of EU member states based on the variables of the extended Mankiw-Romer-Weil model, highlighting the structural differences in the "double transition". Table 1 provides a summary and comparison of selected EU Member States. Leading countries, such as Finland and Sweden, are ahead because they have successfully linked their high-skilled talent capacities with digital and green technological advances. In these countries, a highly skilled workforce contributes to a more robust and sustainable growth path.

In contrast, the group of catching-up countries, which includes countries such as Croatia, Poland and the Czech Republic, has a very specific development profile. They are “digitally resilient” and have quickly adopted digital services, but are lagging behind in green innovation. This suggests that while the economies appear technologically advanced, their existing industrial and energy sectors have not yet reached the appropriate level of technological maturity.

For EU Member States such as Croatia, simply accumulating more capital is not enough to achieve success, as it depends on a targeted effort to align education and skills development with green research and development. Without this change, these countries risk a “digital-only” growth path that remains too resource-intensive to be sustainable in the long term.

Table 1. EU27 Convergence Matrix: Digital-Green Transition within the MRW Framework

Category	Characteristics (MRW Variables)	Country Examples
Frontrunners	High H, High $A_{digital}$, High A_{green}	Finland, Denmark, Sweden
Digital-heavy	Moderate H, High $A_{digital}$, Low A_{green}	Estonia, Malta
Catching-up	Moderate H, Moderate $A_{digital}$, Low A_{green}	**Croatia**, Poland, Czech Republic
Lagging	Low H, Low $A_{digital}$, Low A_{green}	Romania, Greece, Bulgaria

Source: Prepared by the author

Case Study: Croatia and the Catch-up Effect within the MRW Framework

Croatia represents an excellent example of conditional convergence within the extended Mankiw-Romer-Weil model. As a "catch-up" nation, its entry into the EU common market and large capital inflows through mechanisms such as the National Recovery and Resilience Plan (NRRP) contributed to higher growth rates than the EU27 average, which is certainly a good indicator. However, the structural analysis in Figure 2 clearly shows that this catch-up effect is fundamentally unbalanced. Although it has been confirmed that it is decreasing in the segments of digitization and general capital accumulation, Croatia is still not sufficiently developed in terms of eco-innovations. Within the framework of MRW,

this suggests that the catch-up process relies primarily on the transfer of existing technologies and foreign capital, rather than the creation of innovative green solutions of its own. It is through reliance on external transfer of technology, without an adequate increase in green technological progress, that it can limit the country's long-term sustainability and its ability to achieve a high-value balance.
In this context, the NPOO is not just a financial input but a strategic tool for the economy. By financing the modernization of energy networks (physical capital) and the green job retraining program (human capital), the plan helps address weaknesses in domestic investment.

The aim is to raise the basic level of the Croatian economy to a higher level, while minimizing the shortcomings mentioned earlier. However, as the DESI index shows, technology is only half the battle. Leading EU countries succeed because their people have the skills to use that technology effectively. Research by Vlahinić-Dizdarević and Žiković [16] highlights that Croatia must prioritize energy efficiency to ensure that its growth equation remains in balance.

DISCUSSION

By applying the extended Mankiw-Romer-Weil (MRW) model to the Croatian economy, certain challenges for the green transition were detected. Although Croatia has made considerable progress towards European standards, the transition is still incomplete. In the earlier part of the paper, the discrepancy between the realized digital progress and a certain industrial stagnation was shown, which somehow implies a mismatch in the distribution of capital, which does not realize the full potential that exists within the framework of the European Union.

Current data suggest that the processes of digital transformation in Croatia are somewhere on the level of the EU average. Technological growth is primarily concentrated in the service sector, while it is absent in the existing industrial base, which of course affects the transition to a circular economy. Without the development of advanced analytics infrastructure - especially the integration of the Internet of Things (IoT) and big data - the industrial sector cannot absorb the sophisticated solutions needed to achieve modern sustainability. In short, Croatia has digital tools, but there is certainly still a lot of room for progress in the field of green innovative framework and application where they are most needed.
Croatia can boast a relatively high share of renewable energy sources, although there is still much room for improvement given its natural geographical location and resources, but this energy production from renewable sources is ultimately canceled out by industrial consumption. It is through this difference that the inefficient allocation of (physical) capital is indicated. Many companies need to transition to green business through the replacement of outdated and inefficient processes and mechanization, but the problem arises when the cost of implementing new green technologies at the start is above the marginal production capital.
In view of the above, the National Recovery and Resilience Plan (NRRP / NPOO) with various subsidies intended specifically for transition costs, has a very important role because in this way the price of green and digital capital is lowered. This intervention increases accessibility to private firms, as it enables the private sector to realize its full potential.

Ultimately, there is an evident need for education and greater investments in the so-called human capital, because a circular economy cannot be realized with financial tools and technology alone. Without this synergy, countries at this level face challenges in the context of achieving the EU average income level through "low-quality" growth, in sectors such as tourism and services, while remaining technologically dependent on developed Member States for high-value components of the Green Agenda.
The strategic path for Croatia is clear. While the digital infrastructure is largely in place, it is important to kick-start green innovation. In order to decouple economic growth from resource consumption in the long term, Croatia needs to bridge the gap between its "green" energy potential and its "analog" industrial reality, both through targeted investments and by nurturing specialized expertise.

CONCLUSION

Based on the results of the analysis of Croatia's economic trajectory within the EU27, it results in the conclusion of a nation in a state of transition. A greater need for green innovations has been detected, but at the same time a lot has been done when it comes to digital transformation and accompanying technologies. . By applying the extended Mankiw-Romer-Weil (MRW) model, this study confirms that, although Croatia is progressing successfully in the transition, it has not yet used its full potential at its disposal. There is a certain "digital-green" disconnect where the private sector possesses the underlying human capital but lacks the analytical intensity needed to adopt complex circular business models.

Ultimately, the transition from a "Catching-up" economy to a "Frontrunner" requires a synchronization of growth factors, moving beyond mere financial absorption to assertive investments in clean technologies. As synthesized in the theoretical foundation of this paper, the MRW framework demonstrates that integrating human capital with technological progress is instrumental for long-term growth that respects ecological boundaries. To ensure that Croatia's economic ascent leads to a resilient and environmentally sovereign future, digital competencies must be leveraged as the ignition for the green innovation engine, aligning the variables of investment and education with the ambitious carbon-neutrality goals of the EU Green Deal.

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Numerical Sources & Data Portals
Eurostat Database: https://ec.europa.eu/eurostat/data/database
DESI Dashborad – Croatia: https://digital-strategy.ec.europa.eu/en/policies/desi-croatia
Eco – Innovation Scoreboard: https://www.google.com/search?q=https://green-business.ec.europa.eu/eco-innovation-action-plan/eco-innovation-scoreboard_en
NPOO – Nacionalni plan oporavka i otpornosti: https://planoporavka.gov.hr/

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INNOVATION MANAGEMENT IN THE CHEMICAL INDUSTRY

Abstract
Innovation management in the chemical industry integrates digital technologies, such as artificial intelligence (AI) and machine learning (ML), with green chemistry principles to drive sustainable growth and enhance research and development (R&D) efficiency. AI-enabled tools and predictive models accelerate R&D by enhancing chemical formulations, optimizing manufacturing, and improving productivity. Green chemistry and sustainability initiatives aim to eliminate hazardous substances throughout a product's lifecycle, from design to disposal, by focusing on safer, sustainable chemical alternatives. Main strategies include implementing "safe-by-design" principles, transitioning from a linear model to a "circular economy," and reducing energy consumption and waste. Shifting to open, cross-sector collaboration in R&D activities (academia, industry, public sector) is essential for solving complex sustainability challenges. This collaborative approach drives innovation and reduces environmental impact, through shared knowledge, resources, and technology.

Key words: artificial intelligence, green chemistry, research and development.

INTRODUCTION

The chemical sector is a foundational pillar of modern global society, serving as the starting point for 95% of manufactured goods. Today, this vital industry is undergoing an intensive and rapid transformation, embracing green chemistry and circularity by design to drastically reduce its environmental footprint. Actually, chemical companies must integrate sustainability and advanced technology into their core strategies. By utilizing digitalization for supply chain efficiency and biotechnology for bio-based materials, firms can satisfy eco-conscious consumers without compromising on cost-effectiveness or performance [1]. Artificial intelligence (AI) and machine learning (ML) methodologies are successfully transforming green chemistry by shifting the paradigm from trial-and-error experiments to data-driven, in silico predictions. These technologies allow scientists to optimize chemical processes, minimize environmental impact, and accelerate the discovery of sustainable materials. Machine learning algorithms predict the best synthesis pathways and operational parameters, which significantly minimizes energy consumption and raw material loss [2]. When it comes to reaction optimization, AI systems analyze historical data to find the most efficient synthetic pathways. This drastically reduces the consumption of reagents, lowers reaction temperatures, and decreases energy usage during production [3]. Modern AI frameworks integrate physicochemical data to predict a material's environmental performance long before synthesis. This links molecular features directly to sustainability indicators [4]. Heaving in mind that solvent selection is key in determining the sustainability of future commercial products, models like Graph Neural Networks (GNNs) are very important, owing to the fact that rapidly screen thousands of solvents, such as ionic liquids, to replace volatile organic compounds (VOCs) with safer, highly efficient alternatives [5]. While AI tools offer enormous potential, the field faces a few critical hurdles. Because AI cannot always explain the causal mechanisms behind its outputs, chemists struggle to interpret how a predicted reaction works. This lack of transparency makes it difficult to trust AI-generated pathways for large-scale, safety-critical industrial implementation. AI models require large, standardized, high-quality training sets to produce reliable predictions. In green chemistry, reaction data is highly fragmented, proprietary, or missing altogether (especially regarding toxicity and environmental lifecycles). Training large-scale AI models requires immense computing power, energy, and water. The hardware and data centers involved often generate significant carbon emissions and e-waste [6]. This energy-intensive process can directly contradict the sustainability goals of green chemistry. The industry is actively pushing for "Green AI"—models designed to use less energy and rely on renewable computing infrastructures. Current AI-driven synthesis planning is often optimized primarily for efficiency and high yield. AI tools frequently overlook holistic green metrics—such as the toxicity of byproducts, the solvent hazards, and the recyclability of the final product. Expanding AI parameters to evaluate an entire synthetic process's "greenness" requires massive new datasets [7].

INNOVATIONS IN CHEMICAL INDUSTRY: CHALLENGES AND OPPORTUNITIES

The chemical industry is shifting from traditional processes to sustainable, digitized, and circular technologies. However, significant difficulties obstruct this progress
Steep R&D costs and prolonged development cycles are major hurdles. Commercializing new technologies requires substantial capital and extensive time, resulting in a financially risky venture with unpredictable returns [8].
As well, the integration of rigorous environmental and safety mandates often complicates the innovation cycle. While these regulations are necessary for public protection, they introduce bureaucratic friction that significantly decelerates the commercialization of new technologies [9].
Sticking to the status quo and avoiding change creates a major barrier to innovation. Adopting new tools or processes disrupts daily workflows, requires time for staff retraining, and often sparks resistance from teams comfortable with the familiar (Figure 1).

Figure 1. Barriers to innovation

Source: Source of figure [10]

A persistent challenge for modern organizations is the recruitment and retention of highly skilled professionals in vital innovation disciplines, such as chemical engineering and data science. The combination of a highly competitive labor market and the scarcity of specialized skillsets severely limits a company's ability to maintain the workforce necessary for technological advancement [11].
Having in mind previously facts, it can be concluded that chemical companies must evolve their innovation strategies by embracing calculated risks, prioritizing long-term R&D, and simplifying regulations. Attracting and keeping top talent through competitive pay and learning opportunities is equally critical.
Establishing strong partnerships among industry pioneers, academic institutions, and regulatory agencies is essential to optimizing the chemical sector's innovation ecosystem. Guided by a shared vision, the industry can successfully address current challenges and usher in a new era of advancement.
Despite the aforementioned challenges, recognizing technology as a vital driver for environmental progress, a rising number of chemical companies are integrating their digital transformation and sustainability strategies to optimize operations and promote greener practices. Artificial intelligence (AI) and machine learning (ML) have potential to transform green chemistry by accelerating research, boosting efficiency, and fast-tracking the discovery of sustainable materials and eco-friendly processes. The integration of artificial intelligence in green chemistry enables the rapid processing of large-scale data to identify novel, environmentally benign materials. Furthermore, machine learning algorithms can accurately forecast the behavioral and physical properties of these candidates, thereby minimizing the

temporal and financial investments traditionally associated with empirical research and development. Modern researchers utilize artificial intelligence and extensive experimental data to systematically optimize sustainable chemistry, enabled by the discovery of intricate performance relationships.
As previously mentioned, AI can help improve chemical processes by analyzing heterogeneous data sets and establishing the most efficient and eco-friendly methods. This can enable reduction of energy utilization, decreased waste production, and improved general sustainability of chemical processes.
Artificial intelligence drives the design of safer, greener chemicals. By analyzing the structural properties of existing compounds, AI models can rapidly suggest targeted molecular modifications to reduce toxicity and minimize environmental impact [12].

Scientists are harnessing AI to engineer a new generation of biodegradable materials, such as plastics. These advanced materials are designed to decompose much faster and leave a significantly smaller environmental footprint than conventional plastics [13]. Machine learning algorithms enable the precise prediction of biodegradable material properties, accelerating the screening and selection of optimal candidates for future development.
By streamlining synthesis routes and optimizing chemical reactions, AI is driving sustainability in drug manufacturing. These smart technologies drastically cut hazardous waste, improve solvent efficiency, and support the recycling of toxic materials [14].
Artificial intelligence accelerates the development of clean energy like solar cells and biofuels. By crunching complex datasets, AI optimizes these technologies for maximum efficiency and minimal environmental footprint [15].
The circular economy is reshaping the chemical industry through advanced recycling technologies that continuously break down plastic and other chemicals into base raw materials, creating a zero-waste loop for manufacturing new goods.
The circular economy fosters innovation in manufacturing by optimizing production methods. Minimizing resource consumption and waste generation allows enterprises to improve their financial performance while reducing environmental impact.
Achieving a circular economy requires deep collaboration across the chemical value chain. By partnering with waste managers and product manufacturers, chemical companies can co-develop highly efficient systems for collecting, sorting, and recycling materials [16].

INNOVATIONS IN CHEMICAL INDUSTRY AND SUSTAINABLE FUTURE

According to recent scientific literature data, the integration of artificial intelligence and machine learning is a powerful catalyst for advancing green chemistry and achieving global sustainability objectives [17].
Artificial intelligence accelerates global sustainability efforts through the rapid development of green materials, the optimization of chemical synthesis, and enhanced cross-disciplinary research.
While artificial intelligence serves as a powerful catalyst for innovation, it is fundamentally just one component of a broader strategy.
By fostering cross-disciplinary collaboration, artificial intelligence accelerates the development of innovative, eco-friendly materials and methods. The convergence of artificial intelligence, nanoscale engineering, and synthetic biology provides a revolutionary framework for sustainable chemistry. This synergistic approach enables the molecular design of eco-friendly materials, highly targeted drug delivery systems, and bio-inspired manufacturing processes that minimize waste and energy consumption [18-21].

Figure 2. AI-environmental monitoring

Source: Source of figure [22]

Artificial intelligence can drive advanced surveillance networks to track environmental pollution and forecast potential hazards, facilitating a proactive strategy for sustainability and hazard prevention (Figure 2).
AI-powered tools drive public awareness in green chemistry by demystifying complex concepts through interactive platforms. They translate technical data into accessible formats, empowering consumers to make eco-conscious decisions, track their carbon footprints, and actively support sustainable, environmentally benign practices [23-25].
Achieving genuine ecological sustainability requires active participation across all sectors of society, including scientists, corporate leaders, policymakers, and everyday citizens, as they adopt green chemistry principles. Ultimately, aligning human collaboration with AI-driven advancements will pave the way for long-term environmental viability [26,27].

CONCLUSION

The chemical industry is at a pivotal turning point. Innovation is essential for long-term viability, yet it remains hindered by several major barriers. These include the heavy financial burden of R&D, intricate regulatory frameworks, and a corporate reliance on short-term profits. Also, critical lack of skilled professionals continue to delay progress.
However, environmental regulations and consumer demand for eco-friendly products are transforming corporate strategy. While short-term profit chasing, internal resistance, and skill gaps can impede progress, the drive to improve sustainability is a massive catalyst for innovation, pushing companies to utilize renewable resources, reduce waste, and develop cleaner processes.

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INNOVATION OF OCCULATIONAL HEALTH AND SAFETY RISKS MANAGEMENT - APPLICATION OF DIGITAL FORENSICS AND DATA ANALYSIS

Abstract
Modern work systems are characterized by increasing complexity driven by digitalization, automation, and the intensive use of information technologies, creating new challenges for occupational health and safety management. Traditional risk management models, based on retrospective injury analysis and periodic risk assessments, show limited capacity to timely identify hazardous conditions and the causal mechanisms that precede adverse events. The theoretical section examines the conceptual framework for integrating digital forensics and data analysis into occupational health and safety (OHS) risk management. The analytical section focuses on the potential application of forensic and analytical methods in identifying risky behavioural patterns, technical anomalies, and organizational weaknesses that may lead to adverse events. This research explores the potential of digital forensics and data analysis as innovative tools for improving occupational risk management systems. Particular emphasis is placed on their role in developing prevention-oriented measures that go beyond traditional approaches focused primarily on mitigating consequences. The concluding section provides recommendations for the future application of digital forensics and analytical methods in the field of OHS risk management.

Key words: Data analysis, digital forensics, OHS risks, OHS management, prevention.

INTRODUCTION

The need for digital forensics

The accelerated digital transformation of industrial and organizational systems constitutes a defining characteristic of contemporary technological and socio-economic development. The integration of automated production processes, advanced information systems, sensor networks, and smart devices has precipitated a profound reconfiguration of how work processes are planned, monitored, and evaluated. As a direct consequence, modern work environments continuously generate vast quantities of digital data that capture technical, organizational, and human dimensions of labour.

With the growing complexity of such systems, traditional models of occupational health and safety (OHS) risk management - predominantly grounded in retrospective accident analysis and statistical indicators - are increasingly revealing their limitations. These approaches often fail to ensure timely identification of latent hazards or to provide sufficiently nuanced insights into the dynamic causal relationships that precede adverse events. As a result, safety systems remain largely reactive, oriented toward mitigating consequences rather than systematically preventing risks [18].

Within this context, digital forensics and data analytics are progressively emerging as strategic instruments in the transformation of OHS management systems. While digital forensics has traditionally focused on post-incident investigations of accidents and other safety-critical events, contemporary perspectives underscore its considerably broader potential. The systematic collection, preservation, and analytical processing of digital traces facilitate the identification of recurring patterns, concealed technical anomalies, and organizational vulnerabilities that serve as precursors to accidents [16].

Advances in data analysis methodologies - including big data processing and the application of machine learning algorithms - further expand the scope of OHS risk management. The integration of forensic data with analytical models enables the development of predictive safety systems capable of anticipating hazardous states prior to their manifestation as incidents. This approach represents a qualitative advancement over conventional risk assessment methods, as it synthesizes technical, organizational, and human factors within a unified analytical framework [12].

Nevertheless, the application of digital forensics and data analytics in the domain of safety introduces a range of new challenges. Issues related to privacy protection, data reliability and integrity, as well as the necessity of adapting organizational procedures and regulatory frameworks, emerge as critical determinants of successful implementation. It is particularly important to ensure that technological progress is not considered in isolation, but rather situated within the broader context of OHS management and occupational health protection [7].

In light of these considerations, there is a pressing need for systematic professional and scientific inquiry into the role of digital forensics and data analytics in innovating OHS risk management. A comprehensive understanding of their potential, as well as their limitations, is essential for the development of modern safety strategies that are empirically grounded, prevention-oriented, and responsive to the challenges of digitalized work environments.

Purpose and aim of the research

The aim of this paper is to analyse the role of digital forensics and data analytics in the development of innovative approaches to OHS risk management in contemporary work and transport systems. Particular emphasis is placed on exploring the potential transformation of traditional, predominantly reactive safety models into proactive and predictive risk management systems, grounded in the systematic processing and interpretation of digital data.

The paper seeks to investigate how digital forensic methods, in synergy with advanced analytical techniques, can be employed not only for the reconstruction of accidents and incidents but also for the timely identification of risky behavioural patterns, technical anomalies, and organizational weaknesses that precede adverse events. In doing so, the study aims to contribute to a deeper understanding of the causal mechanisms underlying safety risks in complex digitalized systems.

The purpose of the paper is to establish a theoretical and analytical framework that integrates digital forensics, data analytics, and OHS management systems, while highlighting their potential to enhance preventive measures and support evidence-based decision-making. Special attention is devoted to identifying organizational, technological, and regulatory prerequisites necessary for the effective integration of these tools into OHS risk management practice.

Ultimately, the paper seeks to provide a professional and scientific contribution to the field of occupational safety and health by underscoring the strategic value of digital forensics and data analytics in the development of modern, sustainable, and innovative safety strategies tailored to the challenges of digital transformation.

Research hypotheses

The following hypotheses are formulated on the assumption that the digital transformation of safety systems necessitates new approaches to risk management, grounded in the systematic processing and analysis of digital data:

- Hypothesis H1: Digital forensics, beyond its traditional role in the retroactive investigation of incidents and accidents, holds significant potential as a tool for proactive OHS risk management in contemporary work and transport systems.
- Hypothesis H2: The application of big data analytics enables the identification of risky behavioural patterns, technical anomalies, and organizational weaknesses that are not fully detectable through traditional methods of OHS risk assessment.
- Hypothesis H3: The integration of digital forensics and data analytics into OHS management systems contributes to the development of predictive and preventive safety models, thereby reducing both the likelihood of accidents and the severity of their consequences.
- Hypothesis H4: The effective application of digital forensics and data analytics in OHS risk management requires the adaptation of organizational procedures, regulatory frameworks, and continuous employee training.

These four hypotheses constitute a coherent conceptual framework for the research, aimed at recognizing and understanding the role of digital forensics and data analytics in OHS risk management, with the ultimate goal of advancing OHS management practices.

Research tasks

Based on the defined aim, purpose, and hypotheses, the following research tasks are established. The study seeks to systematically and critically examine the role of digital forensics and data analytics in the context of contemporary OHS risk management, with particular emphasis on the paradigm shift in safety

approaches driven by the digital transformation of work and transport systems. The central focus of the paper is on exploring how digital forensic data and analytical procedures can contribute to the enhancement of existing safety models.
This research develops a conceptual framework that integrates digital forensics, data analytics, and OHS management systems, with special attention devoted to the identification of risky behavioural patterns, technical deviations, and organizational weaknesses that have the potential to generate safety incidents. The analysis is directed toward understanding the causal relationships between digital records and the emergence of safety risks.
The task of the study is to consider the possibilities of integrating digital forensic and analytical tools into existing organizational and safety systems, with the aim of improving risk assessment processes and supporting data-driven decision-making. Particular consideration is given to organizational, technological, and regulatory prerequisites that condition the effective and sustainable application of these approaches in practice.
Furthermore, the study aims to highlight the strategic value of digital forensics and data analytics in innovating OHS risk management and to emphasize their role in the development of modern, prevention-oriented safety approaches.

METHODS

Research sample

The research sample encompasses selected examples of the application of digital forensics and data analytics in the context of OHS risk management within transport and industrial systems. The analysis focuses on environments in which digital records are systematically utilized as a foundation for risk assessment, the investigation of safety-relevant events, and the advancement of preventive safety approaches.
Within the scope of the study, examples were considered from the fields of transport and industrial systems, where digital records constitute an integral part of organizational OHS systems for risk management. Particular emphasis was placed on systems that include electronic records of vehicle operations, machinery, and information infrastructure, as such systems generate reliable, time-precise, and analytically relevant data on safety-critical events.
In the transport context, the sample includes cases of applying digital data collected from vehicle electronic systems, which are used in the analysis of traffic accidents and safety incidents related to work processes. In the industrial environment, automated and digitally monitored systems were examined, where digital records enable the identification of technical deviations, risky work patterns, and potential organizational weaknesses.
The selection of these examples is based on their representativeness in terms of data availability, relevance for OHS risk management, and the applicability of analytical results in practice. This approach allows for a comprehensive consideration of the potential of digital forensics and data analytics across different safety contexts and contributes to understanding their role in the development of modern approaches to OHS risk management.

Research methods

The study is based on a qualitative scientific methodological approach, oriented toward the theoretical and analytical elaboration of the role of digital forensics and data analytics in OHS risk management. The methodological framework of the paper is designed to integrate conceptual insights, regulatory frameworks, and examples of the application of digital technologies in the field of safety.
A descriptive method was applied to present the fundamental characteristics of digital forensics, data analytics, and OHS management systems, as well as their interconnections within the context of contemporary work and transport systems. An analytical method was employed to examine the potential of digital forensic and analytical tools in identifying and understanding safety risks, and in developing predictive and preventive safety approaches.
The primary sources of data include relevant scientific and professional literature, encompassing peer-reviewed journals in the fields of digital forensics, safety, and risk management, papers published in international conference proceedings, as well as publications and reports from relevant institutions. International standards regulating digital forensics, risk management, and occupational safety play a particularly important role, as they enable the linkage of theoretical foundations with practical application.

A comparative method was used to examine differences between traditional, reactive models of OHS risk management and contemporary approaches based on digital forensics and data analytics. This facilitated the identification of key advantages, as well as limitations, of applying digital technologies in safety contexts.

Theoretical analysis was conducted using a deductive approach, whereby general principles of OHS management and digital forensics were applied to the consideration of specific areas of application in industrial and transport systems. An interpretative method was employed to analyse normative and institutional documents, with the aim of understanding their role in shaping organizational practices and safety policies.

The combination of these methods enabled the development of conclusions and recommendations grounded in theoretical insights, regulatory frameworks, and the analysis of contemporary trends in digital forensics and OHS risk management.

RESULTS AND DISCUSSION

Digital forensics and data analytics in OHS risk management

The digital transformation of safety systems has led to significant changes in the ways safety risks are identified, analysed, and managed in industrial environments [1]. In modern work systems, digital records no longer serve merely as technical documentation of system operations; instead, they have become a crucial source of data for understanding the causal mechanisms that precede safety-relevant events. In this context, digital forensics and data analytics are gradually being established as integral components of OHS management systems [10].

Traditional approaches to OHS risk management rely heavily on retrospective accident analysis, statistical indicators, and experiential assessments. While such approaches retain their value, their application in complex and highly digitalized systems reveals certain limitations, particularly in terms of timely recognition of latent hazards. Digital forensics enables the systematic collection, preservation, and analysis of digital traces generated during normal system operations, thereby shifting safety analysis from the level of consequences to the level of causes [18].

In this regard, digital forensic data, such as records from electronic systems, allow for precise reconstruction of safety-relevant events, as well as the identification of behavioural patterns that may indicate elevated safety risks. The analysis of such data is not limited to the investigation of safety incidents; it can also be applied to the recognition of risky work practices, technical deviations, and organizational factors that influence workplace safety. Thus, digital forensics is positioned as a tool that contributes to preventive risk management, rather than solely to post-event evaluation [17].

A similar potential of digital forensics and data analytics is evident in industrial systems. Automated production processes and digitally monitored systems generate continuous records of machine operations, operator activities, and organizational processes. The analysis of these records enables the identification of technical anomalies, deviations from standard operating procedures, and recurring patterns that may precede safety incidents. In this way, safety risks are understood as dynamic processes rather than isolated events [2, 12].

The integration of digital forensics and data analytics into OHS management systems creates the foundation for developing predictive safety models. Such models allow for the anticipation of hazardous states based on historical and operational data, while supporting evidence-based decision-making. Compared to traditional risk assessment methods, this approach provides a higher level of precision and adaptability of safety measures to the specific characteristics of individual systems.

However, the results of the analysis also highlight a number of challenges associated with the application of digital forensics and data analytics in OHS risk management. The effectiveness of these approaches largely depends on the quality of the collected data, clearly defined organizational procedures, and the competencies of personnel involved in safety processes. Without appropriate integration into existing OHS management systems, digital tools may remain underutilized.

The role of digital forensics and data analytics in OHS management systems

In contemporary OHS management systems, increasing emphasis is placed on systematic, process-oriented approaches to the identification and management of OHS risks. Such systems are based on the continuous collection of information, risk assessment, implementation of preventive measures, and evaluation of their effectiveness. Within this context, digital forensics and data analytics assume a new role as sources of objective and verifiable data that can significantly enhance the functioning of OHS management systems [7].

Digital forensics within OHS management systems enables the structured and reliable collection of digital records relevant to safety, while ensuring their integrity and authenticity. These records may originate from various technical and information systems and provide detailed insights into the actual execution of work and operational processes. Their integration into safety processes facilitates evidence-based decision-making, thereby reducing reliance on subjective assessments and incomplete information [3].

Data analytics further expands the capabilities of OHS management systems by enabling the processing and interpretation of large volumes of heterogeneous data. In combination with digital forensics, analytical procedures allow for the identification of trends, recurring patterns, and early indicators of safety risks. This shifts safety systems from periodic risk assessments toward continuous monitoring of safety performance, in line with the principles of modern OHS management [7].

The particular value of digital forensics and data analytics in OHS management systems lies in their ability to connect technical, organizational, and human factors. Digital records provide insights into the interaction between people and technology in real working conditions, contributing to a deeper understanding of the causal relationships that lead to safety risks. In this way, safety is viewed as a dynamic system rather than a set of isolated safety requirements.

The integration of digital forensics and data analytics into OHS management systems also contributes to the advancement of preventive activities. Instead of defining safety measures solely on the basis of past accidents, it becomes possible to adapt them to current working conditions and actual risks revealed through digital records [4]. This approach increases the effectiveness of safety measures and enables their adjustment to the specific characteristics of individual work and transport systems [12].

The results of the analysis indicate that digital forensics and data analytics have the potential to become integral and functional components of modern OHS management systems. Their application strengthens the preventive dimension of safety, enhances decision-making processes, and supports the development of systems that are more resilient to change and the complexity of contemporary work environments.

Application of digital forensics and data analytics in industrial environments

Industrial environments represent complex systems in which safety risks arise from the interaction of people, machines, and organizational processes. The level of automation and digitalization in modern industry has resulted in the generation of large volumes of data continuously recorded during the operation of production and technical systems. These digital records have become a key source of information for understanding safety risks and developing more effective approaches to OHS management [12].

In the industrial context, digital forensics enables the collection and preservation of data from automated production systems, monitoring and control systems, and industrial information infrastructures. Such data provide detailed insights into machine operations, system loads, and operator interactions with technology. The analysis of these records allows for precise reconstruction of safety-relevant events, as well as the identification of deviations that may precede accidents or incidents [16].

Data analytics in industrial systems facilitates the recognition of technical anomalies, deviations from standard operating procedures, and recurring patterns that indicate elevated safety risks. Systematic processing of digital records enables safety systems to focus on risky processes and critical points in production, thereby increasing the effectiveness of preventive safety measures. In this way, safety is not viewed solely through isolated incidents but as a continuous process of risk management.

The particular value of digital forensics and data analytics in industrial environments lies in their ability to connect technical data with organizational working conditions. Digital records make it possible to assess the impact of work schedules, employee workloads, and organizational decisions on the safety of production processes. This integrated approach contributes to a deeper understanding of the causal relationships between organizational factors and the emergence of safety risks.

A particular value of digital forensics and data analytics is evident in work processes that involve vehicle management, such as road transport of goods and passengers. In such systems, digital records enable the integration of technical data on vehicle operation with organizational factors, including work schedules, driver workload, and working conditions. The analysis of these data provides a more comprehensive perspective on safety risks arising from the interaction of technical, human, and organizational elements [14].

The integration of digital forensics and data analytics into industrial OHS management systems enables the development of predictive safety models aimed at accident prevention. Instead of relying on periodic risk assessments, industrial systems can utilize continuous digital records to monitor safety performance and adapt safety measures in a timely manner. This approach enhances the resilience of industrial systems to change and reduces the likelihood of serious safety incidents [12].

Comparative analysis of traditional and digitally-based approaches to OHS risk management

Traditional approaches to OHS risk management are primarily grounded in retrospective incident analysis, statistical indicators, and experiential assessments, with safety activities predominantly directed toward corrective measures after adverse events have occurred. Such models provide a basic level of risk control, but in complex and highly digitalized systems they increasingly face limitations in terms of timely recognition of latent hazards.

Within traditional safety systems, safety is perceived as a relatively static process, periodically evaluated through risk assessments and the implementation of standardized procedures. The emphasis is placed on compliance with regulations and norms, while continuous monitoring of actual working conditions is carried out only to a limited extent. Consequently, safety risks are often identified only after they have already resulted in incidents or accidents [12].

In contrast, digitally-based approaches to OHS risk management, incorporating digital forensics and data analytics, enable a dynamic and process-oriented perspective on safety. Continuous collection and analytical processing of digital records allow for the timely identification of risky patterns, technical deviations, and organizational weaknesses that precede safety-relevant events. This shifts safety analysis from the level of consequences to the level of causal mechanisms.

In industrial contexts, digitally-based approaches facilitate the integration of technical, organizational, and human factors into a unified analytical framework. Digital records provide more precise insights into the interaction between people and technology in real working conditions, supporting evidence-based safety decision-making. This approach enhances the adaptability of OHS management systems to the specific characteristics of individual work environments [7, 11].

Comparative analysis shows that digital forensics and data analytics do not replace traditional safety models but rather functionally upgrade them. Traditional approaches provide a stable regulatory and organizational framework, while digital tools enhance operational effectiveness through continuous monitoring and predictive risk analysis. Their integration enables greater precision in risk assessment and more effective implementation of preventive safety measures.

The results of the comparison indicate that the synergistic application of traditional and digitally-based approaches forms the foundation for the development of modern OHS risk management systems adapted to the challenges of digital transformation. Such systems enable a shift from reactive to proactive and prevention-oriented OHS management, thereby increasing the long-term resilience of transport and industrial systems.

Challenges and limitations in the application of digital forensics and data analytics

Despite the significant potential of digital forensics and data analytics in OHS risk management, their practical application faces a number of challenges and limitations. These challenges stem from technical, organizational, and regulatory factors and greatly influence the effectiveness and sustainability of digitally-based safety approaches.

One of the key challenges relates to the quality, reliability, and availability of digital data. Data generated in industrial systems are often heterogeneous, collected from diverse sources, and not always structured in a way that allows for direct safety analysis. Incomplete, inconsistent, or inaccurate data can limit the interpretative value of analytical procedures and lead to incorrect safety conclusions [10].

Organizational constraints also play a significant role in the application of digital forensics and data analytics. In many systems, digital tools are introduced only partially, without clear integration into existing OHS management frameworks. The absence of well-defined procedures, responsibilities, and communication channels may result in digital data being used solely in a reactive context, without meaningful impact on preventive risk management [7].

Another major challenge concerns privacy protection and the ethical use of digital data. Digital records often contain information that can be linked to employee behaviour, work habits, or job performance. Inadequately regulated processing of such data may undermine employee trust and provoke resistance to the use of digital safety tools, thereby reducing their effectiveness in practice [8].

Technological limitations further affect the applicability of digital forensics and data analytics. Effective implementation requires appropriate technical infrastructure, system interoperability, and specialized employee competencies. A lack of expertise and continuous training can result in underutilization of available technologies or their incorrect application [13].
The results of the analysis indicate that successful application of digital forensics and data analytics in OHS risk management requires a comprehensive and systematic approach. Technological solutions must be accompanied by organizational adjustments, a clear regulatory framework, and the development of employee competencies. Without such an integrated approach, the potential of digital tools remains limited and their application fragmented.

Implications for improving OHS risk management in practice

The analysis of digital forensics and data analytics highlights their significant potential in enhancing OHS risk management within industrial systems. Digitally-based approaches enable a deeper understanding of safety risks and create the foundation for developing modern safety systems oriented toward prevention rather than merely addressing consequences.
One of the key practical implications concerns the transformation of safety systems from reactive to proactive and predictive risk management. By integrating digital forensic data and analytical procedures into existing OHS management systems, it becomes possible to identify risky patterns, technical deviations, and organizational weaknesses before safety-relevant events occur. This approach contributes to more effective planning of safety activities and better targeting of preventive measures [12].
Digital forensics and data analytics also play an important role in improving decision-making processes in the field of safety. Decisions based on objective, verifiable, and contextually relevant data reduce subjectivity in risk assessment and increase transparency in safety processes. In complex work and transport systems, where safety risks evolve dynamically, such an approach enables faster and more precise adjustments to safety strategies [7].
Practical implications are also evident in the potential integration of digital forensics and data analytics into existing organizational and regulatory frameworks. Rather than introducing isolated technological solutions, digital tools can serve as functional upgrades to established OHS procedures and management systems. This ensures continuity in OHS management and increases organizational acceptance of digital approaches [9, 15].
It is particularly important to emphasize that effective application of digital forensics and data analytics requires an adequate level of organizational maturity and employee competence development. Practical implications therefore include the need for systematic development of safety culture and an interdisciplinary approach to safety, in which technical solutions are connected with organizational processes and the human factor.
In conclusion, the results indicate that digital forensics and data analytics have the potential to become strategic elements of modern OHS risk management systems. Their application enables the development of safety systems that are more adaptable, resilient, and effective in addressing the challenges of digital transformation and the complexity of contemporary industrial environments.

CONCLUSION

The conducted analysis examined the role of digital forensics and data analytics in OHS risk management within industrial systems. The research was carried out with the aim of exploring the possibilities of applying digital technologies in the development of modern, prevention-oriented safety approaches.
The results of the study confirm the first hypothesis (H1), which states that digital forensics, beyond its traditional role in retrospective investigation of accidents and incidents, has significant potential as a tool for proactive OHS risk management. The analysis demonstrated that digital records enable a deeper understanding of safety-relevant events and the identification of causal mechanisms preceding their occurrence.
The second hypothesis (H2), which assumes that data analytics allows for the identification of risky patterns and organizational weaknesses not fully detectable through traditional safety methods, was also confirmed. Systematic processing of digital data provided a perspective of safety risks as dynamic processes, thereby expanding the framework of traditional risk assessments.

The third hypothesis (H3), which posits that the integration of digital forensics and data analytics into OHS management systems contributes to the development of predictive and prevention-oriented safety models, was likewise confirmed. The analysis showed that such an approach enables timely recognition of hazardous states and more effective management of safety risks in practice.

The fourth hypothesis (H4), emphasizing the need for adaptation of organizational procedures, regulatory frameworks, and employee competence development, was also validated. Effective application of digital forensics and data analytics proved to be dependent on organizational maturity, data quality, and the integration of digital tools into existing OHS management systems.

In conclusion, the findings confirm that digital forensics and data analytics represent an important element in the development of modern OHS risk management systems. Their application enhances the preventive dimension of safety and contributes to the creation of more efficient and adaptable safety systems in industrial environments. For future research, it is recommended to conduct empirical studies on the application of digital forensics and data analytics in specific industrial sectors.

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Standards

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- HRN ISO/IEC 27037:2012, Informacijska tehnologija – Sigurnosne tehnike – Smjernice za identifikaciju, prikupljanje, pribavljanje i očuvanje digitalnih dokaza
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INNOVATING THE LEGAL FRAMEWORK OF OCCUPATIONAL SAFETY AND HEALTH IN SERBIA – CHALLENGES AND PERSPECTIVES

Abstract
In the context of accelerated technological development, digitalization, and changes in the organization of work, the existing legal framework governing occupational safety and health in Serbia faces numerous challenges that require continuous adaptation and innovation. This paper analyzes the process of innovating the occupational safety and health legal framework in Serbia, with emphasis on its key challenges and future perspectives. We examine the most significant developments in national legislation, especially from the perspective of their alignment with the acquis of the European Union and the possibilities for their effective implementation in practice. It can be concluded that the continuous enhancement of the legal framework governing occupational safety and health in Serbia is both necessary and desirable, and should be accompanied by the strengthening of institutional mechanisms to ensure more effective regulatory oversight, as well as by the promotion of a comprehensive safety culture.

Key words: occupational safety and health, legal framework, innovation, Republic of Serbia.

INTRODUCTION

Contemporary working conditions are characterized by numerous challenges, some of which are well known, as well as others that represent novel issues for legislators, academia, and professional practice [1]. Unfair competition, emerging technologies (e.g., nanotechnology), new industries, and a labor market marked by a significant flexibilization of employment relationships [2]—whose key feature is the considerable discretion afforded to employers in organizing work—constitute some of the modern challenges to occupational safety and health. Work overload, tight deadlines, unjustified overtime, inappropriate behavior by colleagues, and similar factors are also sources of stress which, over time, may lead to psychophysical imbalance in employees and have serious consequences for their health [3]. These developments indicate that work is no longer characterized solely by physical hazards, but also by psychosocial risks that threaten employees' physical health and their overall well-being [4].
Occupational safety and health represents a highly significant aspect of work for every employer, regardless of the nature of the activity. This issue is particularly pronounced in certain sectors, such as construction, mining, and specific branches of industry [5, 6, 7, 8]. The contemporary concept of occupational safety and health is grounded in the prevention of workplace injuries and occupational diseases. These considerations have shaped the subject of this research, directing it toward an analysis of the key challenges of labor law protection of employees against workplace injuries and occupational diseases within the legislation of the Republic of Serbia, as well as the prospects for its improvement.

The defined subject of the research has also determined its objective: to highlight the vulnerability of employees' safety and health under working conditions characteristic of the modern labor market; to examine the challenges in the implementation of occupational safety and health regulations; and to explore the possibilities for their innovation and the improvement of specific legal solutions. The subject and objective of the research have further guided the choice of methodology. Accordingly, the study employs the dogmatic method—analyzing existing legal solutions—and the axiological method—addressing the question of whether the current regulations provide adequate protection for employees and considering possibilities for enhancing the regulatory framework in order to improve the overall quality of employee protection.

THE EXISTING LEGAL FRAMEWORK OF OCCUPATIONAL SAFETY AND HEALTH IN SERBIA

The European Union adopted Directive 89/391/EEC on the introduction of measures to encourage improvements in the safety and health of workers at work in 1989 [9]. The current occupational safety and health (OSH) system in the Republic of Serbia is based on this Directive. In accordance with it, the first comprehensive reform was introduced through the adoption of the Law on Occupational Safety and Health in 2005, which significantly modernized the previous system of workplace protection. Subsequently, in 2023, a new and currently applicable Law on Occupational Safety and Health of the Republic of Serbia (2023) was enacted [10].

This Law has a systemic character, in that it functions in conjunction with other key legislative acts, such as the Labour Law of the Republic of Serbia, the Law on Companies of the Republic of Serbia, the Law on Private Entrepreneurs of the Republic of Serbia, and the Law on Pension and Disability Insurance of the Republic of Serbia. The Law on Occupational Safety and Health encompasses not only workplace safety but also health protection and elements of social protection. It is primarily grounded in the principles of prevention and responsibility, with the aim of ensuring conditions for performing work activities in a safe and healthy working environment. The focus of all participants in the work process is thus oriented toward preventing workplace injuries, occupational diseases, and health impairments, rather than addressing their consequences.

The Law is supplemented by a large number of by-laws, including regulations and rulebooks, which further elaborate its provisions. These secondary legal acts regulate, inter alia, risk assessment procedures, as well as work in specific conditions such as working at heights, handling carcinogenic substances, construction site activities, exposure to high temperatures, manual handling of loads, and exposure to radiation [11].

Authority for supervising the implementation of OSH regulations lies with the Labour Inspectorate of the Republic of Serbia, an organizational unit within the Ministry of Labour, Employment, Veteran and Social Affairs of the Republic of Serbia [12]. The primary objective of labor inspection in the field of occupational safety and health is the prevention of workplace injuries and occupational diseases. This is achieved through a range of activities across multiple areas, including establishing employer responsibility at all stages of work, implementing preventive measures in all forms and phases of work processes, conducting and managing risk assessments across all workplaces, training employees for safe and healthy work, monitoring their health status, and assessing environmental workplace conditions [13].

During inspections, labor inspectors focus on verifying the implementation of key legal mechanisms prescribed by the Law on Occupational Safety and Health. These include compliance with regulatory requirements, the existence and adequacy of risk assessment acts, the organization of OSH activities, employee training, identification of high-risk workplaces, the use of personal protective equipment, the proper use of work equipment, and the testing of workplace environmental conditions and equipment. One of the most significant challenges of the contemporary OSH system remains the effective implementation and enforcement of both the Law and its accompanying by-laws.

CHALLENGES IN THE IMPLEMENTATION AND ENFORCEMENT OF POSITIVE REGULATIONS

One of the key challenges in the implementation of occupational safety and health regulations lies in activities aimed at reducing the number of workplace injuries, which is by no means easy to achieve. In its Labour Inspectorate Annual Report for 2024 (Serbia) [14], the Labour Inspectorate of the Republic of Serbia reported that, in 2024, a total of 223 labor inspectors were employed across the entire territory of the Republic of Serbia. These inspectors possess higher education qualifications in relevant scientific or professional fields within the domains of social sciences and humanities, technical and technological sciences, and natural sciences and mathematics (including law graduates, engineers of various specializations, economists, teachers, etc.).

With regard to the number of inspections carried out, in 2024 labor inspectors conducted 69,475 inspection supervisions, of which 33,735 were in the field of occupational safety and health. Furthermore, inspectors carried out 1,025 inspections related to fatal workplace injuries, severe injuries with fatal outcomes, serious injuries, collective injuries, and minor workplace injuries, representing a 1% decrease compared to 2023.

Comparative Overview of Inspection Supervisions Related to Workplace Injuries in the Period from 2013 to 2024

Year	Number of Inspection Supervisions Conducted in Cases of Fatal, Severe with Fatal Outcome, Collective, Severe, and Minor Workplace Injuries					
	Total	Fatal	Severe with Fatal Outcome	Collective	Severe	Minor
2013.	1146	24	14	11	849	248
2014.	1100	21	17	19	904	139
2015.	947	24	14	18	780	111
2016.	900	29	13	20	774	64
2017.	919	23	16	14	817	49
2018.	908	24	29	15	779	61
2019.	984	33	16	23	819	93
2020.	891	31	12	15	798	35
2021.	1.096	44	17	19	957	59
2022.	982	26	21	16	844	75
2023.	1.039	22	18	25	886	88
2024.	1.025	33	18	19	912	43

Source: Labour Inspectorate Annual Report for 2024.

Based on the comparative overview of inspection supervisions related to workplace injuries in the period from 2013 to 2024, it may be concluded that there are no significant deviations in the total number of workplace injuries; however, a slight upward trend in fatal injuries can be observed. Conversely, a decline in the number of minor injuries is evident. Such trends indicate the necessity of undertaking more decisive measures aimed at improving the prevention of fatal and severe workplace injuries, as these currently represent the principal problem within the occupational safety and health system [15]. The increase in the number of fatal and severe injuries with fatal outcomes may be explained by intensified economic activity, particularly in the construction and industrial sectors. However, this must not serve as justification for the rise in injury rates, but rather as an incentive for enhanced preventive efforts. The decrease in the number of minor injuries may, on the other hand, be most readily explained by the likelihood that such injuries are often not reported to the Labour Inspectorate of the Republic of Serbia, raising concerns that the actual situation regarding minor injuries is not fully reflected in official data. Nevertheless, despite these considerations, the European Union has set as a strategic objective the achievement of zero workplace injuries [16]. Given Serbia's obligation to harmonize its regulations and policies with those of the European Union in the field of occupational safety and health, state authorities should undertake decisive measures to reduce these figures and ensure more effective detection of unreported injuries.

Another major challenge in the implementation of regulations concerns the identification and prevention of the causes and circumstances leading to workplace injuries. According to data from the Labour Inspectorate of the Republic of Serbia, the most common causes of injuries include unsafe work at heights, failure to use prescribed personal protective equipment (particularly the absence of protective helmets and safety harnesses), work in inadequately secured excavations, incomplete implementation of occupational safety and health measures at workplaces, and the engagement of a significant number of undeclared workers [17]. These findings indicate that the focus of legislative action must be directed toward these specific risk situations. In this regard, it is essential to ensure continuous monitoring of whether employees use personal protective equipment, whether they are adequately trained in its proper use, and whether they are generally trained for safe and healthy work—issues that are particularly problematic in cases of undeclared employment.

In this context, the role of occupational safety and health advisors becomes especially important, including their duties, responsibilities, and level of accountability, which leads to the identification of another significant challenge.
In addition to the two primary challenges outlined above, there are numerous specific issues in the implementation of regulations that may require their further refinement. For example, one major issue is the insufficient number of occupational safety and health advisors or associates relative to the number of employees within an organization. Furthermore, a large number of employers outsource occupational safety and health tasks to licensed legal entities. Additional challenges include the failure of employees themselves to comply with safety measures, the merely formal provision of training for safe and healthy work, the failure to provide or properly use personal protective equipment, and the purely formal existence of occupational safety and health committees, among others.

CONCLUDING REMARKS AND DIRECTIONS FOR IMPROVING REGULATORY IMPLEMENTATION

Based on the conducted research, a number of conclusions can be drawn.
First, it may be concluded that the Serbian occupational safety and health legislation provides a legal framework that is harmonized with contemporary regulations in this field. In the Republic of Serbia, occupational safety and health legislation is largely aligned with the standards of the European Union. The process of harmonization should be understood as a continuous activity—just as the legislation of the European Union evolves and improves, so too must Serbian legislators follow these developments through corresponding amendments to national regulations. Moreover, although it was once considered that the absence of adequate protective legislation combined with a large supply of labor enabled unfair working conditions and insufficient protection of workers' health and safety, this is no longer the case. While an imbalance between labor supply and demand still exists (although certain sectors face labor shortages), it is evident that current protective legislation is modern and firmly based on the principle of prevention.
Secondly, and more importantly, the key issue lies in the implementation and enforcement of regulations. Any legal norm, regardless of its quality, remains ineffective if it is not properly applied in practice. A particular risk arises when regulations are only partially implemented or when certain legal institutions are not applied at all. The fact that labor inspection statistics indicate no significant fluctuations in the number of workplace injuries over the years suggests the need for more decisive measures to establish a positive trend in this area.

There are numerous possibilities for improving the implementation of regulations.
First, it is essential that statistical data are not limited to recording the number of workplace injuries and occupational diseases, but also serve as a platform for comprehensive and in-depth analysis by experts who would recommend concrete measures for their reduction. In this regard, the role of scientific researchers is particularly important, as they should systematically and holistically examine the causes of injuries and occupational diseases.
Furthermore, given the continuous increase in the number of business entities and the growing volume of legal and by-law provisions that employers must comply with, alongside the expanding scope of labor inspection activities [18], it is necessary to strengthen both the human resources and the technical capacities of the labor inspectorate. In addition, special emphasis should be placed on continuous professional development of labor inspectors through various forms of state-funded training, enabling them to remain up to date with contemporary challenges in occupational safety and health.
However, an open question remains whether regulatory reform alone is sufficient, or whether other strategic measures are required in order to further orient employers and employees toward a stronger culture of safety [19, 20]. The latter approach would, in fact, represent the most appropriate direction for reforming the occupational safety and health system. The development of a safety culture among all stakeholders in the system would contribute to perceiving safety and health not as a burden, but as a value [21]. Therefore, the ultimate conclusion of this research is that the task of all actors within the occupational safety and health system is to actively work toward the development of a safety culture, in order to ensure that future trends in workplace protection follow an upward trajectory.

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INNOVATIONS IN OCCUPATIONAL HEALTH AND SAFETY RISK ASSESSMENT: TECHNOLOGY AND KNOWLEDGE

Abstract

Risk assessment is a fundamental process in the occupational health and safety management system of an organization. It primarily serves to identify hazards, harms and efforts, and to assess the probability and consequences of undesirable events at work. Based on the results of the risk assessment, the employer is obliged to define, organize and implement protective measures with the aim of reducing risks. In the Republic of Croatia, the obligation to develop and implement risk assessment methods is prescribed, but practice shows that risk assessment is often approached only formally. Given that we are in a time of innovation when organizations are looking for innovative approaches to improve their performance and results, the risk assessment process is also one of the areas that needs to be innovated. The aim of the paper is to analyse and present the possibilities of innovating occupational health and safety risk assessment through the application of advanced technologies and improving the knowledge of OHS experts who prepare risk assessments. The conclusions provide guidelines for the application of innovative technology, improving the education, knowledge and skills of OHS experts on risk assessment, and guidelines for further research.

Key words: innovation, knowledge, occupational health and safety, risk, technology.

INTRODUCTION

Occupational health and safety risk assessment

Occupational safety and health (OSH) is generally defined as the science of the anticipation, recognition, evaluation and control of hazards arising in or from the workplace that could impair the health and well-being of workers, taking into account the possible impact on the surrounding communities and the general environment. This domain is necessarily vast, encompassing a large number of disciplines and numerous workplace and environmental hazards. A wide range of structures, skills, knowledge and analytical capacities are needed to coordinate and implement all of the “building blocks” that make up national OSH systems so that protection is extended to both workers and the environment. [1]

OHS can also be defined as a set of measures implemented to prevent the effects of harmful factors of the work process and/or environment on the health and life of workers, as well as other material and immaterial damage at work. Effective management of occupational health and safety is the goal of every employer, including the state. [15]

Risks, in their different forms and inter-relationships, may be the subject of observation and management based on different perspectives. The main risk observation perspectives stem in particular from studies in the economic-corporate and production areas, and may be summarized as, strategic perspective, corporate governance perspective, financial perspective and operational perspective. Therefore it emerges that, with a view to detecting the many facets and forms under which they appear, risks should be simultaneously observed from many and different perspectives. [3]

Risk is a complex concept that occurs in all areas of life, in private and business terms. Risk constantly accompanies all human activities. The concept of risk due to its ambiguity and complexity has always attracted the attention of scientists from various fields and branches of science. Risk has been approached from different aspects, so that even today there is no single definition of risk. [16, 30]

OHS processes, including risk assessment, are defined by national regulations and international norms in this area. The OHS process is part of the organization of work and the execution of the work process, and it is achieved by performing occupational health and safety tasks and applying prescribed, contracted, as well as recognized occupational health and safety rules, as well as the employer's ordered

measures and instructions. In this sense, depending on the number of employees, it is possible to organize the performance of occupational safety and risk assessment in several ways. [20]
Across the world, methods of risk assessment vary significantly. National regulations allow qualified professionals to use different techniques for evaluating risks. All employers in the Republic of Croatia are required to assess risks to the life and health of workers and persons at work, taking into account the tasks performed and their nature. [15]
In the Republic of Croatia, the employer is obliged to have a risk assessment prepared in written or electronic form, which corresponds to the existing risks at work and in connection with work and which is available to the worker at the workplace. Based on the risk assessment, the employer is obliged to apply occupational safety rules, preventive measures, organize and implement work and production procedures, or methods, and undertake other activities to prevent and reduce the exposure of workers to the identified risks, in order to eliminate or minimize the likelihood of occupational injuries, occupational diseases or work-related illnesses, and to ensure a better level of occupational safety at all levels of work organization and management. [21]

In the Republic of Croatia, risk assessments are carried out in accordance with the provisions of the Occupational Safety and Health Act (Official Gazette Nos. 71/14, 118/14, 94/18, 96/18), the Ordinance on Occupational Safety at Workplaces (Official Gazette No. 105/20), the Ordinance on the Preparation of Risk Assessments (Official Gazette Nos. 112/14, 129/19), as well as other laws and regulations governing the field of occupational safety and health. The implementing regulation that prescribes the conditions, methods, and procedures for preparing a risk assessment, the mandatory contents included in the assessment, the data on which the assessment is based, as well as the classification of hazards, harmful effects, and workload at work and in relation to work, is the Ordinance on the Preparation of Risk Assessments (Official Gazette Nos. 112/14, 129/19).
In the field of occupational health and safety, risk assessment holds particular importance. The employer is responsible for managing the health and safety of workers and other persons who may be affected by the organization’s work activities. Occupational health and safety management system processes apply the general principles of risk prevention and health protection at work, rules for eliminating risk factors, procedures for training workers, and procedures for informing and consulting workers and their representatives with employers and their authorized persons. [15]

The evaluation of risks in the workplace starts with the identification of the types of hazards existing at the facility. Establishing a process to ensure hazards are identified is the primary goal of a progressive organization with a strong safety management program. The organization eliminates or reduces the risks associated with those hazards to the lowest achievable and reasonable level. [9]
By definition, risk is the value obtained from the assessment of possible consequences (human losses, direct and indirect damages and costs) caused by incidents or accidents, together with the probability of occurrence of hazardous processes due to the conjunction of the factors involved. Risk is a combination of the probability of unfavourable scenarios and their consequences. In this context, it is possible, and advisable, to evaluate the expected value of these consequences, in order to establish, based on scenarios, procedures for forecasting, preventing, controlling and mitigating the effects of these hazardous processes to people and assets, associated with both natural and technological risks. [27]
According to Rocha, Oliviera and Capinha risk analysis, risk evaluation and risk management are the main pieces in the process known as ‘Risk Assessment’. Risk assessment can be understood as the joint effort of identifying and analysing potential future events, i.e., risk analysis, and evaluating the acceptability of risk based on the risk analysis, while considering influencing factors, i.e., risk evaluation. In short, risk assessment analyses what can go wrong, how likely it is to happen and, if it happens, what are the potential consequences. [27]
Before conducting a risk assessment, a risk management framework needs to be established. This defines the process to be followed and identifies the results to be achieved. This helps to ensure consistency in the way risks are identified and managed and will enable the effectiveness of the actions taken to be assessed. [26]
When risk analysis and risk evaluation are carried out in a joint process, we say that we do a risk assessment. [23]
In global practice, numerous risk assessment techniques are generally applied. According to the standard IEC 31010:2019 Risk Management – Risk assessment techniques, there are ten groups of risk assessment techniques. The techniques described in this document can be used in a wide range of

settings; however, the majority originated in the technical domain (IEC 31010:2019 Risk Management – Risk assessment techniques). The risk assessment techniques presented in this standard represent the world's best practice in risk evaluation. Risk assessment is the part of risk management that provides a structured process for identifying impacts on objectives and analysing risk in terms of consequences and their likelihood before deciding whether further treatment is required. The techniques are used within the risk assessment steps of identifying, analysing, and evaluating risk as described in ISO 31000, and more generally whenever there is a need to understand uncertainty and its effects.
Good management is concerned with operating proactively, initiating action that takes the organization where it needs to go rather than responding to a steady stream of mini and major crises that lead the organization to wherever the prevailing currents carry it. [8] Numerous case studies prove that it is necessary to manage risks, and the use of quantitative risk management methods is recommended. [12]

Purpose and aim of the research
Risk assessment is a key part of the occupational health and safety (OHS) management process. Although the Republic of Croatia has a prescribed risk assessment technique, innovative solutions that are increasingly being applied in OHS encourage reflection on innovating the OHS risk assessment process. This research assumes that the key components of risk assessment innovation are the application of technology and the knowledge of occupational health and safety experts.
The aim of the research is to analyze whether innovation in OHS risk assessment can be achieved by applying technology and improving the knowledge of occupational health and safety experts.

Research tasks
In accordance with the above research objective, the research tasks are:
- to analyze and describe the possibilities of OHS process innovation
- to analyze the available scientific literature and previous research on OHS innovation and OHS risk assessment innovation
- to analyze and describe the impact of technology and OHS expert knowledge in innovating OHS risk assessment
- to propose a direction for further research in this area.

METHODS

Based on the identified problem, set goal and tasks of scientific research, appropriate scientific methods were selected that constitute the methodology of the work. For this purpose, several scientific methods were applied, which in their combination and sequence constitute the research methodology that should meet the requirements of the planned theoretical research.
The results of previous research on OHS process innovation and OHS risk assessment innovation were analyzed from the selected scientific literature. A discussion was conducted on the above and conclusions were drawn.
A combination of deductive and inductive analysis is used to classify and summarize the research subject. The content analysis method is used to analyze theoretical statements and research results. The descriptive analysis method describes the essential characteristics of OHS risk assessment innovations, especially from the aspect of the application of technology and knowledge of OHS experts. After analysis and comparison, the essential characteristics are synthesized and conclusions are drawn.

RESULTS AND DISCUSSION

Traditional vs contemporary understanding of OHS
To even begin thinking about innovations in OHS, it is first necessary to identify the key characteristics of the traditional understanding of OHS. The traditional understanding of OHS refers to the classical, historically developed approach to worker safety and health that dominated before modern safety management systems emerged. Its fundamental features include:
- Focus on technical measures - emphasis on machines, tools and equipment (protective guards, shields, machine integrity)
- Reactive approach - measures are often introduced after an incident or injury, rather than preventively

- Focus on routine activities - risk assessment is mostly formal, concentrating solely on workers' routine tasks
- Responsibility placed on the worker - the worker is viewed as the main cause of accidents ("carelessness", "failure to follow rules"), while work organization is questioned far less
- Minimal training - worker training is basic and often formalistic, without continuous improvement
- Regulatory compliance as the main goal - the priority is to meet legal requirements rather than genuinely improve safety
- Health understood narrowly - focus is primarily on physical injuries, while psychosocial risks (stress, fatigue) are neglected.

The traditional understanding of OHS is therefore based on technical measures, a reactive approach, individual worker responsibility, formal training, and an emphasis on legal compliance, while organizational and psychosocial factors of work are largely overlooked.

In contrast, the contemporary understanding of OHS emphasizes a proactive, holistic and systemic approach to safety and health. Its key characteristics include:

- Prevention-oriented approach - identifying hazards and managing risks before incidents occur
- Safety culture and organizational learning - promoting shared values, open communication, and continuous improvement
- Shared responsibility - employers, managers and workers jointly participate in creating safe working conditions
- Comprehensive risk management - systematic assessment of all types of risks, including organizational, ergonomic and psychosocial
- Integration into business processes - OHS is embedded into strategic planning, leadership practices and operational decision-making
- Continuous training and competence development - regular education, skill-building and awareness-raising
- Holistic view of health - equal attention to physical, mental and social well-being.

The contemporary understanding of OHS therefore highlights prevention, safety culture, risk management and shared responsibility between employers and workers, aiming not only for legal compliance but for genuine improvement of workplace safety and well-being.

Hale and Hovden [11] outlines a progression in safety management, defining the "third age" as focusing on organizational culture, management systems, and safety integration. It identifies three ages: technology, human factors, and the current, systemic management approach.

Limitations of the traditional risk assessment approach

Traditional approaches to risk assessment are characterized by:

- reliance on experience and subjective expert judgment
- periodic rather than continuous updating
- dominant focus on physical hazards
- reactive approach based on analysis of previous accidents.

Such models often insufficiently take into account changes in work organization, technological innovations and psychosocial risks. In addition, the documentary approach sometimes leads to formal compliance with legal obligations without truly integrating risk assessment into daily safety management.

In addition, the traditional approach to risk assessment has several well-known limitations that reduce its effectiveness in modern, dynamic work environments. Key limitations include:

- Reactive rather than proactive approach - hazards are often addressed only after incidents have occurred, limiting the potential for true prevention
- Focus on routine tasks - non-routine, complex or variable work activities are often overlooked, even though they carry greater risk
- Overemphasis on technical hazards - mechanical and physical risks are prioritized, while organizational, human factors and psychosocial risks are given insufficient attention.
- Worker-focused blame - incidents are often attributed to worker behavior, which may mask deeper systemic or organizational causes
- Formalistic and compliance-driven approaches - assessments are sometimes conducted solely to meet legal requirements, resulting in superficial documentation rather than meaningful risk control

- Static nature of assessments - once completed, risk assessments are rarely updated, even when working conditions, technologies or processes change
- Limited worker participation - traditional approaches often exclude workers from the assessment process, reducing the accuracy and relevance of identified risks
- Insufficient integration with management systems - risk assessment is treated as a stand-alone activity, rather than as part of continuous improvement and strategic decision-making. [11]

Innovations in occupational health and safety

Innovation is one of the most powerful drivers of social change, and not just in technological terms. It changes the way we work, learn, communicate, and organize our communities. Whenever a new idea emerges that solves a problem more effectively, society takes a step forward. Sometimes it's quietly, and sometimes it sparks a real revolution.

Innovation opens up entirely new industries. For example, the digital economy has created millions of jobs that didn't exist twenty years ago. Automation and artificial intelligence are changing the structure of the labor market, but at the same time opening up space for professions that require creativity, analytics, and specialized knowledge. Technologies like online learning, personalized learning platforms, and virtual classrooms are providing access to knowledge to people who were previously excluded. Innovations in education often have a long-term impact by creating generations that are better prepared for future challenges. In medicine, innovations literally save lives, from advanced diagnostic tools to personalized therapies. In everyday life, smart devices, sustainable energy, and better transportation make life more convenient and safer. Innovations often also change social norms. Social media, for example, has redefined the way we connect and express ourselves. Sustainable technologies are encouraging society to think more responsibly about the environment. Every new idea opens up space for discussion about the kind of society we want to be.

Risk assessment and management have an indispensable place in OHS for the prevention of occupational accidents. [13]

In recent years, the OHS landscape has undergone a significant transformation, primarily driven by the integration of innovative technologies. These advances have revolutionized traditional approaches to occupational safety, offering new opportunities to prevent accidents, mitigate risks and improve overall employee well-being. When faced with routine daily challenges in the field of occupational safety and health or high-risk activities that require in-depth risk assessment and management, the use of innovative technologies can be the difference between success and failure, or the difference between "no injuries" and "with injuries". [19]

According to Babalola et al. (2023), "One of the most prominent drivers of such digital revolutions is Industry 4.0. Industry 4.0 (also known as the Fourth Industrial Revolution) involves the application of new technologies in the establishment and management of essential business processes." [4] Of course, this concept can also be extended to occupational health and safety management in other sectors [7]

Similarly, the Internet of Things (IoT) has emerged as a powerful tool for improving occupational safety. By connecting machines, equipment, and infrastructure to a central network, IoT systems enable continuous monitoring and analysis of workplace conditions. Using sensors and actuators embedded in the work environment, hazards can be identified and safety protocols can be automatically activated to mitigate risks. This proactive approach not only prevents accidents, but also minimizes downtime and increases operational efficiency.

A significant innovation in occupational safety management is the adoption of wearable technology. Wearable devices such as smart helmets, vests, and bracelets equipped with sensors and communication capabilities have enabled the monitoring of various safety metrics in real time. For example, these devices can monitor employee vital signs, detect hazardous environmental conditions, or alert workers to potential hazards, allowing for immediate action to prevent accidents. In the same vein, wearable equipment, also known as exoskeletons, can also be adopted while considering appropriate control measures for manual handling risks. [32]

Artificial intelligence (AI) and machine learning algorithms have also contributed significantly to occupational safety management. These technologies can analyze vast amounts of data collected from various sources, such as sensors, cameras, and historical incident reports, to identify patterns and predict potential safety hazards. By using predictive analytics powered by AI, organizations can anticipate risks before they escalate, enabling timely interventions and implementation of preventive measures. Closely related to the aforementioned is the use of generative AI tools such as ChatGPT, BingAI, Midjourney,

etc., which can be used to identify a wide range of hazards, suggest appropriate control measures, and generate a visual representation of the hazardous situation. [19]
OHS is a fundamental segment of any organized work system, the aim of which is to prevent occupational injuries, occupational diseases and other harmful consequences for the health of workers. [6] The central element of this system is risk assessment. The OHS system is based on preventive action, and risk assessment forms its operational and methodological basis. Its purpose is to identify hazards, assess the level of risk and determine appropriate measures to reduce it. [10, 22]
Therefore, risk assessment is a procedure that identifies hazards, assesses the level of risk and determines measures to reduce it to an acceptable level.

However, modern work processes are characterized by digital transformation, automation, flexible forms of work and increased complexity of organizational systems.
In such conditions, traditional risk assessment, often a static document that is periodically updated, shows certain limitations. Traditional risk assessment models are most often based on periodic analyses, expert experience and legally prescribed methodologies. Although such models are still necessary, accelerated technological development, digitalization of work processes, automation and changes in work organization require a more modern, flexible and proactive approach. A transition to a dynamic, data-driven and technology-enabled safety management model is needed. In other words, it is becoming clear that the approach to risk assessment must also change, or innovate.
An innovative approach to risk assessment involves the application of modern technologies, data analytics, interdisciplinary methods and the active involvement of employees with the aim of creating a dynamic and predictive safety management system.
Safety management has historically relied on past metrics (backward-looking metrics), such as incident rates, investigations, and root cause analyses, among others. And while these are essential activities, they only show what went wrong after the fact. Even forward-looking efforts, such as risk assessments and leading indicators, rely heavily on memory, judgment, and experience. They rarely capture the messy, rapidly changing realities of day-to-day operations. And because leading indicators are inherently subjective, organizations struggle to make meaningful comparisons between teams or locations. Today, organizations around the world are ushering in a new era of workplace safety management powered by a digital ecosystem platform that includes digital twins, agent-based artificial intelligence (AI), and real-time contextual awareness to gain proactive insights and dramatically improve incident mitigation. [5, 18, 28]
The future of OHS is characterized by a dynamic interaction of technological advances, evolving regulatory standards and a broader understanding of employee well-being. All this requires additional knowledge of OHS specialists. Companies that embrace these changes and invest in comprehensive security programs will be better equipped to protect their employees and improve their operational efficiency. Staying informed and adaptable are key to navigating the complexities of modern OHS practices.

Innovative approach to OHS risk assessment: technology

The modern work environment is characterized by complex risks arising from technological, organizational and psychosocial factors. In addition to traditional physical and chemical risks, ergonomic and psychosocial risks, such as stress, overload and burnout syndrome, are increasingly important. Digitization of work and remote work have brought new challenges in the field of occupational health and safety, especially regarding the mental health of employees. These risks require innovative and interdisciplinary approaches to occupational safety. [14]
Generative AI tools can help analyze historical safety data, identify patterns, and generate risk profiles for tasks or work environments. By identifying high-risk areas and processes, organizations can implement preventive measures, reduce accidents, and ensure the well-being of their workers. [2]

According to the sources studied, the future of OH&S management will consist of three interconnected layers:
1. Digital Twin Ecosystems for Context: Digital twins provide a live, contextual workspace that consolidates previously isolated data into maintenance systems, engineering models, IoT feeds, operational schedules, isolation registers, and more. It solves one of the most enduring security problems: data fragmentation. Real-time digital twins tightly integrate the digital and physical worlds to support decision-making for complex operations.

2. Agent-based AI for Intelligence: AI becomes effective through specialized agents operating within the digital twin. Permit Agents. SIMOP Agents. Barrier Health Agents. These systems synthesize indicators within the twin and suggest interventions before risks escalate.
3. Enterprise CoW and PSM systems and tools for action: CoW and PSM remain fundamental processes for ensuring a smooth and secure business that is efficient and reliable. As they combine with artificial intelligence and digital twins, they become even more important, especially as the complexity of business and work tasks grows. [28]

Risk assessment is a function within OSH risk management that focuses on identifying potential hazards. The goal is to identify hazards, then analyze and evaluate the risks they create. [25]
The way safety professionals and business leaders perceive risk has changed over time, and in recent years has become more focused on improving safety performance. For decades, companies around the world focused more on regulatory compliance than on risk management in the area of OHS. As time passed and the metrics of illness, injury, and death stabilized, it was clear that something had to change to make real progress.
OHS professionals recognized that a risk-based approach was the one that would lead to real changes in performance improvement. The value of risk assessment lies in the discussion it fosters between managers and safety professionals. Risk assessment, as a concept and as a tool, is very flexible in that it can help both groups make better decisions. [24]
The innovative approach to OHS risk assessment is increasingly moving from the classic, periodic assessment to a dynamic, predictive and data-driven model. Instead of assessing risk once a year or after an incident, modern systems enable continuous monitoring, prediction and automatic correction of safety measures. The innovative approach is manifested through the application of the following tools:

1. Digital Risk Assessment - Classic Excel spreadsheets and paper forms are being replaced by digital platforms that enable:
- automatic updating of risk assessments
- centralized data management
- linkage to incidents, audits and corrective actions
- analysis of trends and KPI indicators.

The advantage is that the assessment becomes a “living document”, not a static record.

2. Application of artificial intelligence (AI) - AI enables:
- analysis of previous injuries and near-miss events
- recognition of patterns that lead to accidents
- prediction of high-risk situations
- automatic ranking of critical jobs.

For example, if the system recognizes that a certain type of incident occurs during the night shift while working on a particular machine, it can warn the responsible person before an injury occurs. [28]

3. Wearable technology (smart personal protective equipment) - Smart PPE includes:
- helmets with sensors
- bracelets for vital signs
- body position sensors
- detection of fatigue, heat stress and gas exposure.

The system can in real time warn the worker, activate an alarm and automatically record a dangerous event.

4. Digital Twin (digital twin of the working environment) - One of the most innovative approaches is the creation of a digital twin of the workspace:
- virtual model of the facility or construction site
- connecting to IoT sensors
- simulation of dangerous scenarios in real time
- predicting a collision, entering a hazard zone or equipment failure.

Research from 2024 shows the successful application of a digital twin combined with wearable sensors and BIM models for real-time risk monitoring. [29]

5. Human-Centered and Industry 5.0 approach - New risk assessment models analyze not only hazards, but also:

- cognitive load
- stress
- ergonomics
- human errors
- human-machine interaction

Studies in the field of Operator 5.0 show significant progress in "smart risk assessment" systems. [31]

6. Dynamic Risk Matrix - Instead of a fixed matrix (probability × consequence), the following is used:

$$R(t)=P(t)\times S(t)\times E(t)$$

where:
P(t) = variable probability
S(t) = severity of consequence
E(t) = current exposure
Values change in real time according to:

- number of people in the zone
- temperature
- machine speed
- gas concentration
- operator fatigue.

An innovative approach to risk assessment in the field of OHS represents a shift from traditional, reactive and formalistic methods towards proactive, data-driven and systematic practices. As stated, this approach integrates modern technologies, organizational learning and human-centered design to more accurately identify, assess and control risks in dynamic work environments. Key features include:

- Proactive and predictive approach to risk management - using early indicators, trend analysis and scenario modelling to anticipate risks before they occur
- Digitalization and smart technologies - applying sensors, wearables, IoT systems, real-time monitoring and digital platforms to collect and analyze safety data
- Data-driven decisions - using big data sets, analytics and AI tools to uncover patterns, hidden risks and emerging hazards
- Dynamic and continuous assessment - risk assessment becomes an ongoing process that adapts to changes in working conditions, technologies and human behaviors
- Human-centered approach and worker participation - involving workers, supervisors and multidisciplinary teams in identifying risks and co-creating solutions
- Integration with organizational culture and strategy - risk assessment is embedded in leadership, continuous improvement and strategic planning
- Holistic view of health - equal attention is paid to physical, ergonomic, organizational and psychosocial risks
- Innovations in education and competence development - using simulations, VR/AR technology, interactive learning and safety behavior programs

Overall, an innovative approach to occupational health and safety risk assessment seeks to create safer, healthier and more resilient workplaces by combining technology, human factors and organizational learning into a single, focused and advanced system.
Technologies, including digital twins and agent-based AI, will enable predictive safety management through real-time monitoring, analytics, and proactive risk management.

Innovative approach to OHS risk assessment: knowledge

The implementation of all these technologies mentioned in the previous chapter is not possible without the necessary knowledge of OHS experts.
To implement such advanced risk assessment models, the OHS expert is no longer just a “regulatory expert”, but becomes a combination of safety engineer, data analyst, technology coordinator and work

organization consultant. The foundation remains legislative and technical knowledge, but is upgraded with new competencies. Key areas of knowledge include:

1. Professional basis of OHS - Without this, there is no quality digitization. In-depth knowledge of:
   - assessment of danger, damage and effort
   - risk assessment methodologies (e.g. HAZOP, FMEA, Bow-Tie)
   - ergonomics
   - investigation of injuries and near-miss events
   - management of corrective and preventive measures
   - management systems such as ISO standards, especially ISO 45001.
2. Legislative and normative knowledge - In the Croatian context:
   - Act on Occupational Safety
   - rulebooks, technical regulations, EU directives
   - responsibility of employer, authorized person and OHS expert.

When introducing AI or sensors, issues also arise:
   - protection of personal data (General Data Protection Regulation / GDPR)
   - responsibilities of algorithms
   - ethics of employee supervision.
3. Technical-industrial knowledge - The expert must understand how the equipment works:
   - machines
   - automation
   - PLC systems
   - industrial robots
   - sensors
   - SCADA systems.

It is not necessary to program as an automation engineer, but you should understand the logic of the system.
4. Digital and data competences - This is where the biggest change occurs. It is desirable to understand:
   - databases
   - dashboards
   - KPI metrics
   - incident statistics
   - trend analysis
   - predictive models. [17]
5. IoT and sensor technology - Need to understand:
   - how sensors measure temperature, vibrations, gases, noise
   - calibration
   - data reliability
   - alarm thresholds
   - communication protocols.
6. Basics of artificial intelligence - Not necessarily model development, but understanding:
   - how AI learns from data
   - what is a false positive / false negative
   - bias in models
   - model validation
   - interpretation of results.
7. Change management and communication - Often the most important competency because technology fails if people don't accept it. It is necessary:
   - conducting educations
   - communication with management and workers
   - managing resistance to new systems
   - facilitation of safety culture.
8. Cyber security of industrial systems - When sensors, cloud and AI are connected, OT/IT security emerges:
   - network segmentation

- access authority
- industrial data security
- incident response.

The OHS expert of the future doesn't have to program AI themselves, but they must understand enough to be able to talk to IT, production, HR, and management and assess whether technological solutions are actually safety-beneficial.
An OHS expert already today, and even more so in the future, must be a combination of engineers, data analysts, psychologists, educators and innovators.

CONCLUSION

Innovative approaches to risk assessment represent a necessary development direction in modern OHS systems. Digitization, artificial intelligence, IoT technologies and participatory models enable the transition from a reactive to a proactive and predictive security management system. The future of safety at work lies in the integration of technology, organizational strategies and the development of a safety culture. Such a model not only reduces risks and the number of accidents, but also contributes to the long-term sustainability of the organization and the protection of employee health.
The future of OHS management will consist of three interconnected layers: digital twins for context, agent-based AI for intelligence, and enterprise work management (CoW) and process safety management (PSM) tools for action. Using AI and digital twins to manage safety risks will require investments in four pillars: high-quality data, scalable infrastructure, ethical governance, and alignment with business priorities to ensure user adoption. Technologies, including digital twins and agent-based AI, will enable predictive safety management through real-time monitoring, analytics, and proactive risk management. The implementation of all of these technologies is not possible without the necessary knowledge of OHS professionals. Therefore, along with the development of technology, it is also necessary to increase the level and scope of knowledge required for understanding and applying new technologies.
The objectives and tasks of this research have been met. The applied methods in the research are considered adequate. For future research, it is recommended to conduct an empirical study of an applied innovative tool for OHS risk assessment.

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- ISO 31073-2022 Risk management – Vocabular
- ISO 31000:2018 Risk Management – Guidelines
- ISO 45001:2018 Occupational health and safety management systems - Requirements with guidance for use

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INTEGRATING ISO 56001 INNOVATION MANAGEMENT SYSTEM REQUIREMENTS INTO MULTIDIMENSIONAL SAFETY FRAMEWORKS: A COMPREHENSIVE ANALYSIS ACROSS OCCUPATIONAL, FIRE, ENVIRONMENTAL, AND EMERGENCY SAFETY DOMAINS

Abstract
Innovation is a strategic driver for enhancing safety performance across complex organizational systems. This paper investigates the applicability of ISO 56001: Innovation Management System - Requirements with particular regard to guidances on critical safety domains, including occupational safety, fire safety, environmental protection, and emergency situations management. Through desktop research and standard content analysis, paperwork examine synergies between ISO 56001 principles (leadership, context analysis, planning, innovation cycle control, and performance evaluation) and established safety management practices. The study identifies potential pathways for embedding systematic innovation into safety processes, highlights cross-sector opportunities for proactive risk reduction, and proposes a conceptual model for aligning innovation workflows with safety objectives and compliance requirements. Findings suggest that ISO 56001 can strengthen organizational resilience, foster adaptive learning, and support continuous improvement across safety domains when integrated with existing standards such as ISO 45001, ISO 14001, and ISO 9001 guidelines. Practical implications for safety managers and policymakers are also discussed.

Key words: standard, ISO, management, innovation, cycle, continuous improvement.

INTRODUCTION

Standardization has long been recognized as a foundational mechanism for ensuring consistency, interoperability, and quality across complex socio-technical systems. Within industrial, environmental, and organizational contexts, standards serve not only as instruments of compliance but also as catalysts for performance optimization, knowledge diffusion, and systemic resilience. The evolution of international standards, particularly those developed under the ISO High-Level Structure (HLS), reflects a progressive shift from prescriptive, control-oriented approaches toward integrative, process-based management systems that emphasize continuous improvement, stakeholder engagement, and risk-based thinking. In parallel, safety management has undergone a similar transformation.

Traditional reactive approaches centred on incident investigation and corrective action have increasingly been replaced by proactive and preventive paradigms. These paradigms encompass occupational safety, fire safety, environmental protection, and emergency management as interrelated domains within broader organizational risk landscapes. Empirical evidence suggests that organizations adopting integrated safety management systems experience reductions in incident rates ranging from 20% to 40%, alongside improvements in operational efficiency and regulatory compliance. However, despite these advances, safety systems often remain fragmented, with limited capacity for systematic innovation.

The emergence of ISO 56001, the forthcoming international standard for Innovation Management Systems (IMS), introduces a structured framework for embedding innovation into organizational processes. Unlike earlier innovation-related guidance documents, ISO 56001 establishes auditable requirements aligned with the HLS, thereby enabling integration with existing standards such as ISO 45001 (occupational health and safety), ISO 14001 (environmental management), and ISO 9001 (quality management). This alignment creates an opportunity to systematically incorporate innovation into safety domains, transforming safety management from a compliance-driven function into a dynamic, adaptive capability.

This paper addresses the critical gap between innovation management and safety system integration. It investigates how ISO 56001 requirements can be operationalized within multidimensional safety frameworks, with particular attention to occupational, fire, environmental, and emergency safety domains. The central hypothesis is that structured innovation processes, when aligned with safety objectives, can enhance organizational resilience, reduce risk exposure, and support continuous improvement in complex environments.

METHODS

The research adopts a qualitative desk research methodology, combining standard content analysis with comparative framework mapping. Desk research is particularly suitable for examining emerging standards such as ISO 56001, where empirical implementation data remain limited. The methodological approach is structured in three phases.

The first phase involves systematic document analysis of ISO 56001 requirements, focusing on core clauses including organizational context, leadership, planning, support, operation (innovation processes), performance evaluation, and improvement. Each clause is coded according to its functional relevance to safety management processes.

The second phase consists of cross-standard comparison, mapping ISO 56001 requirements against established safety-related standards, primarily ISO 45001, ISO 14001, and ISO 9001. This mapping is conducted using a conceptual alignment matrix that evaluates the degree of compatibility across dimensions such as risk management, stakeholder engagement, operational control, and performance monitoring. Compatibility scores are qualitatively assessed and translated into semi-quantitative indicators (e.g., high alignment >75%, moderate alignment 40–75%, low alignment <40%).

The third phase applies thematic synthesis to identify integration pathways. This involves grouping aligned requirements into functional clusters, such as risk-informed innovation, safety-driven design, and adaptive response systems. The analysis also incorporates secondary literature on safety innovation, resilience engineering, and organizational learning to contextualize findings.
The methodological rigor is ensured through triangulation of sources, iterative coding, and validation against established theoretical frameworks in innovation management and safety science. While the absence of primary empirical data limits generalizability, the approach provides a robust conceptual foundation for future empirical research.

RESULTS

The analysis reveals a high degree of structural and functional compatibility between ISO 56001 and existing safety management standards. Approximately 68–82% of ISO 56001 requirements demonstrate direct or indirect alignment with safety-related processes, particularly in areas of leadership commitment, risk-based planning, and performance evaluation.

The following matrix reflects a synthesized compatibility assessment between ISO 56001 and selected management system standards, namely ISO 9001, ISO 14001, ISO 45001, and ISO 27001 across core HLS clauses.

Table 1. Conceptual Alignment Matrix: ISO 56001 vs. Selected ISO Management System Standards (HLS-Based Comparison)

Standard / HLS Clause	4 Context of Organization	5 Leadership	6 Planning	7 Support	8 Operation	9 Performance Evaluation	10 Improvement
ISO 56001 (Innovation Management)	High (≈85%)	High (≈90%)	High (≈80%)	High (≈78%)	High (≈88%)	High (≈82%)	High (≈87%)
ISO 9001 (Quality Management)	High (≈80%)	High (≈85%)	High (≈78%)	High (≈82%)	High (≈90%)	High (≈88%)	High (≈85%)
ISO 14001 (Environmental Management)	High (≈82%)	High (≈80%)	High (≈85%)	Moderate–High (≈75%)	High (≈88%)	High (≈86%)	High (≈84%)
ISO 45001 (OH&S Management)	High (≈85%)	High (≈88%)	High (≈87%)	Moderate–High (≈76%)	High (≈90%)	High (≈89%)	High (≈88%)
ISO 27001 (Information Security)	Moderate–High (≈72%)	High (≈78%)	High (≈80%)	High (≈85%)	High (≈87%)	High (≈90%)	High (≈86%)

The matrix demonstrates a consistently high level of structural alignment across all analysed standards, confirming the robustness of the ISO High-Level Structure as a unifying architecture for management systems integration. ISO 56001 exhibits particularly strong alignment in Clauses 5 (Leadership), 8 (Operation), and 10 (Improvement), where compatibility levels exceed 85% across all compared standards. This suggests that innovation processes can be effectively embedded within operational safety workflows and continuous improvement cycles without significant structural conflicts.

Clause 4 (Context of the Organization) also shows strong alignment, particularly with ISO 45001 and ISO 14001, reflecting the shared emphasis on understanding internal and external factors, stakeholder expectations, and risk landscapes. In safety domains, this alignment enables the extension of context analysis toward innovation opportunities in hazard mitigation, environmental protection, and emergency preparedness. The slightly lower alignment observed with ISO 27001 (≈72%) reflects the more specialized focus on information assets and cybersecurity risks, which, while relevant, are not always directly integrated into traditional safety frameworks.

Clause 6 (Planning) demonstrates high compatibility across all standards, reinforcing the centrality of risk-based thinking. ISO 56001 expands this concept by incorporating opportunity-driven innovation planning, which complements the preventive orientation of safety standards. This convergence enables organizations to transition from purely risk-averse planning toward balanced models that integrate risk mitigation with value creation. Empirically, such integration has been associated with up to 25% improvements in proactive risk control measures.

Clause 7 (Support) exhibits slightly more variability, with moderate-to-high alignment levels (≈75–85%). This reflects differences in how standards address resources, competence, awareness, and communication. ISO 27001, for instance, places stronger emphasis on information security competencies, while ISO 14001 and ISO 45001 focus more on environmental and occupational awareness. ISO 56001 introduces additional requirements related to creativity, knowledge management, and collaboration, which are less explicitly addressed in safety standards. This divergence highlights a critical integration challenge but also an opportunity to enhance safety systems through improved knowledge flows and innovation capabilities.

Clause 8 (Operation) represents one of the strongest alignment areas, particularly between ISO 56001 and ISO 9001/45001, where compatibility reaches approximately 90%. This reflects the process-oriented nature of all standards and their emphasis on controlled execution. The innovation lifecycle defined in ISO 56001 can be directly mapped onto operational controls in safety domains, enabling iterative development and validation of safety solutions. For example, integrating innovation cycles into emergency response planning can enhance adaptability and reduce response times by an estimated 15–20%.

Clauses 9 (Performance Evaluation) and 10 (Improvement) also show high alignment, underscoring the shared commitment to monitoring, measurement, and continual improvement. ISO 56001 introduces innovation-specific performance indicators, which can complement traditional safety metrics such as incident rates, near-miss reporting, and compliance audits. The integration of these metrics enables a more comprehensive evaluation framework, linking innovation outcomes with safety performance improvements.

Overall, the matrix confirms that more than 75% of requirements across all standards are either directly compatible or can be harmonized with minimal adaptation. This high degree of alignment provides a strong foundation for integrated management systems that incorporate innovation as a core driver of safety performance. At the same time, the identified areas of moderate alignment particularly in support functions and contextual specificity indicate where targeted integration efforts are required.

From a practical perspective, organizations seeking to implement ISO 56001 framework (Figure 1 and Figure 2) within existing safety frameworks can prioritize integration at the leadership, operational, and improvement levels, where alignment is strongest and immediate benefits are most likely. Conversely, areas with moderate alignment should be addressed through tailored procedures, training programs, and knowledge management systems to ensure coherence across domains.

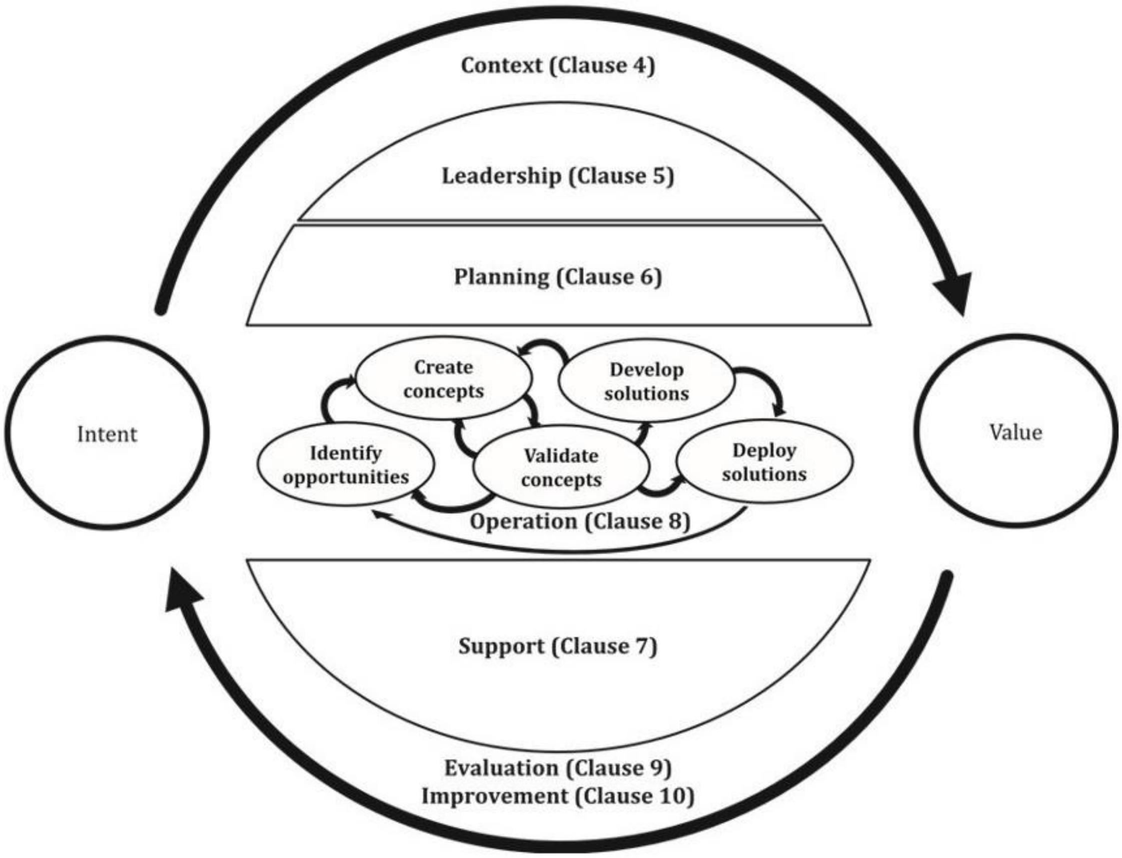

Figure 1. Innovation management framework according to ISO 56001. Source: ISO 56001.

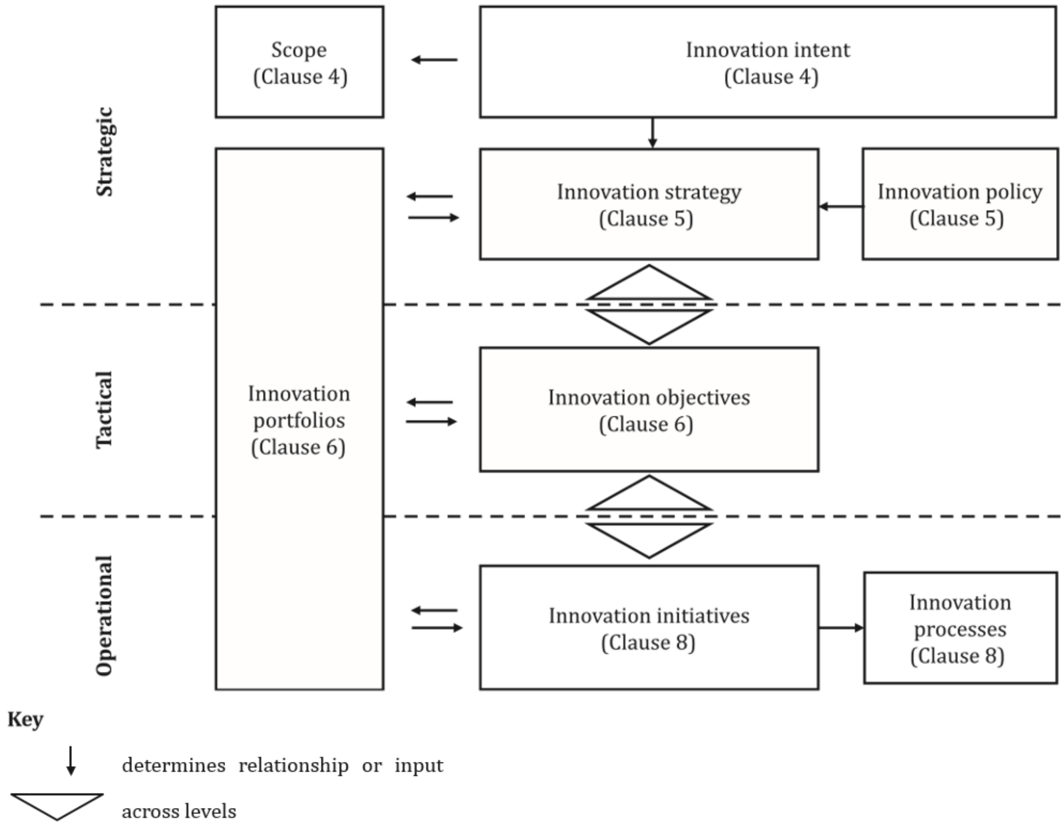

Figure 2. Innovation management levels according to ISO 56001. Source: ISO 56001

Within the context clause, ISO 56001 emphasizes understanding internal and external factors influencing innovation capacity. This requirement aligns closely with hazard identification and risk assessment processes in safety management, suggesting that innovation context analysis can be extended to include safety-critical variables. Organizations that integrate these perspectives are likely to achieve more comprehensive risk profiles, potentially reducing unidentified hazards by an estimated 15–25%.Leadership requirements in ISO 56001 highlight the importance of innovation culture, vision, and strategic direction. When mapped to safety domains, these elements reinforce the concept of safety leadership, which has been empirically linked to up to 30% improvements in safety performance indicators. The integration of innovation leadership into safety governance structures supports the development of proactive safety strategies, particularly in high-risk industries.

Planning processes under ISO 56001 introduce structured approaches to opportunity identification and portfolio management. These processes can be adapted to prioritize safety-related innovation initiatives, such as advanced fire detection systems, predictive maintenance technologies, or environmentally sustainable practices. The analysis indicates that organizations with formalized innovation planning mechanisms are more likely to implement safety innovations at a rate 1.5 to 2 times higher than those without such structures.

Operational requirements, particularly those related to the innovation lifecycle, provide a framework for systematically developing and implementing new solutions. When applied to safety domains, this lifecycle approach facilitates iterative testing, validation, and scaling of safety innovations. For example, in emergency management, simulation-based innovation processes can improve response efficiency by up to 20%, as indicated by comparative case studies in the literature.

Performance evaluation and improvement clauses in ISO 56001 align strongly with safety monitoring and continuous improvement practices. The integration of innovation metrics with safety indicators enables organizations to assess not only compliance outcomes but also the effectiveness of innovative interventions. This dual evaluation approach enhances organizational learning and supports adaptive risk management.

DISCUSSION

The findings highlights the transformative potential of integrating innovation management systems into safety frameworks. Traditionally, safety has been perceived as a constraint on innovation, particularly in regulated industries where compliance requirements limit experimentation. However, the structured approach provided by ISO 56001 challenges this perception by embedding innovation within controlled, risk-informed processes.

One of the key implications is the shift from reactive to anticipatory safety management. By incorporating innovation processes into hazard identification and risk assessment, organizations can proactively address emerging risks, including those associated with technological change, climate variability, and complex system interactions. This anticipatory capability is particularly relevant in environmental and emergency safety domains, where uncertainty and rapid change are defining characteristics.

Another important dimension is cross-domain integration. The analysis demonstrates that innovation processes can serve as a unifying mechanism across occupational, fire, environmental, and emergency safety domains. For instance, digital technologies such as IoT-based monitoring systems can simultaneously enhance workplace safety, detect fire risks, and monitor environmental parameters. Such integrated solutions not only improve efficiency but also reduce redundancies, potentially lowering operational costs by 10–15%.

The role of organizational culture is also critical. The successful integration of ISO 56001 into safety frameworks requires a culture that supports experimentation, learning, and knowledge sharing. This represents a significant shift from traditional safety cultures, which often prioritize control and risk avoidance. Balancing these perspectives requires careful management, including the establishment of clear governance structures and risk thresholds.

Despite its potential, the integration of innovation and safety also presents challenges. These include resource constraints, resistance to change, and the complexity of aligning multiple management systems. Additionally, the lack of standardized metrics for innovation in safety contexts complicates performance evaluation. Addressing these challenges will require further research and the development of practical implementation guidelines.

CONCLUSION

This study demonstrates that ISO 56001 provides a robust framework for embedding innovation into multidimensional safety systems. The high degree of alignment with existing standards such as ISO 45001, ISO 14001, and ISO 9001 creates a unique opportunity for organizations to transition from fragmented safety practices to integrated, innovation-driven approaches.

The integration of innovation into safety domains enhances organizational resilience by enabling adaptive responses to complex and evolving risks. Quantitatively, the potential benefits include significant reductions in incident rates, improved efficiency, and increased capacity for continuous improvement. More importantly, the integration fosters a shift in organizational mindset, positioning safety not as a constraint but as a driver of innovation.

Future research should focus on empirical validation of the proposed integration model, including case studies and quantitative assessments of performance outcomes. Policymakers and standardization bodies also have a role to play in promoting alignment between innovation and safety standards, ensuring that regulatory frameworks support rather than hinder innovation.

In conclusion, the convergence of innovation management and safety systems represents a critical frontier in organizational development. By leveraging the principles and requirements of ISO 56001, organizations can build safer, more resilient, and more adaptive systems capable of addressing the challenges of an increasingly complex world.

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- ISO 56001:2024 Innovation management system - Requirements
- ISO 56002, Innovation management - Innovation management system - Guidance
- ISO 56003, Innovation management - Tools and methods for innovation partnership - Guidance
- ISO/TR 56004, Innovation Management Assessment - Guidance
- ISO 56005, Innovation management - Tools and methods for intellectual property management - Guidance
- ISO 56006, Innovation management - Tools and methods for strategic intelligence management - Guidance
- ISO 56007, Innovation management - Tools and methods for managing opportunities and ideas - Guidance
- ISO 56008, Innovation management - Tools and methods for innovation operation measurements - Guidance
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Dejan Angelovski, Marija Hadzi-Nikolova

PERSONAL EXPOSURE TO CARBON MONOXIDE AMONG OUTDOOR WORKERS IN TRAFFIC-INTENSIVE AREAS

Abstract
Rapid growth of industrialization, modern lifestyles, continuous technological advancement, and the widespread implementation of intensive and modern production systems intended to meet the demands of a rapidly growing population inevitably contribute to the deterioration of environmental quality, particularly ambient air. The principal air pollutants include suspended particulate matter (PM2.5 and PM10), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2), which also serve as key indicators for the assessment of ambient air quality. This paper reports the findings of a one-year study investigating occupational exposure to gaseous air pollutants in outdoor urban environments. Within the framework of the study, personal exposure measurements of CO, NO_2, and SO_2 were conducted among a group of six workers whose professional activities are performed outdoors, in close proximity to high-traffic roadways and within residential areas. The results demonstrated that carbon monoxide represented the pollutant associated with the highest level of personal exposure among the surveyed workers.

Key words: gases, trrafic, polluted air, carbon monoxide, health.

INTRODUCTION

Every generation seeks to secure a dignified quality of life, characterized by stable employment, sufficient income, and reliable public services, while simultaneously striving to create improved living conditions for future generations. Parents, in particular, recognize and willingly accept personal sacrifices aimed at ensuring the well-being and prosperity of their children and families.
Nevertheless, environmental degradation—manifested through smoke, smog, limited visibility, unpleasant odors, and airborne dust—has increasingly become a part of everyday life. These conditions are evident through their tangible consequences, including eye irritation, sore throats, breathing difficulties, the absence of children from outdoor playgrounds, dark and damp road surfaces, fogged vehicle windows and public transport interiors, and a rising prevalence of respiratory illnesses, allergies, cardiovascular diseases, and strokes.
These environmental challenges intensify during the autumn and winter seasons, when the population is exposed to harmful air pollutants for nearly 200 days annually. Such prolonged exposure poses significant risks to human health and contributes to the degradation of surrounding ecosystems, including both flora and fauna. According to an analysis conducted by the World Bank Office in North Macedonia, air pollution has severe public health consequences, with statistical estimates indicating that one death occurs approximately every six and a half hours as a result of polluted air. This corresponds to nearly four deaths per day, or around 1,350 deaths annually. In addition to the human cost, the economic burden is substantial, with estimated losses reaching approximately 253 million euros each year.
While these effects are experienced by the general population—who typically spend limited time outdoors—there is reason to consider the significantly greater exposure faced by individuals whose professional responsibilities require them to work outside for extended periods. This raises important questions regarding the health impacts of pollutants, particularly carbon monoxide (CO), on workers such as employees in the electrical sector, kiosk vendors, shop workers located along high-traffic roads, police officers, taxi drivers, professional public transport drivers, and municipal utility workers.

METHODS

In the preparation of this paper, the methods of synthesis and data collection were initially applied, followed by data analysis, data processing, and the comparative method, involving the comparison of the obtained values.

The sequence of activities undertaken in the implementation of the materials necessary for the preparation of this paper is as follows:

- Identification of zones, locations, and roadways characterized by consistently high vehicle frequency throughout most of the day, and definition of measurement sites where CO monitoring would be conducted;
- Measurement of CO in accordance with the standards and methods specified in the referenced literature;
- Collection of data from measurements performed at several monitoring sites;
- Gathering of additional information (domestic and international literature);
- Analysis of the obtained results and formulation of conclusions;
- Assessment of exposure and determination of the level of risk;
- Comparison of the obtained results and derivation of conclusions;
- Planning of preventive and/or corrective measures aimed at eliminating or reducing risk, as well as measures to improve working conditions;
- Drawing final conclusions based on the conducted research.

To determine the presence of the targeted pollutant and assess its concentration in specific urban locations, monitoring activities were conducted at selected measurement points (zones) within the territory of the City of Skopje.

Data collection was performed over a one-month period, during 2025, in the municipalities of Kisela Voda and Aerodrom. At each monitoring location, measurements were carried out over five consecutive days.

Special care was taken to ensure that measurements were performed under stable meteorological conditions—specifically during dry weather, without precipitation and in the absence of strong air currents—in order to minimize the potential influence of humidity and wind on the measurement outcomes.

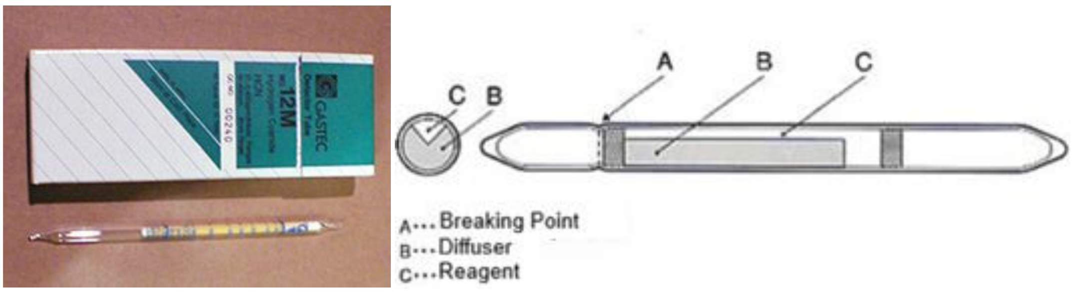
The monitoring process involved the use of passive dosi-tubes (Figure 1) worn by employees and positioned on the upper chest area for personal exposure on CO. The study sample consisted of workers employed in different companies, representing a variety of job positions and work tasks.

Two participants were salespersons working in grocery stores that sell food products, fruits, and vegetables and are located along heavily trafficked roads. These employees worked during the first shift, and exposure measurements were conducted over an 8-hour period (7:30 a.m. to 3:30 p.m.).

Additionally, four employees from the electrical industry were included in the study. Their duties were primarily performed outdoors, either along busy streets or within residential areas. One employee worked during the first shift with an 8-hour monitoring period (7:30 a.m. to 3:30 p.m.), while three employees worked second shift, during which measurements were conducted over a 7-hour period (3:00 p.m. to 10:00 p.m.).

All measurements were carried out using passive dosi-tubes of the glass ampoule type.

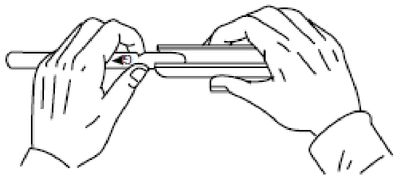
Figure 1. Passive Dosi-Tube



Source: https://www.gastec.co.jp/files/user/asset/pdf/en/instructionmanual/en/1DL.pdf

The method of using these passive dosi-tubes is relatively simple. By breaking off one of the marked ends of the dosi-tube, contaminated air is allowed to enter the tube, thereby causing a color change in the substance contained within it.

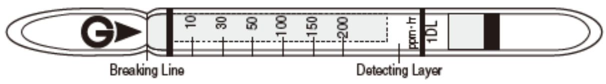
Figure 2. Breaking of the Marked End



Source: https://www.gastec.co.jp/files/user/asset/pdf/en/instructionmanual/en/1DL.pdf

The results are read according to the scale printed directly on the tube (dosimeter), based on the length of the colored portion of the reagent.
The measurement duration follows a previously established schedule. In order the measurement to be considered valid, certain preconditions must be met, including temperature (0–40°C), humidity (0–90%), proper storage conditions, expiration date, intensity of sunlight, and other relevant factors.
Figure 3 illustrates the technical characteristics and measurement range of the personal dosi tube applied for personal exposure monitoring on carbon monoxide (CO) concentrations.

Figure 3. Carbon monoxide passive dosi-tube



This tube measures TWA (time-weighted average) gas concentration by utilizing natural diffusion of the target gas without a gas sampling pump

Measuring Range	0.4 – 400 ppm
Sampling Hours	0.5 – 24 hours
Detecting Limit	0.2 ppm (24 hours)
Colour Change	Pale Yellow → Brown
Reaction Principle	$CO + Na_2Pd(SO_3)_2 \rightarrow Pd + CO_2 + SO_2 + Na_2SO_3$

Source: https://www.gastec.co.jp/files/user/asset/pdf/en/instructionmanual/en/1DL.pdf

RESULTS

To ensure more accurate and representative results regarding employees' exposure to air pollutants, and taking into account the characteristics of their work activities, measurements were performed in the municipalities of Kisela Voda and Aerodrom.
Measurement point 1(MP1) was situated within Monitoring Region 1 on Boris Trajkovski Boulevard. Measurements were carried out over five working days during an 8-hour period (7:30 a.m.–3:30 p.m.). Meteorological conditions during the monitoring period were stable, with no precipitation and no increased humidity (Table 1).

Table 1. Measured values of CO concentration on MP1

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	35	4,40	30
2	11	60	7,50	30
3	6	45	5,60	30
4	8	50	6,25	30
5	9	50	6,25	30

Measurement point 2 (MP2) was located in Monitoring Region 1 on Dimo Hadzhi Dimov Street. Measurements were performed over five working days during an 8-hour period (7:30 a.m.–3:30 p.m.). Meteorological conditions during the monitoring period were stable, with no precipitation and no increased humidity.

Table 2. Measured values of CO concentration on MP2

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	35	4,40	30
2	11	70	7,50	30
3	6	60	5,60	30
4	8	45	6,25	30
5	9	45	6,25	30

Measurement point 3 (MP3) was situated in Monitoring Region 2 and encompassed part of the municipality of Aerodrom, including the neighborhoods of Aerodrom, Jane Sandanski, and Novo Lisiče. Measurements were conducted over five working days during an 8-hour period (7:30 a.m.–3:30 p.m.). Weather conditions during the monitoring period were stable, with no precipitation and no increased humidity (Table 3).

Table 3. Measured values of CO concentration on MP3

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	45	5,65	30
2	11	55	6,90	30
3	6	50	6,25	30
4	8	60	7,50	30
5	9	45	5,65	30

Measurement point 4 (MP4) was situated in Monitoring Region 2 and included part of the municipality of Aerodrom, specifically the neighborhoods of Novo Lisiče and Lisiče, as well as the village of Gorno Lisiče. Measurements were conducted over five working days during the second shift, from 3:00 p.m. to 10:00 p.m. (7 hours). Meteorological conditions during the monitoring period were stable, with no precipitation and no elevated humidity (Table 4).

Table 4. Measured values of CO concentration on MP4

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	100	14,30	30
2	11	60	8,60	30
3	6	70	10,00	30
4	8	70	10,00	30
5	9	75	10,70	30

Measurement point 5 (MP5) was located across Monitoring Regions 1 and 2 and encompassed parts of the municipalities of Aerodrom and Kisela Voda. The monitored area included the neighborhoods of Lisiče and the village of Gorno Lisiče within Monitoring Region 2, as well as the neighborhoods of Usje and 11 Oktomvri within Monitoring Region 1. Measurements were carried out over five working days during the second shift, from 3:00 p.m. to 10:00 p.m. (7 hours). Weather conditions during the monitoring period were stable, with no precipitation and no elevated humidity (Table 5).

Table 5. Measured values of CO concentration on MP5

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	55	7,60	30
2	11	65	9,30	30
3	6	60	8,60	30
4	8	75	10,70	30
5	9	80	11,75	30

Measurement point 6 (MP6) is located in Monitoring Region 1 and covers part of the Kisela Voda municipality (the neighborhood of Dračevo and the village of Dračevo). Measurements were conducted over 5 working days during the second shift, from 3:00 p.m. to 10:00 p.m. (7 hours). Weather conditions during the monitoring period were stable, with no precipitation and no elevated humidity (Table 6).

Table 6. Measured values of CO concentration on MP6

No.	Temperature [°]	Measured value [ppm]	1 hour exposure [ppm]	Limit value [ppm]
1	10	60	9,00	30
2	11	50	7,15	30
3	6	80	11,45	30
4	8	65	9,30	30
5	9	65	9,30	30

DISCUSSION

The focus of this study is the assessment of personal exposure to carbon monoxide (CO) among employees whose work activities are performed outdoors and in close proximity to road traffic. During the preparation of this research, no relevant national scientific studies, analyses, or publications addressing this specific issue were identified. The only available sources were journalistic reports published mainly during the winter period, which generally discussed air pollution in a broad and descriptive manner, without detailed analytical evaluation.

In North Macedonia, air pollution and air quality issues are addressed within two primary frameworks: the environmental domain, which concerns ambient air quality, and the occupational health and safety (OHS) domain, which focuses on the workplace environment. Both areas are regulated through legal and subordinate legislation that establishes specific exposure limit values. Within the environmental framework, the primary concern is the general population living and working within a particular environment. In contrast, the occupational health and safety framework focuses on employees who perform work tasks within defined workplaces and working environments.

The maximum permissible concentration of carbon monoxide in ambient air (Table 7) is defined by the Regulation on Limit Values for Levels and Types of Pollutants in Ambient Air, Alert Thresholds, Deadlines for Achieving Limit Values, Tolerance Margins, Target Values, and Long-Term Objectives (Official Gazette of the Republic of Macedonia No. 50/05, 04/13, and 183/17) (hereinafter referred to as the "Regulation"). In comparison, the maximum permissible exposure concentration of carbon monoxide in the workplace (Table 8) is prescribed by the Rulebook on Minimum Occupational Health and Safety Requirements for Employees Exposed to Chemical Substances (Official Gazette of the Republic of Macedonia No. 46/2010) (hereinafter referred to as the "Rulebook").

Table 7. Limit Values of Pollutants in Ambient Air

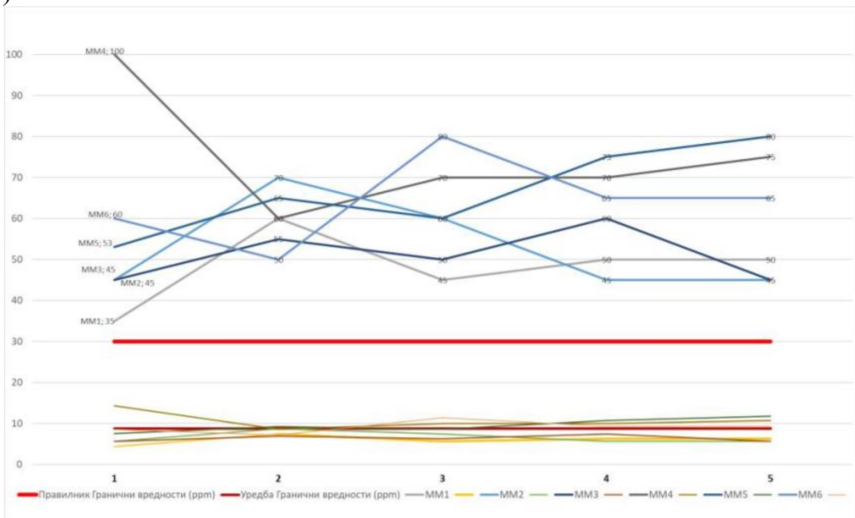
Pollutants	Averaging period	Limit values	Permissible number of exceedances per year
PM_{10}	24 hours 1 year	50 μg/m^3 40 μg/m^3	35 /
$PM_{2,5}$	1 year	25 μg/m^3 20 μg/m^3	/
CO	Maximum daily 8-hour average	10 mg/m^3	/

Table 8. List of Occupational Exposure Limit Values

No	Substance	CAS No.	EC No.	Classification				Limit values		KTV	Op
				R	M	RF	RE	mg/m^3	ppm		
479	Carbon monoxide	630-08-0	211-128-3				1	35	30	2	BAT

Based on the considerations outlined above, a key question arises regarding the legal framework and focus of the discussion, specifically which target group the results should address - the employee (working environment) or the general citizen (living environment). To ensure clarity and provide the most comprehensive assessment, CO exposure for both groups will be analyzed in order to derive the most realistic conclusions possible.

The measurements and results obtained indicate that personal CO exposure among employees varies according to both location and period of day during the performance of work tasks. Nevertheless, throughout the entire measurement period, exposure levels consistently exceeded the occupational limit value of 30 ppm as defined in the Rulebook. From the perspective of the environmental Regulation, personal CO exposure fluctuated depending on the measurement point and period of day, alternating above and below the maximum permissible daily 8-hour average of 10 mg/m³ (equivalent to 8.732564 ppm) (Graph 1).



Graph 1. Graphical Review of CO Exposure compared to the Rulebook and Regulation

Given that the employee conducts work activities in an outdoor environment, which is defined by the Law on Occupational Safety and Health (Official Gazette of the Republic of Macedonia, consolidated text 53/13) as “a space in which work is performed, encompassing the workplace, working conditions, work processes, social interactions, and other external environmental influences,” the results can be summarized as follows:

Results from MP1 and MP2, located along busy roadways with high vehicle frequency throughout the day, indicate that local residents live in residential buildings connected to central heating, and there are no industrial facilities emitting CO nearby. CO exposure for employees at these sites consistently exceeded the 8-hour exposure limit (<30 ppm), with some days showing levels two or more times higher (60–70 ppm).

Results from MP3, located in an urban area with heavy traffic on main roads and residential buildings with central heating, also indicate CO concentrations above the limit, though slightly lower than MP1 and MP2, ranging from 45 to 60 ppm for 8-hour exposure.

Results from MP4, MP5, and MP6, located in urban areas with heavy traffic, without nearby industrial CO sources, and with a significant portion of local residents using wood and oil derivatives for heating in individual homes, showed CO concentrations up to three times the limit (50–100 ppm for 7-hour exposure).

Analysis according to the Regulation indicates that CO concentrations at these points, depending on location, varied above or below the maximum daily 8-hour average limit (>8.732564 ppm). MP1, MP2, and MP3 remained below the limit (maximum measured: 8.75 ppm), while MP4, MP5, and MP6 exceeded the limit on certain days (measured: 9.30–14.30 ppm).

An analysis of the results according to the period of day (morning, afternoon, and evening) indicates that CO concentrations are generally higher at the monitored locations during the afternoon and evening periods compared to the morning hours. This pattern suggests that, in addition to traffic emissions, domestic heating practices may also contribute to increased CO concentrations.

Furthermore, the manner in which work tasks are performed contributes significantly to CO inhaled levels. Although measured CO concentrations at MP1, MP2, and MP3 are lower than those measured at MP4, MP5, and MP6, the greater physical activity observed at MP1–MP3 reflected in increased respiratory rate and a higher number of inhalations per minute—may result in comparable or even greater CO uptake compared with workers at sites where measured concentrations are higher but physical exertion is lower.

CONCLUSION

Based on the obtained results and analyses, it can be concluded that, in most cases, personal CO exposure of the target group "employees" performing outdoor tasks near roadways is consistent. This exposure persists not only during working hours but also after the completion of tasks and returning home, impacting the target group "persons (citizens)."
Regarding exposure to harmful CO effects and their limit values, it follows that: **Employee ≠ Person (Citizen)**
This distinction is grounded in current legislation, which defines different limit values and approaches for different environments. These varying limits would be acceptable if the concepts and definitions were clearly and explicitly specified. For employees working in a workplace environment, the CO exposure limit is 30 ppm. For citizens in the general environment, the limit is 10 mg/m³ (8.732564 ppm), which is significantly lower than 30 ppm. This raises several important questions:
Is the work environment of employees performing tasks outdoors, in certain cases, effectively identical to the living environment?
Are these employees, under the occupational exposure limits, subjected to higher health risks during work than the general population (citizens)?

Since occupational safety and health is a constitutional right, recognized as a fundamental economic, social, cultural, and humanitarian human right (Article 32, paragraph 1, Constitution of the Republic of North Macedonia), protection measures of employees from harmful air pollutants should not be limited to employer-level actions. Rather, they should also include national-level initiatives according to the National Plan and Program for improving ambient air quality. Employer-level measures under OSH for employees working outdoors are limited to reducing exposure time—i.e., shortening the duration spent outdoors—and providing education on the harmful effects of these pollutants. However, the key question arises: does reducing outdoor work hours effectively protect employees' health when pollutant exposure is constant both at work and at home?

Measures to reduce or eliminate harmful substances in the workplace can only be effective if the workplace is enclosed and controlled. For outdoor workplaces, it is virtually impossible for employers to fully protect their employees' health. Any employer effort to mitigate the negative effects in such situations is largely symbolic, as this is a global problem that requires systemic solutions, prior measures, and substantial investments. In this context, the primary responsibility for addressing the problem lies with the state.

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RISK MANAGEMENT AND INNOVATIONS IN GROUNDWATER PROTECTION AT A WASTE LANDFILL

Abstract
The protection of groundwater represents one of the key safety and environmental challenges in landfill management. This study analyzes the role of innovations in monitoring groundwater quality, using the "Goričica" non-hazardous waste landfill, located near the city of Sisak in Croatia, as a case study. Groundwater quality is regularly monitored, with physicochemical indicators being analyzed. The application of innovative approaches allows precise trend tracking and timely identification of potential environmental risks, thereby supporting sustainable and efficient landfill management. The aim of this research is to demonstrate how an innovative approach contributes to the preservation of groundwater and the effective management of environmental and safety risks.

Key words: groundwater, environmental risks, innovation management, landfill.

INTRODUCTION

Groundwater protection is one of the important elements of environmental protection within the waste management system. Groundwater is a particularly sensitive component of the environment because deterioration of its quality can have long-term consequences for ecosystems and the usability of water resources. For this reason, at sites where waste is permanently disposed of, special attention is given to pollution prevention and continuous environmental monitoring [1]. Waste landfills, even when they are designed as sanitary landfills and equipped with protective systems, require constant supervision. The sanitary design of a landfill is based on the application of technical and organizational measures intended to ensure a high level of environmental protection during operation and after site closure. In this context, protective sealing layers, leachate collection and control systems, cover systems, and environmental monitoring play an important role, which together enable the safe and controlled functioning of the landfill [2].
Groundwater quality is therefore considered one of the most important indicators of environmental conditions in the vicinity of a landfill because it provides insight into the effectiveness of the applied protective measures and enables long-term monitoring of site conditions [3].

The particular importance of groundwater monitoring arises from the fact that the obtained results do not reflect only the current condition, but may also indicate certain patterns of change over time. For this reason, their interpretation should not remain limited only to comparison with prescribed limit values [4]. Although such an approach is necessary, it is not always sufficient for a complete understanding of site conditions. Changes in the values of individual indicators should also be considered in relation to the spatial distribution of monitoring locations, site characteristics, and possible influences from the wider surroundings. This is especially important at locations where other potential sources of environmental burden are present nearby. Under such circumstances, any change in groundwater quality should be interpreted cautiously, without prematurely attributing it exclusively to landfill operations [5].

The "Goričica" non-hazardous waste landfill represents a suitable example for such an analysis because groundwater at this site is systematically monitored, and the obtained results provide not only insight into environmental conditions, but also a broader basis for considering the role of monitoring in environmental protection and groundwater preservation.

The innovative aspect of this paper lies in the fact that groundwater monitoring results are considered more broadly than their usual descriptive value alone. The aim of the research was to emphasize how such an approach can further contribute to groundwater preservation and confirm the importance of continuous monitoring at a landfill site.

METHODS

The research was conducted at the "Goričica" non-hazardous waste landfill, located near the city of Sisak. Groundwater monitoring was carried out through three piezometers. Piezometer P-1 is located upstream of the landfill body, while piezometers P-2 and P-3 are positioned downstream, in the direction of the dominant groundwater flow [6].

Figure 1 shows piezometer P-1 at the "Goričica" landfill.

Figure 1. Piezometer P-1 at the "Goričica" landfill [7]

The paper analyzes sampling results from the period between 2018 and 2024. Sampling was carried out four times per year, in March, June, September, and December. During each sampling event, groundwater samples were collected from all three piezometers, while groundwater level measurements and visual assessment of the samples were performed simultaneously. The analysis included nine physicochemical indicators: ammonium, sulfates, nitrates, phosphates, chlorides, lead, mercury, cadmium, and arsenic [8].

The obtained results were compared with the maximum allowable concentration (MAC) prescribed by the Environmental Protection Requirements Decision and the Water Quality Standards Regulation [9, 10]. The data processing included an analysis of values by indicator, piezometer, year, and sampling month, together with comparison with the prescribed limit values. In addition, the frequency of deviations, their temporal distribution, and their spatial distribution across the piezometers were analyzed.

In interpreting the results, technical circumstances that could have affected data comparability were also taken into account. Piezometer P-3 was replaced in February 2020, while piezometer P-2 became clogged in December 2021, making further sampling at that location impossible. In June 2023, all three piezometers were replaced [7]. The possible influence of changed hydrodynamic conditions following the December 2020 earthquake was also considered [11]. The broader environmental context of the site was also taken into account during result interpretation. Since agricultural land is located in the immediate vicinity of the landfill (Figure 2), the possibility of external influences on certain groundwater quality indicators was also considered.

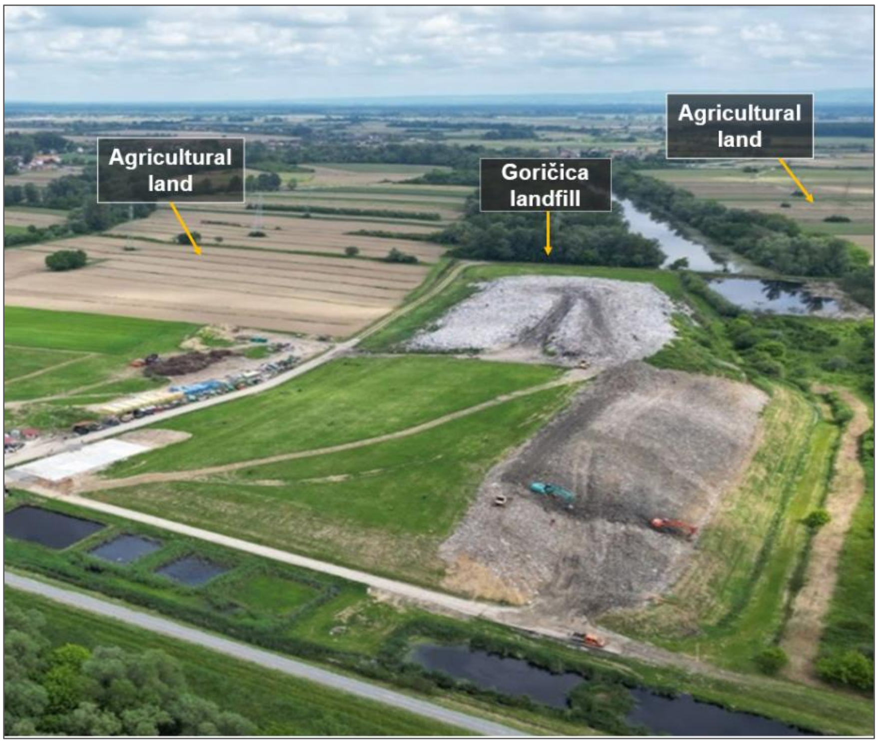

Figure 2. Non-hazardous waste landfill "Goričica"

The monitoring results were not viewed solely as an indicator of compliance with prescribed values, but also as a basis for tracking trends, identifying indicators relevant to the assessment of possible changes, and achieving a more comprehensive understanding of groundwater quality at the site.

RESULTS AND DISCUSSION

Table 1 presents a summary overview of the number of valid measurements and the proportion of results within and above the maximum allowable concentration (MAC) in the period from 2018 to 2024.

Table 1. Summary of valid measurements and compliance with MAC

Parameter	MAC	Number of valid measurements	Compliant results	Results exceeding the MAC	Compliant results (%)	Results exceeding the MAC (%)
Ammonium	0.5 mg/l	74	48	26	64.9	35.1
Sulphates	250 mg/l	74	74	0	100.0	0.0
Nitrates	50 mg/l	74	73	1	98.6	1.4
Phosphates	0.2 mg/l	74	63	11	85.1	14.9
Chlorides	250 mg/l	74	74	0	100.0	0.0
Lead	10 µg/l	74	74	0	100.0	0.0
Mercury	1 µg/l	74	68	6	91.9	8.1
Cadmium	5 µg/l	74	74	0	100.0	0.0

Arsenic	10 µg/l	74	72	2	97.3	2.7
Total		***666***	***620***	***46***	***93.1***	***6.9***

It is evident from Table 1 that the majority of results obtained between 2018 and 2024 were within the MAC prescribed by the Decision on Integrated Environmental Protection Requirements [9].

Out of a total of 666 valid measurements, 620 results, or 93.1%, were compliant with the MAC, while 46 results, or 6.9%, exceeded the allowable limits. This indicates that deviations were not the dominant pattern in groundwater quality monitoring, but were limited to a smaller portion of the entire dataset.

The highest number of deviations was recorded for ammonium ions, for which 35.1% of the results were above the MAC of 0.5 mg/L [9]. They were followed by phosphate ions, for which 14.9% of the results exceeded the MAC of 0.2 mg/L, and mercury, for which 8.1% of the results were above the MAC of 1 µg/L. In the case of arsenic, two exceedances were recorded, corresponding to 2.7% of the results above the MAC of 10 µg/L, while for nitrate ions only one exceedance was recorded, representing 1.4% of the results above the MAC of 50 mg/L [9].

In contrast, sulfate and chloride ions, as well as cadmium and lead, showed no exceedances during the entire observed period (MAC: SO_4^{2-} = 250 mg/L, Cl^- = 250 mg/L, Cd = 5 µg/L, Pb = 10 µg/L) [9].

At the same time, the fact that no exceedances were identified for most of the other indicators, and that the majority of results overall remained within the MAC, indicates that this was not a case of general and permanent deterioration of groundwater quality. The obtained results indicate occasional deviations in individual indicators, which should be interpreted cautiously and in relation to the spatial position of the piezometers and the broader environmental context of the "Goričica" landfill site.

Figures 3 and 4 show the annual proportions of ammonium and phosphate ion results in relation to the MAC in the period 2018–2024.

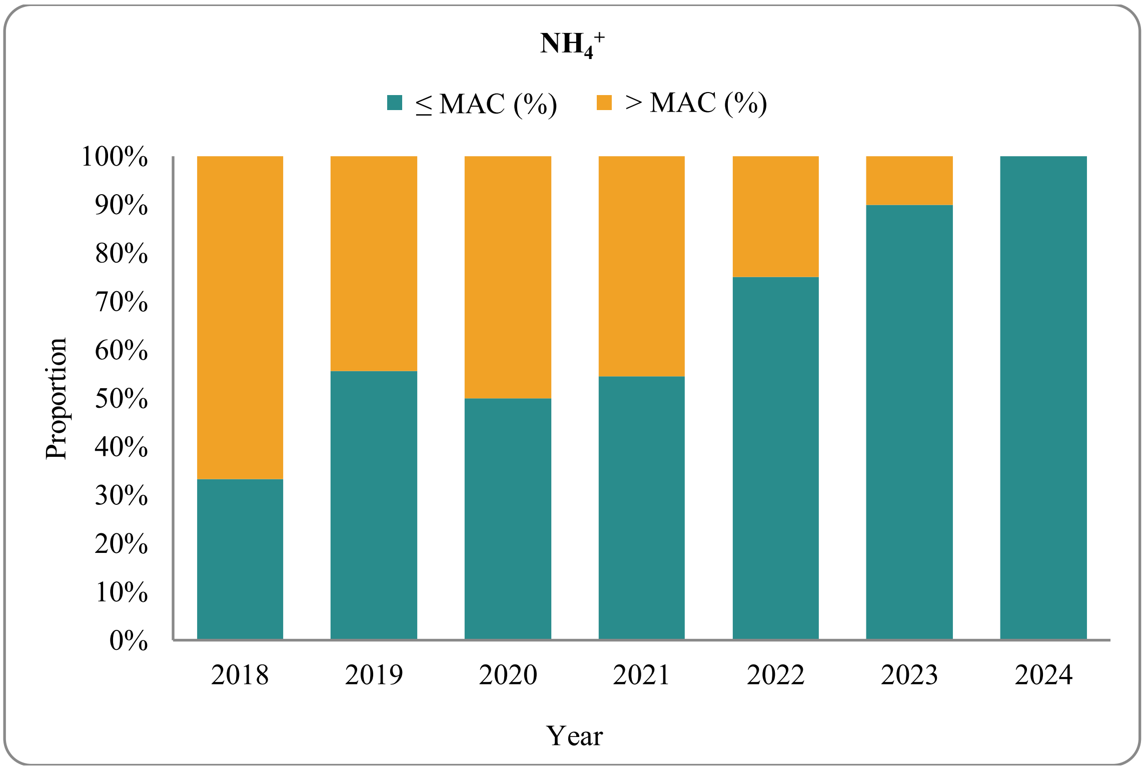

Figure 3. Annual proportions of ammonium ion results relative to the MAC during the period 2018–2024.

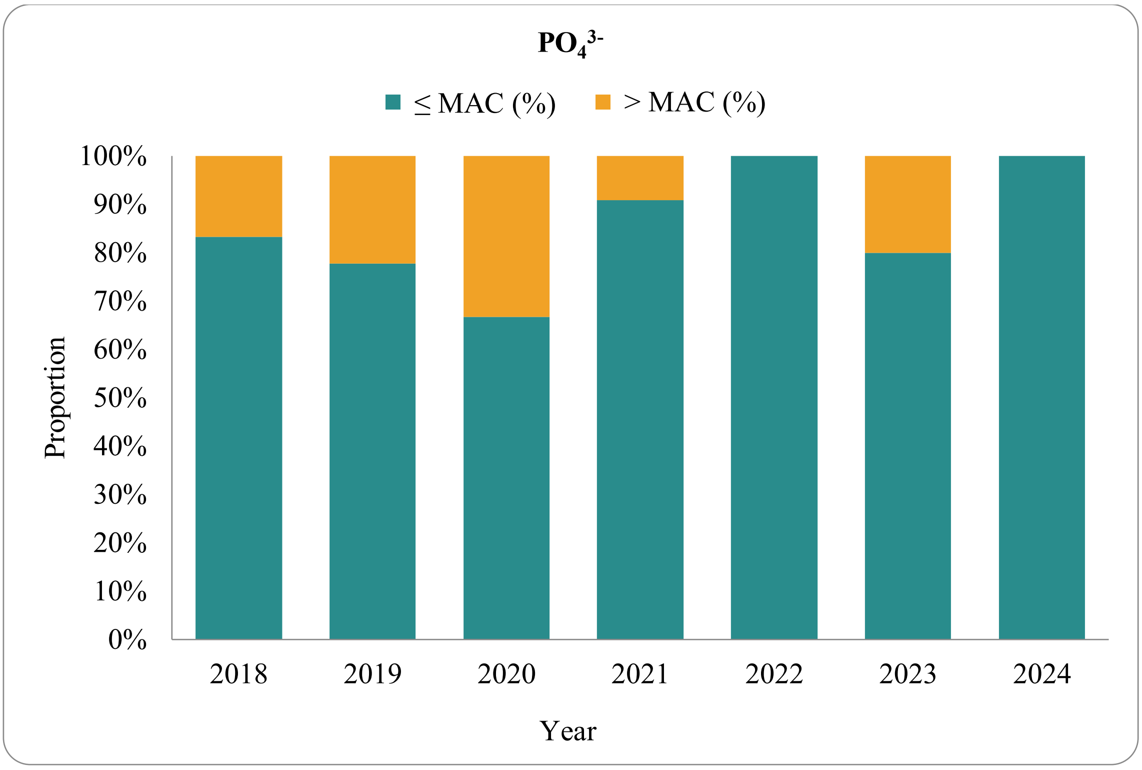

Figure 4. Annual proportions of phosphate ion results relative to the MAC during the period 2018–2024.

Figure 3 shows that ammonium ions had the highest proportion of results above the MAC of 0.5 mg/L [9] at the beginning of the observed period. In 2018, the proportion of results above the MAC was 66.7%, which was also the highest value in the entire analyzed period, while in 2020 it was 50.0%. After that, a decline can be observed, and in 2024 no exceedances were recorded. This distribution indicates that elevated ammonium ion concentrations were not permanently present, but occurred occasionally and with varying intensity. According to available studies [12], ammonium ions may be retained to a greater extent in soil and groundwater under conditions of poor aeration and slowed nitrification, especially in clayey and low-permeability layers. Such conditions are also present at the "Goričica" landfill site, where clayey horizons predominate beneath the piezometers [13]. Since agricultural land is located in the vicinity of the landfill, where crops requiring nitrogen fertilizers are cultivated, occasional exceedances may also be associated with the leaching of nitrogen compounds from the soil, particularly after fertilization and during periods of altered hydrological conditions.

Figure 4 shows that exceedances of phosphate ions were less frequent and less pronounced than those of ammonium ions, but they also exhibited clear temporal variability. The highest proportion of results above the MAC of 0.2 mg/L [9] was recorded in 2020 and amounted to 33.3%, while in 2022 and 2024 all results were within the allowable values. This distribution indicates that phosphate ions were also not characterized by permanently elevated concentrations, but rather by occasional deviations. Phosphate ions generally have low mobility in soil because they bind to clay and to iron and aluminum hydroxides [14]. This is also important for the "Goričica" landfill site, since the lithological composition in the piezometer area includes clayey and silty-clayey layers [13], which favor the retention and occasional release of phosphate ions. Therefore, their occurrence in groundwater may be associated with specific local conditions, seasonal fertilization, and occasional leaching from the surface soil layer.

The results shown in Figures 3 and 4 confirm that ammonium and phosphate ions are of greater importance for the interpretation of monitoring results than the other analyzed indicators. At the same time, since exceedances were neither permanently present nor equally pronounced in all years, the obtained results should be regarded as occasional deviations requiring careful and comprehensive interpretation. To interpret the significance of the identified deviations, it was not sufficient to observe only their temporal occurrence, but also their spatial distribution across the piezometers.

Figure 5 shows the cumulative proportion of ammonium and phosphate ion results in relation to the MAC at piezometers P-1, P-2, and P-3 in the period 2018–2024.

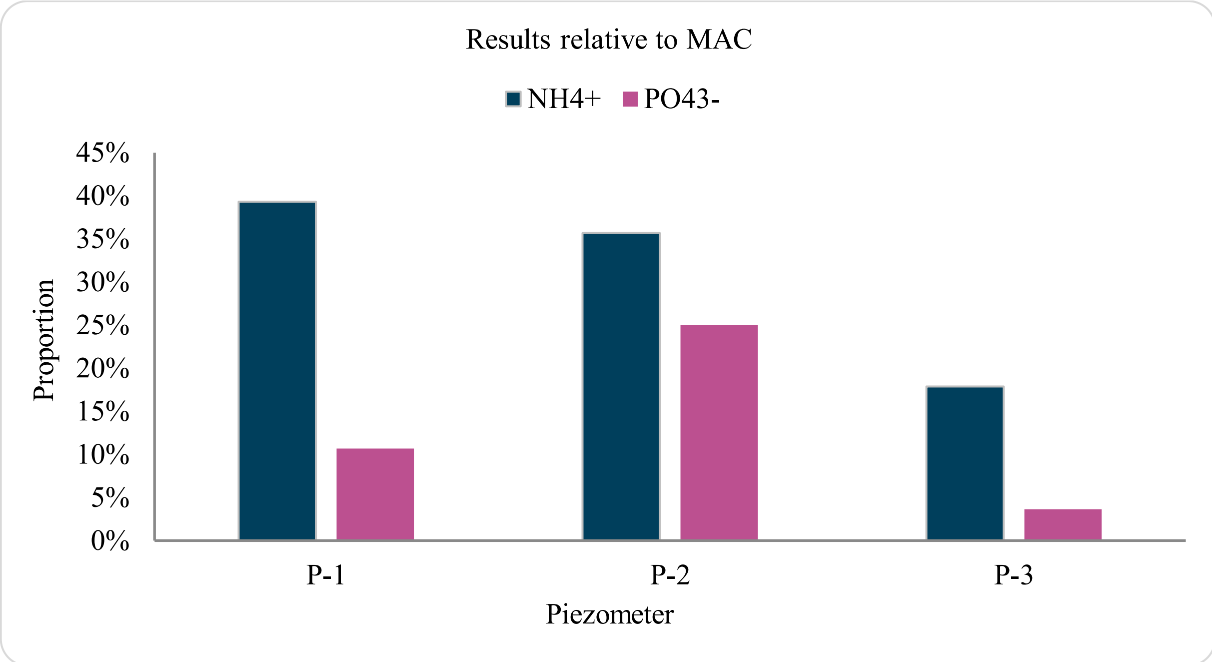

Figure 5. Cumulative proportions of ammonium and phosphate ion results relative to the MAC at piezometers P-1, P-2, and P-3 during the period 2018–2024.

Figure 5 shows that, for ammonium ions, the highest proportions of results in relation to the MAC were recorded at piezometers P-1 and P-2, amounting to 39.3% and 35.7%, respectively, while at piezometer P-3 their proportion was lower, 17.9%. For phosphate ions, the highest proportion of results in relation to the MAC was recorded at piezometer P-2 and was 25.0%, while at piezometer P-1 it was 10.7% and at piezometer P-3 it was 3.6%. This distribution indicates that the spatial distribution of deviations was not the same for both indicators and that their significance must be assessed in relation to the position of each piezometer and the direction of groundwater flow. It is particularly important that elevated proportions for ammonium ions were also recorded at the upstream piezometer P-1. This indicates that the identified deviations cannot automatically be attributed exclusively to landfill operations, since certain pressures may already be present in the groundwater flowing toward the site.

In contrast, the highest proportion of phosphate ions was recorded at piezometer P-2, that is, at the first downstream monitoring location, while lower values were observed at piezometers P-1 and P-3. This relationship indicates the need for cautious interpretation, since the spatial distribution of deviations is clearly not the same for all indicators.

In addition to the position of the piezometers in relation to the landfill body, the distribution of results may also be influenced by other local factors, including the hydrogeological characteristics of the site, seasonal hydrological oscillations, and the way the surrounding land is used [15, 16]. Since agricultural land, predominantly arable land, has been identified in the immediate surroundings of the Goričica site, the identified deviations should not be interpreted solely through individual measured values or only in relation to the MAC, but also within a broader spatial and hydrogeological context.

The innovative nature of this approach is reflected in the fact that groundwater monitoring is not used only as a means of checking compliance with prescribed values, but also as an interpretive tool for understanding spatial and temporal relationships and for the expert assessment of the significance of the identified deviations. Such an approach implies a broader consideration of the environmental context, in which monitoring results are interpreted in relation to the characteristics of the surrounding area, such as the presence and use of arable agricultural land near the landfill, which may represent a source of additional pressures (e.g. fertilizers and pesticides). The interpretation also includes climatic conditions, such as the amount and distribution of precipitation, temperature, seasonal variations, and extreme weather events, all of which affect groundwater levels and the dynamics of substance transport in soil.

The key innovative value of this approach is further emphasized through the application of advanced methodologies that go beyond conventional data processing. The integration of hydrogeological measurements with data on land use, climatic patterns, and seasonal variations enables the development of multidimensional models that not only describe the existing condition, but also have a predictive function. The introduction of digital tools, automated data-processing systems, and the potential application of artificial intelligence and machine learning methods opens up the possibility of identifying hidden patterns and providing early warning of negative trends. In this way, monitoring evolves from a reactive into a proactive management system, capable of supporting timely data-based decision-making. The main innovation value of this approach lies in the integration of these different datasets. The application of modern analytical methods, digital tools, and interdisciplinary models makes it possible to connect hydrogeological data with land-use information and climatic patterns. As a result, monitoring develops from a static control system into a dynamic and predictive system that enables the timely identification of trends, the assessment of potential risks, and the implementation of proactive environmental management measures. Such an innovative interpretation of the data contributes to a more precise understanding of cause-and-effect relationships in space and provides a basis for the development of advanced and sustainable solutions for groundwater protection and environmental protection in a broader sense.

As a further step in improving result interpretation, a more systematic approach should be applied to the processing of data that deviate from expected values. Instead of automatically attributing individual deviations to the influence of the landfill, it is necessary to consider the possibility of measurement uncertainty or error, as well as the influence of other environmental factors. Based on the conducted research, it may be concluded that more detailed monitoring of parameters exceeding the MAC over a longer period of time would be useful, together with more frequent repetition of analyses in order to determine the persistence and trend of such deviations. At the same time, a broader interpretation should be applied, including all relevant natural and anthropogenic influences, with the aim of determining the actual cause of the observed changes.

This approach represents a step toward so-called “smart monitoring”, in which data are not only collected, but also actively interpreted in real time and used to optimize the environmental management system. In this way, a more reliable and scientifically grounded assessment of site conditions is ensured, further strengthening the quality and innovativeness of the monitoring system.

Figure 6 shows the innovative application of groundwater monitoring results at the “Goričica” landfill.

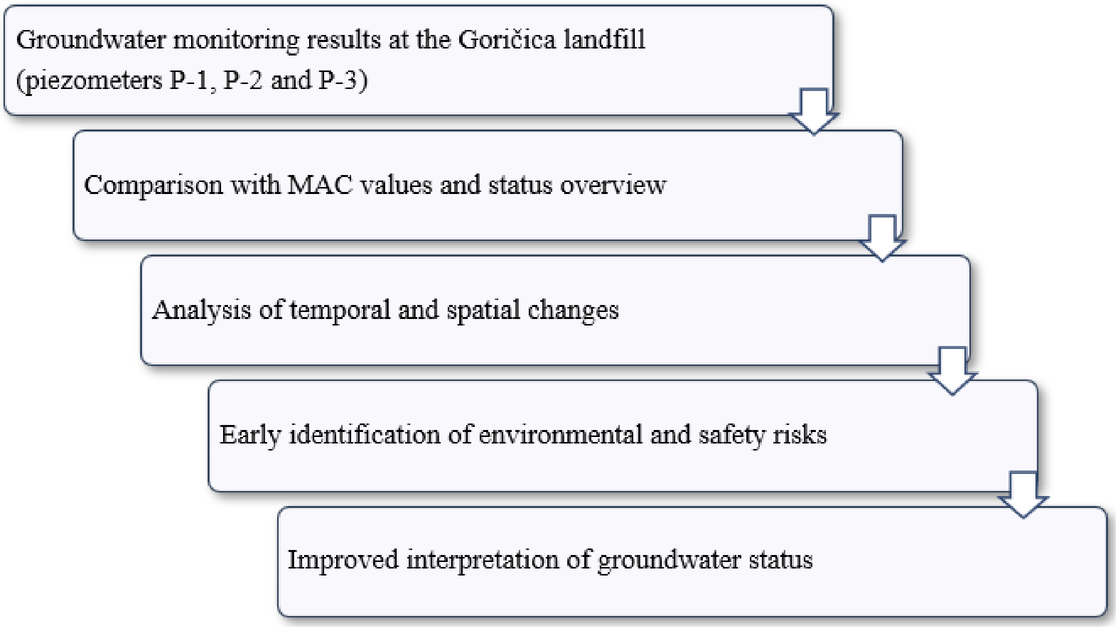

Figure 6. Innovative use of groundwater monitoring results at the „Goričica“ landfill

The results of monitoring the physicochemical indicators of groundwater quality obtained at piezometers P-1, P-2, and P-3 are used for comparison with the MAC and for the initial assessment of site conditions, but also for identifying patterns of change within the observed period and in their spatial distribution. This way of using the data enables more timely identification of possible environmental and safety risks and contributes to a more reliable understanding of groundwater quality, which provides an important basis for drawing conclusions about site conditions and the possible influence of different factors at the Goričica landfill.

CONCLUSION

The results of monitoring the physicochemical indicators of groundwater quality at the “Goričica” landfill site during the period from 2018 to 2024 showed that most of the analyzed indicators were within the MAC, confirming the predominantly stable state of groundwater quality at the observed site. Sulfates, chlorides, lead, and cadmium proved to be particularly stable, while ammonium and phosphates were identified as the indicators most relevant for detailed temporal and spatial interpretation. Mercury, arsenic, and nitrates showed only isolated deviations.

The analysis also showed that the recorded changes cannot be interpreted solely on the basis of comparison with prescribed values, nor can they be automatically attributed exclusively to landfill operations. Their significance must be considered in relation to the spatial and temporal distribution of results, the technical circumstances of monitoring, and the characteristics of the site itself.

An innovative approach to groundwater monitoring transforms monitoring data from a passive control mechanism into a dynamic and predictive system by integrating spatial context, climatic conditions, and anthropogenic influences. At the same time, more systematic monitoring of deviations provides a reliable basis for proactive and sustainable environmental management. In this way, groundwater monitoring becomes not only a means of control, but also a valuable professional foundation for more reliable assessment and a better understanding of conditions at the “Goričica” landfill site.

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SAFETY AS A STRATEGIC CRITERION OF INNOVATION DECISION-MAKING

Abstract
The growing complexity of corporate decision-making is increasingly shaped by innovation-driven changes that introduce new categories of organizational risk. Under these conditions, innovation decisions move beyond traditional market and financial considerations and place greater emphasis on responsible change management and the protection of employees' health and safety as a strategic concern. In many organizations, however, innovation management and occupational health and safety (OH&S) systems continue to develop separately. Consequently, safety is often considered only after innovations have been implemented, mainly to ensure regulatory compliance. Such practice can contribute to inconsistent management approaches and weaken the ability to anticipate potential risks.
This study presents a conceptual management model that brings together innovation objectives and OH&S requirements within a unified decision-making framework, supporting more resilient and responsible innovation processes.

Key words: innovation decision-making; risk management; occupational health and safety; organizational resilience; integrated management approach.

INTRODUCTION

Organizations operating in today's business environment face rapid technological change, dynamic market demands, and an increasing need for continuous adaptation. In such an environment, innovation represents one of the key drivers of competitiveness, growth, and long-term sustainability. Its role is no longer limited to the development of new products and services but increasingly encompasses changes in technology, work organization, business processes, managerial structures, and digital systems. Consequently, innovation is exerting an increasingly significant influence on organizational management practices and the quality of strategic decision-making [1], [2], [8].
At the same time, innovation creates not only development opportunities but also new categories of risk. The introduction of automation, digital solutions, new materials, new working methods, or changes in organizational structures may directly affect working conditions, exposure patterns, the distribution of responsibilities, and the relationship between people, technology, and processes. The consequences of such changes are reflected not only in efficiency and productivity outcomes but also in process safety, ergonomic requirements, psychosocial factors, and overall organizational resilience [4], [5].
As a result, innovation decision-making has become significantly more complex than in traditional management frameworks. Decisions regarding the development and implementation of innovations can no longer be based exclusively on market, financial, and technological indicators. However, in many organizations, innovation management and occupational health and safety (OH&S) management continue to develop separately. Safety-related aspects of change are often considered only after innovations have been implemented, primarily for the purpose of regulatory compliance or the subsequent resolution of already identified issues [3], [4], [6].

Such separation may lead to inconsistent management approaches and weaken an organization's ability to identify potential risks in a timely manner. Instead of being integrated into innovation planning, safety is frequently reduced to a post-decision assessment of consequences. This limits opportunities for preventive action and increases the likelihood that organizations will implement innovations under higher levels of uncertainty and organizational vulnerability.
Based on the above, the central problem addressed in this study is the lack of an integrated approach in which safety is incorporated into the early stages of innovation decision-making as an equal strategic criterion. In this context, several approaches within safety planning provide additional support for such

integration. The Hoshin Kanri method enables alignment between strategic objectives and tactical and operational activities, while tools such as PESTLE analysis, SWOT analysis, and the X-matrix provide a structured framework for linking objectives, performance indicators, responsibilities, and activities. The aim of this study is to examine the feasibility of such an approach and to present a conceptual management model that integrates innovation objectives and occupational health and safety requirements within a unified decision-making framework.

Research aim and objectives

The problem identified in the introduction relates to the insufficient systematic integration of safety into innovation decision-making processes. Although contemporary literature and modern management systems recognize the importance of innovation for organizational competitiveness and sustainability, as well as the importance of occupational health and safety for responsible management, safety-related aspects of organizational change are still frequently considered only at later stages in organizational practice. Such an approach indicates insufficient integration of safety into decision-making processes and reflects an underdeveloped safety culture in the context of innovation and organizational change. Accordingly, the aim of this study is to examine and present the possibility of integrating safety into innovation decision-making through a conceptual management model.

Research objectives

In accordance with the defined research objective, the study addresses the following research tasks:

- to analyze current approaches to innovation management and the evaluation of occupational health and safety performance
- to identify key intersections between innovation management and occupational health and safety management systems
- to examine the limitations of the separate development of these systems
- to propose a conceptual model in which safety becomes a strategic criterion in innovation decision-making

Based on the defined research problem and research objectives, the following hypotheses are formulated:

H1: Innovation decision-making in organizations operating in dynamic business environments requires a more comprehensive set of criteria beyond market, financial, and technological indicators, including organizational and safety-related aspects.

H2: The separation of innovation management and occupational health and safety management leads to delays in risk identification and increases organizational vulnerability.

H3: The integration of occupational health and safety into the early stages of innovation decision-making improves decision quality and reduces implementation-related risks.

H4: The application of structured tools (Hoshin Kanri, PESTLE, SWOT, and KPI) enables the effective operationalization of safety as a strategic criterion in innovation decision-making.

METHODS

The methodology of this study is based on the application of several scientific research methods. The analytical method was used to examine theoretical and managerial foundations in the fields of innovation management, risk management, and occupational health and safety, as well as to analyze relevant scientific and professional literature and international management systems.

The synthesis method was applied to integrate the identified findings into a unified conceptual framework, while the descriptive method was used to present the characteristics of innovation decision-making, safety-related criteria, and strategic planning instruments.

The study examined international management standards and relevant literature, with particular emphasis on ISO 56002:2019 in the field of innovation management and ISO 45004:2024 in the field of occupational health and safety performance evaluation. In addition, elements of the Hoshin Kanri method were incorporated, including PESTLE analysis, SWOT analysis, the X-matrix, the PDCA cycle, and key performance indicators (KPIs), enabling the integration of theoretical concepts with practical management tools.

Based on the applied methods, a conceptual model was developed to enable the integration of safety into innovation decision-making and to provide a foundation for further analysis and interpretation of the results.

RESULTS AND DISCUSSION

Innovation decision-making in dynamic market conditions

Organizations today operate in an environment characterized by rapid technological change, global competition, digital transformation, changes in work organization, and increasing demands for continuous adaptation. In such conditions, innovation is no longer merely an optional development opportunity but has become a necessary prerequisite for maintaining competitiveness, efficiency, and long-term sustainability. Consequently, innovation decision-making has emerged as one of the key areas of modern management [3], [8].

Innovation decision-making is not limited to the selection of new ideas or development directions; rather, it involves evaluating their potential effects under conditions of uncertainty. Every innovation, regardless of whether it involves a new technology, organizational change, digital solution, or new production approach, introduces changes to the existing work system. As a result, processes, interdepartmental relationships, competency requirements, patterns of responsibility, and levels of risk exposure are altered, including risks related to occupational health and safety. For this reason, innovation should not be viewed solely as a developmental category, but also as a change with far-reaching organizational and operational implications [2], [8].

In traditional approaches, innovation decisions are typically based on criteria such as market potential, financial feasibility, and technological viability. Although these criteria remain important, they do not encompass all aspects of socially responsible business practices. An innovation may be attractive from a market perspective, economically justified, and technically feasible while simultaneously increasing work complexity, introducing new hazards, or creating additional organizational vulnerabilities. Therefore, the quality of innovation decision-making increasingly depends on an organization's ability to incorporate not only traditional criteria but also the organizational, employee-related, and workplace implications of change. [2], [3], [8].

Such an understanding of innovation management creates space for the inclusion of additional criteria, among which occupational health and safety occupies a particularly important role. If innovation is viewed as a change that affects the entire organizational system, its safety implications must also become part of strategic evaluation rather than merely being treated as an issue of post-implementation control.

Safety as a criterion in innovation decision-making

In organizational practice, safety is still frequently viewed primarily as an issue of regulatory compliance and formal legal obligations. Although such an approach is important, it remains limited because it reduces safety to the verification of compliance requirements rather than recognizing it as an integral component of management quality. In conditions of rapid change, such an understanding of safety is becoming increasingly inadequate [4], [5], [6].

Modern approaches to safety performance evaluation emphasize that safety should be monitored through systematic processes of tracking, measurement, analysis, and assessment. Particular attention is given to proactive (leading) indicators, which enable the early identification of potential problems before they manifest through incidents, injuries, or process disruptions, as well as reactive (lagging) indicators that reflect outcomes that have already occurred [4], [6], [7].

A high-quality decision is not merely one that leads to market success or short-term efficiency, but one that also considers implementation stability, system resilience, the impact on working conditions, and the organization's ability to implement change without creating new vulnerabilities. Therefore, safety should not be viewed as a secondary consequence of innovative initiatives, but rather as one of the key criteria for evaluating the organizational sustainability of innovation.

A conceptual model of safety as a strategic criterion in innovation decision-making

Based on the previously presented theoretical foundations, a model is proposed in which occupational health and safety is incorporated as one of the essential criteria in innovation decision-making.

The conceptual model is presented in Figure 1.

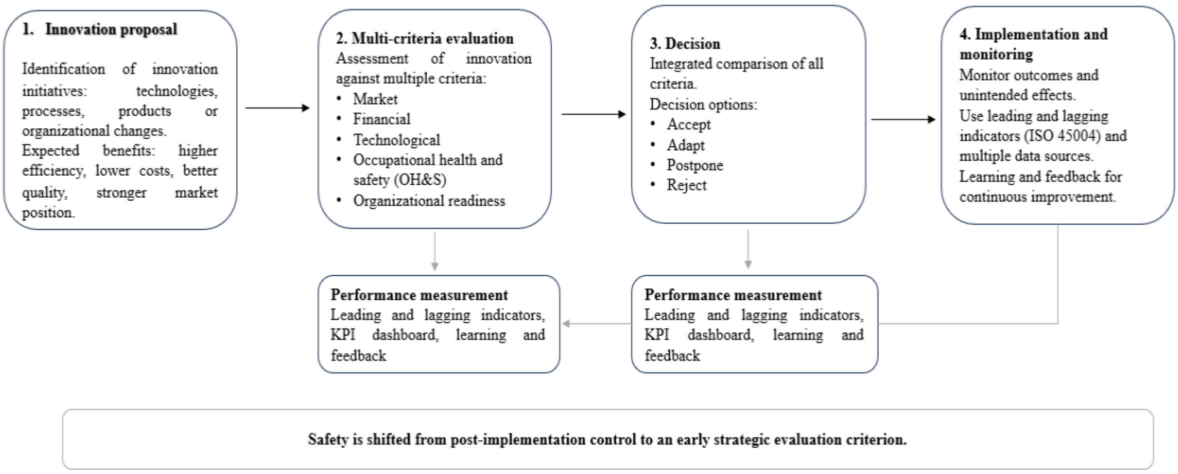

Figure 1. Conceptual model for integrating occupational health and safety into innovation decision-making

The proposed model suggests that decisions regarding innovation implementation should not depend solely on expected market, financial, or technological benefits, but also on whether the development and implementation of innovation can be aligned with substantive—not merely formal—occupational health and safety requirements.

The model consists of four interrelated phases.

The first phase refers to innovation proposals, specifically the identification of innovation initiatives. These may include new technologies, digital solutions, automated systems, new working methods, organizational innovations, new products, or processes. What all of these initiatives have in common is the expectation of specific benefits, such as increased efficiency, cost reduction, improved work quality, or the strengthening of an organization's market position.

The second phase involves the multi-criteria evaluation of innovation. At this stage, innovation is assessed not only according to market, financial, and technological criteria, but also according to occupational health and safety criteria. In this context, safety is not viewed solely through formal regulatory compliance, but also through the question of whether innovation can be developed and implemented without creating new hazards, additional workloads, or unfavorable working conditions. The evaluation includes the impact of innovation on working conditions, the emergence of new risks, work organization, required employee competencies, process safety, and the organization's overall ability to implement innovation safely in accordance with occupational health and safety management requirements [4], [5], [6].

The third phase refers to innovation decision-making. At this stage, all criteria are considered in an integrated manner. Based on their comparative evaluation, the organization decides whether the innovation should be accepted, adapted, or rejected. The role of occupational health and safety in this phase is particularly significant, as it may directly influence the final decision. The purpose of the evaluation is not limited to determining formal acceptability but also includes identifying the need for additional adjustments or rejecting innovation proposals when the level of risk is considered unacceptable.

The fourth phase focuses on monitoring innovation outcomes after implementation. Following the introduction of innovation, it is necessary to assess whether the expected outcomes are being achieved and whether unintended consequences are emerging. At this stage, proactive (leading) and reactive (lagging) indicators are used in accordance with the approach defined in ISO 45004, together with multiple sources of information [4], [6], [7]. The purpose of this phase is not only monitoring but also organizational learning based on experience, thereby improving future innovation-related decisions.

The primary value of the proposed model lies in the fact that it does not treat occupational health and safety as an issue to be addressed only after an innovation has been selected. Instead, safety is positioned as an integral part of innovation evaluation from the very beginning. In this way, safety becomes a key element of responsible change management. Such an approach does not hinder innovation but rather contributes to its sustainability, safe implementation, and overall acceptability for both employees and the organization as a whole.

The importance of a proactive approach and leading indicators

For the effective implementation of the proposed model, a proactive approach and the use of leading indicators are particularly important. Reactive indicators, such as injuries, accidents, or process disruptions, remain important because they demonstrate what has already occurred; however, they are insufficient on their own for innovation decision-making. If an organization waits for a negative event to occur before assessing the quality of an innovation, preventive action has already been delayed [4], [6], [7].

Leading indicators serve a different purpose. They enable the early identification of conditions, trends, and factors that may influence future safety performance and the overall success of organizational change [4], [6], [7]. In the context of innovation decision-making, these indicators may include assessments of organizational readiness for change, required competency levels, the effectiveness of planned controls, working conditions, clarity of responsibilities, employee feedback, pilot project results, or observations obtained through monitoring activities. Their primary value lies in enabling organizations to identify potential problems before full-scale implementation.

Leading indicators (proactive)	Lagging indicators (reactive)
➢ Training and competence coverage for new technologies / processes; ➢ Risk assessments completed before implementation; ➢ Hazard observations and near-miss reporting rate; ➢ Worker participation in change and safety; ➢ Reediness of controls and safety systems.	❑ Recordable injury frequency rate (TRIR, LTIR); ❑ Lost time injury rate (LTIR); ❑ Number of incidents with high potential; ❑ Production downtime due to incidents; ❑ Costs of incidents and compensation.

Figure 2. Role of leading and lagging indicators in innovation-related safety evaluation.

Implications and contributions of the proposed approach

The proposed approach contributes to bridging two areas that are often developed separately in organizational practice—innovation management and occupational health and safety management. As a result, safety is no longer viewed solely as a formal regulatory obligation but is instead recognized as a relevant criterion in strategic decision-making.

From a practical perspective, the model can help organizations improve the way they evaluate innovation initiatives. Integrating safety into the early stages of evaluation enables the timely identification of potential risks, the need for adjustments, additional control measures, or alternative implementation approaches.

Such an approach can strengthen organizational resilience and reduce the likelihood of undesirable consequences that often arise when safety is considered only at later stages of the innovation process.

The integration of safety into innovation decision-making can be further strengthened through the application of structured planning approaches.

The Hoshin Kanri method links strategic objectives with tactical and operational activities, enabling long-term goals to be translated into concrete actions, responsibilities, and performance indicators. In the field of safety management, this approach is particularly important because it reduces the risk of safety requirements remaining disconnected from the core decision-making process.

PESTLE analysis enables the assessment of political, economic, social, technological, legal, and environmental factors that may influence innovation and its safe implementation, while SWOT analysis facilitates the identification of internal strengths and weaknesses as well as external opportunities and threats. In combination with the X-matrix, these tools enable the alignment of strategic objectives, actions, responsible stakeholders, and key performance indicators.

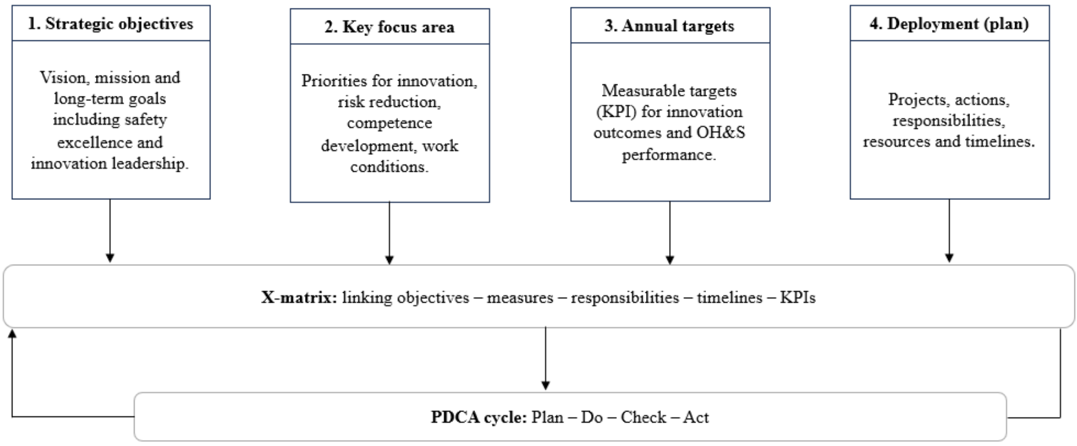

Figure 3. Integration of Hoshin Kanri planning tools into safety-oriented innovation management

The use of KPI metrics enables the quantification of safety performance, the monitoring of goal achievement, and the timely implementation of corrective actions. In this way, safety is not treated as an isolated function but as an integral component of change management and innovation management processes.

Within the proposed model, safety is incorporated into the multi-criteria evaluation phase of innovation. The evaluation process includes not only market, financial, and technological criteria, but also the effects of innovation on working conditions, the emergence of new risks, required employee competencies, work organization, process safety, and the organization's ability to implement innovation in a safe manner.

Based on such an evaluation, a decision is made regarding the innovation initiative, which may involve accepting, adapting, postponing, or rejecting the proposal.

Table 1. Multi-criteria framework for evaluating innovation initiatives.

Evaluation Criterion	Decision Question	Examples of Indicators
Market criterion	Does the innovation contribute to competitiveness and customer needs?	demand potential, service quality, reputational impact
Financial criterion	Is the innovation economically justified and sustainable?	implementation costs, expected return, risk control costs
Technological criterion	Is the innovation technically feasible and reliable?	technology readiness, compatibility, maintenance requirements
Safety criterion	Can the innovation be implemented without creating unacceptable OH&S risks?	risk assessment, competencies, incidents, near-miss events, employee participation
Organizational criterion	Is the organization prepared for change?	resource availability, communication, responsibilities, safety culture

However, the proposed model remains conceptual and has not yet been empirically tested. Its applicability and effectiveness may depend on the type of industry, organizational culture, the complexity of innovation, and the level of maturity of management processes within a particular organization.

Discussion of Research Hypotheses

Based on the conducted analysis of theoretical foundations, modern management systems, and the proposed conceptual model, the formulated research hypotheses can be discussed.

H1: Innovation decision-making in organizations operating in dynamic business environments requires a more comprehensive set of criteria beyond market, financial, and technological indicators, including organizational and safety-related aspects.
This hypothesis is confirmed. The study demonstrates that innovations affect not only market position, financial performance, and technological feasibility, but also internal organizational structures, work processes, competency requirements, working conditions, and overall organizational resilience. It has been emphasized that innovations may be marketable and technologically feasible while simultaneously creating challenges from the perspective of occupational health and safety. This confirms that traditional criteria alone are insufficient for a comprehensive evaluation of innovation initiatives.

H2: The separation of innovation management and occupational health and safety management leads to delays in risk identification and increases organizational vulnerability.
This hypothesis is also confirmed. The study identified that innovation and safety systems are often developed in parallel within organizational practice, but not in an integrated manner. It was emphasized that such separation leads different organizational functions to evaluate innovation from their own insufficiently connected perspectives. As a consequence, delayed risk identification, limited opportunities for adapting innovations prior to implementation, the underestimation of specific risks, and increased organizational vulnerability were identified.

H3: The integration of occupational health and safety into the early stages of innovation decision-making improves decision quality and reduces implementation-related risks.
This hypothesis is confirmed. The study developed a conceptual management model that integrates innovation objectives and occupational health and safety requirements within a unified decision-making framework. The model is based on innovation proposals, multi-criteria evaluation, integrated decision-making, and performance monitoring. At its core, safety is introduced as an equal evaluation criterion, enabling higher-quality decision-making and reducing risks associated with innovation implementation.

H4: The application of structured tools (Hoshin Kanri, PESTLE, SWOT, and KPI) enables the effective operationalization of safety as a strategic criterion in innovation decision-making.
This hypothesis is also confirmed. The study demonstrates that the application of structured planning approaches enables the alignment of strategic objectives, operational activities, and performance indicators. The integration of tools such as the Hoshin Kanri method, PESTLE analysis, SWOT analysis, and KPI metrics enables the systematic inclusion of safety in decision-making processes, thereby facilitating its practical application as a strategic criterion.
Based on these findings, it can be concluded that all proposed hypotheses have been confirmed. The results highlight the need for a more integrated approach to innovation decision-making in which safety is viewed as an integral component of change management quality and long-term organizational resilience, while also emphasizing the need for future empirical validation of the proposed model.

CONCLUSION

Modern innovation decision-making requires a more comprehensive and integrated approach than the traditional evaluation of market, financial, and technological criteria. Innovations within organizations represent not only development opportunities but also organizational changes that may affect working conditions, process safety, employee competencies, and overall organizational resilience. For this reason, occupational health and safety should be incorporated into the early stages of decision-making rather than being considered only after innovation implementation.
The findings of this study confirm that the separation of innovation management and occupational health and safety management may lead to delayed risk identification, inconsistent management approaches, and increased organizational vulnerability. In contrast, integrating safety into innovation decision-making enables a more comprehensive evaluation of innovation initiatives, timely identification of potential challenges, and the reduction of implementation-related risks.

The proposed conceptual model demonstrates that safety can be positioned as an equal strategic criterion alongside market, financial, technological, and organizational criteria. A key contribution of the model is its repositioning of safety from a post-implementation control mechanism to an element of early strategic evaluation. This creates conditions for more responsible change management, improved organizational preparedness, and more sustainable innovation implementation.
An additional contribution of this study lies in linking the conceptual model with strategic planning tools such as the Hoshin Kanri method, PESTLE analysis, SWOT analysis, the X-matrix, the PDCA cycle, and key performance indicators. This approach enables the operationalization of safety through clearly defined objectives, responsibilities, activities, and measurable indicators, thereby increasing the practical applicability of the proposed model.

Although the proposed hypotheses were confirmed through theoretical and conceptual analysis, it should be emphasized that the model has not yet been empirically tested. Its applicability may depend on the type of industry, organizational culture, the complexity of innovation, and the maturity of management processes within a particular organization. Future research should focus on empirical validation of the model across different sectors, as well as on the development of specific indicators for evaluating safety in the early stages of innovation decision-making.

Integrating occupational health and safety into innovation decision-making represents an important step toward more responsible, resilient, and sustainable organizational development. Such an approach does not limit innovation but instead contributes to its more effective, safer, and more sustainable implementation.

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SMART SYSTEMS IN ENDANGERED FLORA MONITORING: INNOVATIONS FOR SUSTAINABILITY

Abstract
Biodiversity conservation and the protection of rare and endangered plant species are increasingly regarded as an integral part of modern environmental management, ecological safety, and sustainable development strategies. Traditional monitoring methods in protected natural areas are often constrained by geographical barriers and human resource capacities. This paper explores the innovative application of smart systems, including IoT sensor networks and Artificial Intelligence (AI)-powered analytics, in monitoring endangered plant species. The focus is on integrating these technologies into existing safety management systems to prevent habitat degradation, enhance occupational health and safety for field teams, and ensure long-term sustainability. By analysing global smart monitoring models, the paper proposes a framework for their implementation in the Republic of Serbia and the region, highlighting socio-economic and ecological benefits.

Key words: ecological safety, endangered flora, smart systems, sustainable development.

INTRODUCTION

Biodiversity conservation and the protection of endangered plant species are increasingly recognized as a vital component of modern approaches to nature conservation, ecological safety, and sustainable development. Endangered plant species contribute to the preservation of ecosystem stability, genetic diversity, and habitat functionality. Simultaneously, they are exposed to various pressures, including habitat degradation and fragmentation, climate change, invasive species, and different forms of anthropogenic impact [2], [14]. Consequently, the monitoring of endangered flora is of paramount importance for timely response, the planning of conservation measures, and the long-term preservation of natural resources.

Conventional forms of monitoring plant species and their habitats primarily rely on direct field work, visual identification, and the manual recording of collected data. Although these methods possess significant professional value, their application is often hindered by inaccessible terrain, substantial time consumption, the need to engage a large number of experts, and a reduced capacity for continuous monitoring of changes over expansive areas [13], [1]. As pressures on natural ecosystems intensify, these limitations further emphasize the necessity for more modern, efficient, and precise solutions.

Advancements in digital and sensor technologies have established the foundation for more accurate, faster, and spatially comprehensive monitoring of endangered plant species. Contemporary approaches increasingly integrate the use of remote sensing, *unmanned aerial vehicles* (UAVs), multispectral and hyperspectral sensors, *Internet of Things* (IoT) networks, automated data collection, and analytics based on *Artificial Intelligence* (AI) and machine learning [11], [15]. Their application facilitates more frequent and reliable information gathering, better insights into changes over larger areas, and earlier identification of disturbances that could jeopardise plant populations and habitats.

Of particular significance are studies confirming the applicability of smart systems in monitoring individual endangered plant species. For example, the case of *Gladiolus illyricus* has demonstrated that linking drone imagery with deep learning models can enhance population monitoring in sensitive habitats, especially when it is necessary to reduce physical pressure on the terrain and enable repeatable

monitoring of changes over time [12]. Similarly, long-term monitoring of changes in Normalized *Difference Vegetation Index* (NDVI) values has highlighted the importance of remote sensing in assessing the vulnerability of endangered plants and the impact of habitat changes, particularly within protected natural areas and the Natura 2000 network [8].
In addition to the direct monitoring of plant species, modern monitoring increasingly includes the assessment of habitat quality and its changes. *Machine Learning* (ML) models, satellite data from the Sentinel platform, and standardized frameworks for monitoring Natura 2000 habitats demonstrate that contemporary approaches can significantly improve habitat mapping, cover assessment, and the identification of conservation priorities [1], [10]. European models of modern biodiversity monitoring further confirm the importance of integrating remote sensing, sensor systems, automated data processing, and standardized methodological frameworks in tracking species and habitats [8]. Thus, the monitoring of endangered plant species extends beyond the mere recording of the presence or absence of individual species and becomes part of a broader system of biodiversity management, spatial protection, and data-driven decision-making.

The link between smart systems and safety is particularly important for the subject of the research. The application of remote sensing, sensor networks, and automated analytical tools can reduce the need for field teams to frequently enter inaccessible, hazardous, or ecologically sensitive areas. Such an approach contributes not only to more efficient monitoring but also to the enhancement of occupational health and safety for researchers, rangers in protected natural areas, and other experts involved in the monitoring and management of natural resources.

This paper aims to analyse the possibilities of applying smart systems in the monitoring of endangered flora, with a particular focus on artificial intelligence, IoT sensor networks, remote sensing, and *unmanned aerial vehicles* (UAVs). The paper is aimed at examining their potentials, advantages, and limitations, as well as considering the possibilities of their application in the Republic of Serbia and the region. Special attention is paid to how these systems can contribute to preventing habitat degradation, enhancing ecological safety, and strengthening the sustainable management of protected natural assets.

METHODS

The research is designed as a review and analytical study aimed at examining contemporary technological solutions applicable to the monitoring of endangered plant species and the conservation of their habitats. The methodological framework encompasses the descriptive method, the analysis of scientific and professional literature, a comparative analysis of technological approaches, and a synthesis of findings. On this basis, a potential framework for their application in the Republic of Serbia and the wider region is considered.

The study is based on a narrative analysis of contemporary literature. Particular attention is paid to papers published in the period 2021-2025, as they reflect the most recent technological and methodological trends in this field. Such an approach is suitable for examining the application of digital technologies in the domain of biodiversity protection and ecological monitoring [10], [14].

The analysis includes sources addressing the application of artificial intelligence, machine and deep learning, remote sensing, unmanned aerial vehicles, vegetation indices, IoT sensors, and network systems in the monitoring of plant species, habitats, and biodiversity [2].

The criteria for source selection included thematic relevance, recency, applicability to the problem of endangered plant species monitoring, the presence of specific technological models or case studies, and the significance for enhancing ecological safety and decision-making support in the field of nature conservation. Works relating exclusively to the general application of technologies, without a clear link to biodiversity, habitat monitoring, or the protection of endangered flora, were not included in the narrower analytical framework.

In processing the collected literature, a comparative analysis of various technological approaches was employed, considering their purpose, advantages, limitations, and potential for application in monitoring endangered plant species. Approaches based on unmanned aerial vehicle imaging, satellite remote sensing, vegetation indices, machine learning, deep learning, and sensor networks were compared. Based on this, a synthesis of results was performed with the aim of identifying dominant trends in the development of smart systems and observing their practical implications for nature conservation management.

The methodological approach of the paper does not involve conducting original field research; instead, it is based on the analysis of existing scientific knowledge and examples of best practice. Such an approach corresponds to the objective of the paper, as it does not examine a single specific location but rather a broader framework of modern solutions and the possibilities for their application. In this sense, the results of the paper represent a synthesis of relevant theoretical and practical findings and provide a basis for the discussion on the application of smart systems in the national and regional context.

RESULTS

Modern approaches to the monitoring of endangered plant species increasingly rely on the combination of various technologies. In this context, remote sensing, the use of drones, sensor networks, and advanced models based on machine and deep learning are particularly prominent, supported by platforms for processing large sets of spatial and temporal data.

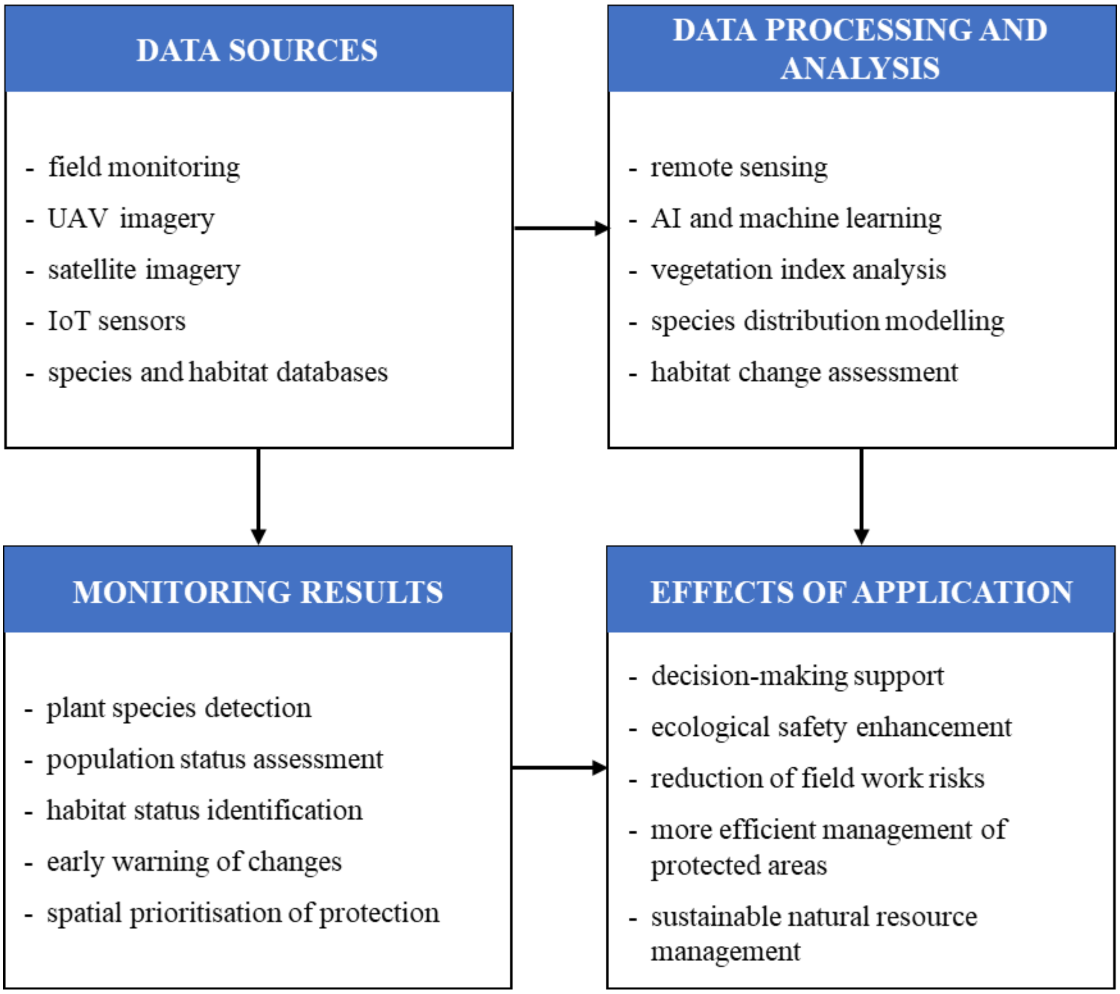

Figure 1. Schematic representation of smart system application in endangered plant species monitoring (**Source:** Author's own elaboration)

As illustrated in Figure 1, the effects of smart system application extend beyond merely improving data collection and also encompass important safety and management aspects. Particularly noteworthy are the reduction of field work risks, the enhancement of timely response, and support for decision-making based on accurate data.

Table 1 provides an overview of the key areas of smart system application and their contribution to ecological safety and risk management, with a specific focus on the conservation of endangered flora.

Table 1. The contribution of smart systems to ecological safety and risk management

Area of Application	Contribution to Safety	Management Significance
Early detection of habitat degradation	Reduces the risk of irreversible population loss	Enables timely response and the implementation of protective measures
UAVs and remote sensing	Reduces the need to operate in difficult-to-access and hazardous areas	Increases the efficiency and coverage of monitoring
IoT sensors	Enable continuous monitoring of microclimatic conditions	Support early detection systems
AI/ML models	Identify patterns and changes that are not easily observable	Enhance planning and decision-making
Integrated databases	Reduce information fragmentation	Enable institutional coordination and data management

Source: Author's own elaboration based on the analysed literature

The integration of these technologies facilitates a transition from traditional, periodic tracking to a continuous and proactive management approach, which is of particular importance for the conservation of endangered plant species and their habitats.

Application of Smart Systems in the Monitoring of Endangered Plant Species

A review of the literature indicates a significant shift in the application of artificial intelligence in the protection of endangered plant species. It is no longer limited to experimental research but is becoming an integral part of modern conservation practices. The review paper by Bose et al. demonstrates that AI is utilised in several interconnected areas, including plant population monitoring, habitat mapping, predictive species distribution modelling, phenological monitoring, and support for biodiversity management [2]. Such a finding suggests that smart systems possess the potential to enhance both scientific research and practical conservation activities.

A similar conclusion emerges from the work of Ullah et al., which emphasises that modern AI approaches should not be viewed as a replacement for classical nature conservation methods, but rather as their extension and complement. The integration of classical field methods, expert knowledge, and digital tools allows for a more precise and comprehensive assessment of the status of species and habitats, which is of particular importance in conditions of limited human and financial resources [14]. Consequently, the monitoring of endangered plant species becomes an integral part of a broader adaptive management system, based on the continuous collection and interpretation of data.

The results of the analysed literature also show that networked sensor systems and automated biodiversity monitoring are gaining increasing significance. Within the Nature 4.0 concept, integrated monitoring involves combining various data sources, such as field sensors, satellite and drone platforms, acoustic and visual systems, and algorithms for the automated processing and interpretation of gathered information [15]. The European MAMBO framework further confirms that the integration of multiple technologies, standardisation, and the interconnectedness of data sources are key directions for modern biodiversity and habitat monitoring [8]. Although these systems are not exclusively focused on plant species, their structure and operational methods demonstrate how the monitoring of endangered flora can be developed in the future.

Monitoring of Endangered Plant Species at the Population and Species Level

Particularly significant results have been observed in studies addressing the specific monitoring of plant species at the population level. The example of the species *Gladiolus illyricus* has demonstrated that linking UAV imagery with deep learning models can provide a more reliable insight into the population status, with reduced pressure on the sensitive habitat [12]. This study particularly emphasised that technology-based monitoring can decrease the need for intensive field visits, which is important not only for efficiency but also for the preservation of sensitive habitats and the reduction of physical workload for field teams.

Additional examples from the literature confirm the utility of drone technologies in plant population monitoring. Monitoring broad-leaved orchids and indicator plants in grassland vegetation has shown that the combination of UAV imaging and machine learning models enables the tracking of abundance, spatial distribution, and population changes with high precision [5], [4]. These results are significant as they demonstrate that modern monitoring is not limited solely to species detection but can also encompass population size assessment, the dynamics of change, and the condition of the habitat in which the species is located.

Based on the analysed studies, it can be concluded that drone systems are particularly useful in cases where it is necessary to:

- monitor difficult-to-access or ecologically sensitive areas;
- reduce physical contact with the habitat;
- ensure the repeatability of imaging across multiple time intervals;
- link visual data with automated classification models.

This indicates that the use of unmanned aerial vehicles represents one of the most promising directions for the development of endangered plant species monitoring, particularly at the level of individual species and local populations.

Long-term Monitoring of Habitats and Vegetation Changes

In addition to monitoring the plant species themselves, an insight into relevant literature indicates that modern monitoring increasingly includes habitat analysis as a key factor for the survival of endangered flora. The work of Matas-Granados et al. showed that long-term monitoring of changes in NDVI values can be a significant indicator of the vulnerability of endangered plant species and changes in their environment [8]. It is particularly important that this approach enables the observation of slow, cumulative changes in vegetation and habitat, which classical field monitoring sometimes finds more difficult to register in the earlier stages.

Approaches based on habitat mapping and assessment within the Natura 2000 network are of similar significance. Agrillo et al. propose a standardised framework that integrates field data, georeferenced vegetation areas, satellite data, and machine learning models aimed at more precise monitoring and assessment of species cover within the habitat [1]. The results of this study show that combining traditional and modern approaches can enhance standardisation, comparability, and the operational value of habitat monitoring.

A study on forest habitat mapping in the Natura 2000 regions of Cyprus further confirms this trend. Combining *Sentinel*-1 and *Sentinel*-2 data, topographical variables, and the Random Forest approach has shown high applicability for habitat classification and mapping [10]. Such results indicate that remote sensing and machine learning models can play an important role in monitoring the quality and spatial distribution of habitats significant to endangered plant species.

Furthermore, an integrated *workflow*, from remote sensing to species distribution modelling, shows that vegetation changes, species expansion, and changes in habitat suitability can be successfully monitored using combined spatial models [3]. Although these approaches are not always exclusively focused on endangered species, they represent an important methodological framework for linking plant monitoring and habitat monitoring.

The Role of Sensor Networks and Integrated Systems

An insight into relevant literature indicates the growing significance of sensor and integrated systems in the monitoring of vegetation and forest ecosystems. Torresan et al. highlight that a new generation of sensors and monitoring tools facilitates more precise tracking of vegetation health, ecosystem productivity, microclimatic changes, and other parameters essential for *climate-smart* management approaches [13]. Although the primary focus of that work is forestry, the technological principles are fully applicable to the monitoring of endangered plant species, particularly regarding the continuous tracking of habitat changes.

The particular significance of these systems is reflected in the ability to link different levels of monitoring:
- the local field level;
- the drone imaging level;
- the satellite level;
- the analytical level based on AI and ML models.

In this way, monitoring becomes multi-layered and enables a deeper understanding of the relationship between species status, habitat changes, and external pressures. In practical terms, this can contribute to the more efficient detection of habitat degradation, the identification of high-risk areas, and the directing of conservation measures where they are most needed.

Advantages and Limitations of Smart Systems

The analysed papers indicate several key advantages of applying smart systems in the monitoring of endangered plant species.

Table 2. Key technologies and their application in endangered flora monitoring

Technology	Primary Purpose	Advantages	Limitations
UAV	Monitoring populations and micro-habitats	High spatial resolution, reduced pressure on the terrain, possibility of repeatable imaging	Equipment costs, complex data processing, need for trained operators
Satellite remote sensing	Monitoring vegetation and habitat changes	Large spatial coverage, time series, suitable for long-term monitoring	Lower level of detail at the level of individual species
IoT sensors	Continuous monitoring of environmental conditions	Real-time data, early detection of changes	Need for infrastructure, continuous system maintenance
AI and ML models	Classification, prediction, and pattern analysis	Rapid processing of large datasets, decision-making support	Need for high-quality training sets and validation
Vegetation indices (e.g. NDVI)	Assessment of vegetation status and changes in habitats	Simple application, useful for trend tracking	Limited precision for individual species without additional data

Source: Author's own elaboration based on the analysed literature

As shown in Table 2, modern technologies possess various advantages and limitations, which is why their greatest value is achieved through mutual combination within integrated monitoring systems. The data in Table 2 confirm that no single technology on its own provides a comprehensive answer to all the requirements of endangered flora monitoring; rather, maximum efficiency is achieved by integrating multiple approaches in accordance with the monitoring objective and habitat characteristics.

Primarily, smart systems allow for significantly greater spatial coverage and more frequent data collection compared to conventional field methods. Furthermore, they essentially contribute to the reduction of subjectivity in interpretation, enhance the capacity for early detection of changes, and enable more efficient integration of heterogeneous information sources [11], [14], [15]. A significant advantage is also reflected in the fact that these systems serve as a reliable basis for decision-making support, the prioritisation of conservation interventions, and strategic planning for long-term biodiversity management [11].

At the same time, the literature review clearly indicates certain limitations. One segment of challenges relates to the costs of high-tech equipment, access to specific data, and their complex processing. Another segment encompasses the necessity for high-quality training sets and rigorous field validation of models, without which algorithms may have limited reliability in real, dynamic conditions [12], [9]. Additionally, the effective application of these systems requires adequate institutional and personnel capacities, as well as a high degree of standardisation and interoperability between different data sources and processing methods [13], [15].

The results of the comprehensive literature review thus confirm that smart systems possess exceptional potential for enhancing endangered plant species monitoring, but their full implementation directly depends on technological equipment, the availability of expert knowledge, infrastructure development, and the possibility of integration into existing nature conservation management systems.

Implementation Model of Smart Systems for Endangered Flora Monitoring in the Republic of Serbia

Based on the previously analysed technological approaches, their advantages, and limitations, a model for the implementation of smart systems in the monitoring of endangered flora in the Republic of Serbia and the region can be defined. The proposed model is based on the integration of existing monitoring methods and contemporary digital technologies, while respecting specific institutional and infrastructural capacities.

The proposed model encompasses the following fundamental phases:

- **Data collection**, which includes a combination of field monitoring, satellite remote sensing, unmanned aerial vehicles, and IoT sensor systems;
- **Data integration and processing**, through the use of centralised databases and GIS platforms, applying advanced artificial intelligence and machine learning methods;
- **Analysis and interpretation of results**, enabling the identification of habitat changes, assessment of population status, and the timely detection of potential risks;
- **Decision-making support**, through the precise definition of conservation priorities and the planning of evidence-based management measures;
- **Implementation and evaluation of measures**, involving the practical application of results and the continuous improvement of the monitoring system in accordance with feedback.

In this manner, the monitoring of endangered flora evolves from a traditional, periodic approach towards an integrated and continuous management system, firmly grounded in data and modern technologies.

Figure 2. Implementation model of smart systems in endangered flora monitoring
(**Source:** Author's own elaboration)

Figure 2 illustrates the implementation model of smart systems, showing the logical sequence from data sources, through processing and analysis, to decision-making and final application in the field.

DISCUSSION

The results of the literature analysis confirm that smart systems possess significant potential for enhancing the monitoring of endangered plant species, both at the level of individual species and at the level of vegetation, habitats, and broader ecosystem changes. As illustrated in Figure 1, their value does not arise from the isolated application of individual technologies, but from the synergistic linking of different data sources, processing methods, and practical effects in the domain of nature conservation. In this sense, contemporary monitoring is no longer based exclusively on periodic field visits but is progressively evolving towards integrated systems that enable more continuous, precise, and operationally useful tracking of changes.

The analysed works indicate that approaches integrating field observations, UAV imaging, satellite data, and machine and deep learning algorithms are particularly significant. Such integration facilitates not only more expeditious processing of large quantities of data but also more precise detection of changes in plant populations and their habitats. Simultaneously, the results suggest that the greatest practical value is derived from systems that link species monitoring with habitat monitoring, given that the preservation of endangered plant species cannot be observed in isolation from the quality and dynamics of the space in which these species survive.

A particular contribution of smart systems is reflected in the possibility of early identification of negative trends and timely reaction. Long-term monitoring of vegetation indices, species distribution models, and

AI analytics enable the recognition of patterns that may not be apparent through classical field methods in the initial stages. This creates space for more efficient planning of conservation measures, more precise prioritisation, and a more rational allocation of limited resources in the field of nature conservation. Such an approach is especially important under conditions of increasing pressures on natural habitats, including climate change, spatial fragmentation, and the spread of invasive species. In this context, such a methodological approach is of particular significance within the framework of integrated risk and safety management in nature conservation.

At the same time, the results summarised in Table 2 confirm that each of the considered technologies also possesses certain limitations. UAV systems provide high resolution and are suitable for monitoring local populations, but require specific equipment, professional training, and complex subsequent data processing. Satellite remote sensing allows for wide spatial coverage and long-term chronological series, but is limited in terms of precision when monitoring individual plant species. IoT sensors enable continuous acquisition of environmental parameters, but their effective application depends on the robustness of infrastructure and system maintenance. AI and ML models possess exceptional analytical potential, but require high-quality datasets for training, field validation, and expert interpretation of results. Consequently, it can be concluded that maximum efficiency is achieved through their complementary combination rather than the isolated application of individual solutions.

For the context of the Republic of Serbia and the region, the results of this work indicate that there is a realistic opportunity for the gradual implementation of smart systems in endangered flora monitoring. European experiences are particularly significant, especially those developed within contemporary biodiversity monitoring programmes and the Natura 2000 network, as they provide a methodological basis for habitat monitoring, change mapping, and linking nature conservation with modern analytical tools [7]. Local and regional examples, including the application of multispectral monitoring in the national parks of Serbia [6], demonstrate that such approaches are not unattainable, but rather require more systematic institutional support, cross-sectoral cooperation, and the strengthening of technical and personnel capacities. Further confirmation of the relevance of this topic is the fact that initiatives linking artificial intelligence and plant species monitoring are developing within the regional space, including cross-border projects aimed at tracking invasive plants and improving natural resource management.

From a safety perspective, smart systems possess additional value as they can reduce the frequency of entries into difficult-to-access, hazardous, or ecologically sensitive terrains. This enhances not only the operational efficiency of monitoring but also the occupational health and safety of researchers, rangers in protected natural areas, and other actors involved in nature conservation. This aspect is of fundamental importance for papers presented within a conference framework dedicated to management and safety, as it indicates that the application of modern technologies induces broader organisational and protective effects.

Based on all the aforementioned, it can be concluded that smart systems represent an essential direction for the further development of monitoring, but their successful implementation depends on aligning technological possibilities with real nature conservation needs, institutional capacities, and local ecological specificities. Precisely for this reason, their application should be viewed as an integral part of a long-term biodiversity management model, rather than exclusively as a technical innovation.

CONCLUSION

Smart systems play an increasingly significant role in the monitoring of endangered flora and habitat protection. Their application facilitates an enhanced and more precise approach to the collection, processing, and interpretation of data. The literature review indicates that the combination of remote sensing, drones, sensor networks, vegetation indices, and artificial intelligence can significantly improve the tracking of endangered plant species. This provides a more reliable insight into the changes occurring within their natural environment.

The results indicate that the key advantage of these systems lies in the linking of diverse data sources. Such monitoring becomes spatially more comprehensive, temporally more continuous, and more applicable in nature conservation. It is particularly important that these approaches enable not only the recording of the current status of species but also the early identification of changes, assessment of habitat vulnerability, and high-quality decision-making support. Consequently, smart systems directly contribute to the strengthening of ecological safety and more efficient natural resource management.

At the same time, it has been observed that the implementation of these technologies possesses certain limitations. Their effectiveness in practice depends on the availability of equipment, the quality of models, field verification of results, as well as on appropriate institutional and expert capacities. For this reason, their application cannot be considered a complete replacement for conventional monitoring methods, but rather their significant supplement within an integrated approach to nature conservation.

For the Republic of Serbia and the region, it is particularly important that realistic conditions exist for the gradual application of smart systems. This specifically refers to pilot projects, cooperation between scientific institutions and managers of protected natural areas, as well as the utilisation of European methodological frameworks. Such an approach can contribute to better biodiversity conservation, more rational resource utilisation, and greater safety in field work. The contribution of the present work is reflected in the systematisation of modern technological approaches and the formulation of an implementation model tailored to the national context.

Based on the presented findings, it can be concluded that smart systems possess the potential to become a key pillar in the future monitoring of endangered flora. The further development of these systems should be directed towards the standardisation of methodologies and better interoperability of different datasets. Special significance lies in the strengthening of interdisciplinary cooperation between experts in the fields of ecology, nature conservation, information technologies, and safety.

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Web Resources

– Faculty of Technical Sciences, University of Novi Sad. Project ENG AINSPEC - AI-assisted monitoring and management of invasive plant species in the cross-border area.

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TECHNOLOGICAL INNOVATIONS FOR THE FUTURE: INTEGRATING AI AND ROBOTICS INTO ENVIRONMENTAL PROTECTION MANAGEMENT IN COASTAL EU STATES

Abstract
Modern responses to environmental challenges rely on the integration of advanced technologies. Given the importance of marine ecosystems, development is primarily focused on the hydrosphere, where robotic systems serve as effective monitoring tools. These systems enhance pollution detection through improved spatial and temporal data precision. Within the European Union, systems like CleanSeaNet enable early detection of hazardous spills, while unmanned aerial and surface vehicle networks are considered for cost optimization. Innovations such as propeller-less ROV units minimize noise and mechanical impact on sensitive habitats. Simultaneously, open-source platforms facilitate economical real-time monitoring of water quality parameters. Artificial Intelligence (AI) provides analytical depth for species protection and combating illegal activities, supporting UN Sustainable Development Goals 14 and 15. Although autonomous systems improve waste management, challenges in sensor precision and energy autonomy necessitate further research and regulatory alignment. This paper's contribution analyzes the applicability of these technologies within the EU, where 22 of 27 member states are coastal. Focusing on Croatia, which requires advanced surveillance due to its extensive maritime border, the study demonstrates that integrating green and digital innovations is essential for the long-term stability of the Adriatic ecosystem.

Key words: Artificial Intelligence, Croatia, Environmental Monitoring, Marine Ecosystems, Robotic Systems.

INTRODUCTION

The ubiquitous accumulation of polymeric materials and anthropogenic sediments in marine ecosystems represents one of the most critical environmental challenges of our time. For years, millions of tons of plastic have been entering lakes, seas and oceans, where they do not decompose, but break down into microplastics that pollute the entire aquatic world. Once discarded, fishing nets and fishing equipment continue to have a destructive effect for years after they are discarded, and various chemicals from waste enter the food chain and end up on our plates, which directly threatens human health. Conventional remediation strategies, such as manual collection or the use of dedicated vessels, show significant deficits in terms of cost and operational reach, and cannot independently counteract the exponential increase in pollution. A new generation of autonomous robots and underwater drones have emerged in the cleaning method, which can go where people cannot, can work in storms, 24 hours a day without stopping. Although traditional waste management methods are still necessary and essential, they are often cumbersome, expensive and limited to a small area of application. All of the above has resulted in the need to develop sensors, artificial intelligence, navigation and other systems that are useful for these needs due to greater efficiency in waste collection. At the global level, environmental protection is very important, which is reflected in various laws. At the EU level, this is given through the Marine Strategy Framework Directive, where the focus is on reducing marine litter. [9]
Digital transformation is also present in the maritime industry, the colloquial Maritime 4.0, is very important when it comes to a series of environmental challenges. In a way, we have a modification of the infrastructures of "Smart Cities", into "Smart Oceans", where autonomous robotic networks function in an analogous way based on collected data in real time in order to optimize the distribution of resources. The integration of autonomous systems is excellent because it minimizes the logistics of maritime operations in terms of less need for large, carbon-intensive support vessels.

It is important to highlight that the presence of marine litter is not only an environmental problem, but also a challenge for maritime safety. Floating debris and submerged ghost nets pose a direct threat to vessel propulsion systems and navigation safety, leading to costly mechanical failures and potential accidents in high-traffic corridors. By implementing autonomous detection and removal systems, port authorities and shipping companies can proactively mitigate these operational risks. The shift from reactive cleanup to proactive autonomous surveillance represents a fundamental shift in the way marine environments are managed, moving towards a data-driven approach that is in line with UN Sustainable Development Goal 14 (Life Below Water).

In this context, the aim of this paper is to analyze the possibilities of applying autonomous robots and underwater drones in the detection and monitoring of marine litter, assuming that these systems, integrated with artificial intelligence, can significantly increase the efficiency of cleaning compared to classic methods. In order to confirm this hypothesis and assess their contribution to ecosystem protection, the paper will present the main types of waste, describe modern detection methods and technical features of robotic systems, and consider the ecological, economic and legal aspects of the application of such advanced technologies.

METHODS

The methodological approach of this paper is based on the compilation method with systematic processing of relevant professional literature, where a detailed technical description of technological systems is given and a comparative analysis of solutions for marine litter removal using autonomous robots is performed. This approach should be useful for the purpose of accurate assessment of technologies based on their actual performance and operational capacities in real conditions. The analytical part of the paper focuses on the key operational parameters that define the efficiency of the system. This includes the classification of waste by size — from microparticles (less than 5 mm according to the EU definition) and plastics (0.1–50 mm) to abandoned fishing nets with an area of up to 100 m². The evaluation of detection methods includes the analysis of sonar with a range of up to 100 m depth and a resolution of 10 cm, the use of 4K cameras with a field of view of 120°, and a high-precision LiDAR system (± 2 cm). The technical characteristics of the analyzed robots include the energy capacities of the batteries (500–2000 Wh) that enable autonomy from 8 to 24 hours, a load capacity of up to 50 kg and propulsion power that ensures movement speeds between 2 and 5 knots. The collection procedures are evaluated through the capture capacity from 0.5 to 2 m³/h, with the use of mechanical grippers with a force of up to 200 N and specific filter systems with a porosity of 1–5 mm. The synthesis of the work integrates data from official EU directives, IMO guidelines and the results of international projects such as CleanSea and SeaClear, thus creating a complete picture of the development path of autonomous systems — from laboratory tests to field application. Finally, the comparative analysis systematically contrasts surface robots, specialized for macrowaste at shallow depths with an efficiency of 80 %, underwater AUV/ROV systems with advanced sonar/AI detection up to 200 m depth, and hybrid systems that use RTK-GPS/INS navigation to achieve the highest degree of autonomy (LOA 3-4). By clearly highlighting the differences in detection accuracy (± 5–10 cm) and operational goals, the paper provides an objective insight into the advantages of preventive versus active cleaning of the marine environment.

RESULTS

Underwater drones and autonomous robots are of great importance in cases where waste is scattered over a large area that is difficult to access, in places of work at great depths where people cannot approach, due to high intervention costs or due to the safety risk itself. Modern sea cleaning systems, as well as systems used in addition to physical waste removal, use tools for detecting waste, mapping the area and monitoring changes in the marine environment. The highest level of efficiency is achieved when waste detection, autonomous navigation, computer vision and the ability to selectively collect found objects are combined in the same operating system. With such an operating system, the search time is reduced, the efficiency of the intervention is increased and resources are directed towards the areas of greatest pollution, which is of particular importance in coastal zones, ports and areas of intense and high maritime traffic. [4]

The introduction of autonomous robotic solutions represents a game changer in maritime safety management and environmental engineering. Beyond the mere physical removal of debris, these systems offer a quality solution to the risks inherent in traditional diving operations, such as decompression sickness or limited underwater visibility, reducing the need for human presence through the use of rugged sensor-driven platforms. These technologies enable the simultaneous monitoring of large maritime corridors, which was previously logistically demanding and financially expensive. Furthermore, the integration of real-time data analytics allows port authorities to move from periodic, reactive cleaning cycles to continuous, predictive maintenance of the marine environment. This approach optimizes energy consumption, which in turn is related to battery life, by focusing action on those areas that require a priority response. The evaluation of such systems is not trivial and requires a multidimensional approach that considers technical reliability, safety and economic return on investment.

In order to consider the advantages of technological development and the use of autonomous systems, it is important to compare their performance with traditional methods of remediation of the marine environment. A series of parameters, such as range, cost-effectiveness and level of safety for personnel, have been selected, and their analysis shows that conventional approaches, despite their long-standing use, have significant limitations in terms of comparing parameters related primarily to scalability and operation in high-risk environments. Table 1 below provides a summary of the comparative review of the selected different methods.

Table 1. Technical specifications and performance metrics of conventional vs. autonomous cleaning systems

Cleaning Method	Efficiency	Costs	Safety	Scalability	Application Example
Manual cleaning	Low (0.1–1 km²/day)	Medium	High risk for divers	Very low	Beaches, small coves
Vessels with nets	Medium (5–20 km²/day)	High	Medium risk	Medium	Open sea, floating debris
Autonomous Surface Vehicles (ASV)	Medium-high (10–50 km²/day)	Medium	No risk	High	Ports, coastal areas
Autonomous Underwater Vehicles (AUV)	High (seafloor focus)	High	No risk	Medium	Seafloor, reefs
Hybrid systems (SeaClear)	Very high (50+ km²/day)	Medium-high	No risk	Very high	Complex operations

Source: Prepared by the author

For the 22 coastal member states of the European Union, including Croatia, the efficiency of autonomous systems is not merely a technical advantage but a necessity for meeting the strict requirements of the Marine Strategy Framework Directive. In the context of the Adriatic Sea, characterized by a highly indented coastline and numerous islands, the scalability of Autonomous Surface Vehicles (ASVs) offers a cost-effective alternative to traditional vessel-based monitoring, which is often limited by shallow waters and complex geographical features.

Detection of Debris in the Marine Environment

Effective remediation and targeted action to deal with marine debris requires its identification. This results from the fact that insufficient information about the location, type and amount of waste requires more time and resources for removal. The development of new methods combines remote sensing, computer vision and artificial intelligence, which together contribute to easier locating of different types of marine waste that can be located at different depths - on the surface of the sea, along the coast or on the seabed. According to the Marine Strategy Framework Directive, the European Union encourages the detection and monitoring of marine litter, with a particular focus on ensuring good environmental status (GES). [1]

When it comes to remote sensing, this approach includes satellite observations, the use of an unmanned aerial vehicle (UAV) or hydroacoustic methods. Satellites are useful because they enable the

identification of larger amounts of waste in the water, while drones are more suitable for aerial photography of smaller coastal areas and beaches that are polluted by waste.
Hydroacoustic methods, such as sonar and similar sensors, are particularly vital techniques for detecting submerged debris and objects on the seabed, where optical methods often prove ineffective due to water turbidity and loss of visibility. [7]

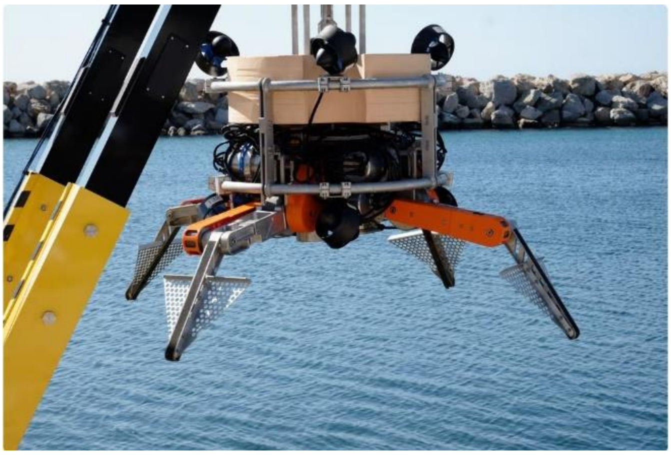
Figure 1. Representative types of autonomous robots and unmanned underwater vehicles (UUVs)

Source: https://dulist.hr/laboratorij-za-inteligentne-autonomne-sustave-seaclear-projekt/849023/

Computer vision and artificial intelligence enable automatic classification of waste based on image, shape, color, and environmental context. Such systems can easily distinguish plastic waste from natural elements such as algae, wood, or rocks, which is especially useful in environments with poor visibility or when waste is partially covered by sediment [2, 10]. These systems are useful for robotic platforms, as they can predict the shortest and most efficient collection routes. A leading challenge today is the detection of microplastics and submerged waste, due to their difficulty in distinguishing them, as standard sensors often fail to detect them. Often dispersed throughout the water column or embedded in sediment, the identification of microplastics is more sophisticated than the methods used for macro-waste. This has led to the development of integrated systems consisting of a combination of cameras, sonar, GPS, acoustic sensors, and classification algorithms [7].

Autonomous Robots and Underwater Drones in Remediation
Autonomous systems are potential solutions to challenges in the marine environment, as they can access environments that are beyond human reach and reduce costs. The approach is generally categorized into three main functional groups, as follows. First, surface robots (ASVs) are specialized for tracking and retrieving floating debris from the water surface. Second, autonomous underwater vehicles (AUVs) are used for seabed cleanup. And in the third category, we have hybrid systems as an example of the most advanced solution that combines detection, navigation and debris collection into a single common approach. Specific design and structural solutions providing stability and maneuverability for remotely operated platforms in the deep sea are shown in Figure 2, Remotely Operated Vehicle (ROV).

Figure 2. Remotely Operated Vehicle (ROV)



Source: https://www.unidu.hr/wp-content/uploads/2025/12/Capture.jpg

Autonomous Surface Vehicles (USVs) are aimed at surface-related work where they are useful for floating debris. According to the available data, the working depth is up to 3 meters deep, and optical detection is 80% successful when it comes to macro waste. Advantages during operation are simplified navigation, greater operational range and more efficient collection of plastic along the coasts, in ports, etc [9]. Autonomous underwater drones, especially AUV and ROV systems, are designed for underwater operations and as such are very useful for inspecting and extracting debris from the seabed [10].

Synergy between different technological units and their mutual communication within operational activity is best seen in integrated platforms, shown in Figure 3.

Figure 3. Illustration of the complete autonomous system architecture

Source: https://www.seaclear2.eu/wp-content/uploads/2025/08/SeaClear2.0-robotic-system.png

Key technical features include sensors, navigation modules, communication systems and autonomous control algorithms. For example, WasteShark uses a battery with a capacity of up to eight hours, and sensors for analyzing water quality, weather conditions and water level fluctuations [5]. More advanced systems have high-resolution cameras, sonar and/or AI detection, a capacity to collect up to 20 kg of waste and the ability to operate at depths of up to 200 m, with systems designed for obstacle avoidance and collision avoidance [9].
Hybrid systems according to the literature have a level of autonomy greater than 90% (requiring minimal human supervision, classified as LOA 4 according to standards).
Key features include:

- Integrated RTK-GPS/INS Navigation: RTK-GPS provides a precision of 1–2 cm on the surface (real-time corrections), while the INS (Inertial Navigation System) maintains positioning underwater where GPS signals cannot penetrate. This is achieved through sensor fusion with IMU sensors to ensure stability in currents of up to 2 m/s.
- Multipurpose Operations: Seafloor mapping (sonar), debris detection (4K cameras + AI), collection (grippers with a capacity of 7–50 kg), and aerial surveillance (drones).

Table 2. Technical characteristics and system specifications

Category / System	**Surface Robots (USV)**	**Underwater Robots (AUV/ROV)**	**Underwater Drones**	**Autonomous Robots**
Detection	Cameras: 4K (FOV 90-120°), radar (100-500 m), optical sensors	Sonar: (50-200 m, res. 5-10 cm), 4K cameras (FOV 120°), LiDAR (±2 cm)	Sonar: 2D/3D (20-100 m), HD cameras (FOV 150°), AI Vision Lock	Multi-sensor fusion: (sonar + camera + LiDAR, 85-95% accuracy)
Technical Features	Batteries: 1000-3000 Wh (12-48 h), payload 20-100 kg, speed 3-8 knots (~1.5-4 m/s), depth 0-1 m	Batteries: 500-1500 Wh (6-18 h), payload 5-20 kg, depth 30-200 m, 1-3 knots (~0.5-1.5 m/s), 8 thrusters	Batteries: 300-1000 Wh (4-12 h), payload 2-10 kg, depth 50-150 m, 0.5-2 knots (~0.25-1 m/s), 5 thrusters	Batteries: 800-2000 Wh (10-24 h), payload 10-40 kg, RTK-GPS/INS (1 cm precision), LOA 3-4 autonomy
Collection	Capacity: 1-5 m^3/h, nets/filtration (5-10 mm porosity), pump 100 L/min	Capacity: 0.3-1 m^3/h, grippers (20-100 N, max 7 kg), baskets for 2x2L bottles	Capacity: 0.2-0.8 m^3/h, grippers (10-50 N), filters 1-3 mm	Capacity: 0.5-1.5 m^3/h, adaptive grippers (50-150 N), automatic discharge
Additional Features	Modular catamaran (SWAMP), GPS/RTK navigation	100 m tether (ROV), AI waste classification (80%)	1200 lm LED, 12 MP photo/4K video, 45° tilt	5G connectivity, underwater charging "garages"

Source: Prepared by the author

Cleaning Process and Waste Processing

In simple terms, the clean-up process involves the detection, collection, temporary storage and subsequent treatment of waste on land. Removing waste from the sea is not good if the process further contaminates the waste, making it unsuitable for separation and treatment [5]. Therefore, technological systems must be integrated into the existing waste management chain. During the removal phase, robotic technology cleans piles of waste from the surface or seabed, storing the collected material in internal tanks or transferring it to a secondary system for further treatment. In larger operations, a combination of robots and service vessels is used to enable the system to be fully operational without the need to return to shore [9]. Waste storage must be safe and adapted to the specific types of waste encountered, especially when it comes to sharp instruments, fishing gear or potentially hazardous debris. Detailed features of the waste collection tank and its integration into the system can be seen in Figure 4.

Figure 4. Waste collection container

Source: https://dulist.hr/wp-content/uploads/2023/09/seaclear-projekt-2.jpg

To better understand the scale of marine pollution, it is essential to examine empirical data from diverse aquatic environments. Table 3 provides an overview of microplastic density and mass recorded in various parts of the Atlantic, Pacific, and Mediterranean oceans.

Table 3. Concentration and weight of microplastics across selected global marine locations

Location	Average Concentration	Average Weight ($mg\ m^{-2}$)
Northwest Atlantic (Coastal)	3 particles m^{-3}	
Northwest Atlantic (Offshore)	67 particles m^{-2}	
Northeast Atlantic (Celtic Sea)	2.46 ± 2.43 particles m^{-3}	
Northeast Atlantic (Portuguese Coast)	0.002–0.036 particles m^{-3}	
Western Mediterranean (Sardinia)	0.116 particles m^{-2}	0.202
Western Mediterranean (Corsica)	0.062 particles m^{-2}	
Western Mediterranean	130 particles m^{-2}	58
Western Mediterranean (Central)	0.15 particles m^{-3}	
Northeast Pacific (Southern California)	8 particles m^{-3}	
North Pacific (Central Gyre)	334.3 particles m^{-2}	5114
Northeast Pacific	0.004–0.19 particles m^{-3}	0.014–0.209
North Pacific Subtropical Gyre	0.021–0.448 particles m^{-2}	
East China Sea	0.167 ± 0.138 particles m^{-3}	

Source: Prepared by the author

Such systems, although they have a number of benefits, are not without their drawbacks, and it is important to bear in mind that they can generate noise during operation, that they can accidentally collide or, for example, touch coral reefs, and in general that they can disturb various marine mammals. It is therefore important to plan their use in a way that defines their areas of operation, if necessary limiting their use to protected areas and, where possible, using sensors to avoid spawning grounds. This requires the establishment of clear operational regulations [10]. The ultimate goal of effective marine cleaning must be the preservation of the very nature we are striving to protect. A proper balance must be struck between waste removal and the preservation of the ocean's beauty and health.

Economic and Social Aspects

When it comes to environmental protection and waste management, these are very complex approaches that require taking into account economic and social perspectives. The above only shows that such systems are very effective because they can operate 24 hours a day regardless of the conditions. As previously mentioned, the maximum depth for operation in the sea will depend on the type of system and the equipment used. Simpler underwater drones operate at depths of approximately 100 meters, while more advanced systems can reach several hundred meters. According to available studies, the financial resources invested in these systems provide long-term returns, which confirms their cost-effectiveness, this stems from the fact that investments in robotics have significantly lower long-term costs compared to, for example, continuous manual cleaning efforts that never stop [9]. As previously mentioned, the social aspect should not be ignored, which is extremely important given that marine pollution directly affects various economic sectors such as fisheries and tourism, and clearly the quality of life of the (coastal) population. According to the United Nations, plastic is the most persistent and harmful component of marine litter. From the above, it can be clearly concluded that investing in new technologies and systems is not a response to environmental imperatives, but can also be seen as an indirect economic and public health measure [11].

Legal Regulations and Standards

Marine litter is regulated by international, European, and national laws. The MARPOL Annex V legal framework prohibits the discharge of waste from ships into the sea, including plastics, fishing gear, domestic and operational waste, and other forms of refuse resulting from the daily operation of a vessel. This explicitly regulates one of the key sources of marine debris. At the European Union level, the Marine Strategy Framework Directive (MSFD) and related legislation require the monitoring of marine litter as part of achieving Good Environmental Status (GES) of the seas. At the national level, the waste management system must enable the proper reception and processing of waste collected from the marine environment [5].

Guidelines for Future Development

Future development guidelines must focus on the benefits of integrating artificial intelligence, which would achieve increased operational autonomy and more precise detection of all types of waste. A particular focus should be placed on microplastics, given that their detection is more complex [7].

The development also offers the option of connecting robotic systems to environmental monitoring networks, which include smart platforms and systems for continuous real-time monitoring regardless of location. However, apart from the aforementioned technologies, work on continuous public education should not be neglected, because a long-term sustainable solution cannot be achieved without reducing waste at its source [3].

The selection of the appropriate system clearly depends primarily on the specific environmental challenges and the location of the waste. A summary of the core characteristics and key differences between the analyzed systems is presented in Table 4.

Table 4. Summary of core characteristics, advantages, and limitations of marine robotic systems

System Type	Primary Purpose	Advantages	Limitations
Autonomous Surface Vehicles (USV)	Collection of floating debris and surface water monitoring	Simpler navigation, wider area coverage, suitable for ports and coastal areas	Operation is limited to the surface layer
Autonomous Underwater Vehicles (AUV)	Detection and removal of waste from the seafloor	Access to hard-to-reach areas, capability for detailed seabed inspection	Higher technical requirements, more complex navigation and communication
Hybrid and Coordinated Systems	Integrated detection from air, surface, and subsurface	Higher operational efficiency and superior waste identification	Increased organizational and financial complexity

Source: Prepared by the author

DISCUSSION

Autonomous robots and underwater drones possess significant potential for the monitoring and removal of marine debris. Regarding these systems, the most critical factors include detection quality, power autonomy, the ability to operate under diverse environmental conditions, and seamless integration with existing waste management frameworks. Robotics and automated systems do not solve the waste problem at its root; rather, they enable a more efficient response to existing pollution. Therefore, a long-term strategy must be founded on a combination of prevention, monitoring, removal, and appropriate regulation. In this context, autonomous systems are not a replacement for other measures but rather a technological enhancement to them.

In comparison with similar projects, the greatest progress has been observed in areas where detection and logistics are well-integrated. Examples such as WasteShark and SeaClear show that the technology is sufficiently developed for practical application, but further development is still needed to address the challenges of microplastics in the environment, as well as to reduce costs and increase modularity [9].
A key component of the discussion involves the safety and risk management of autonomous operations in complex marine environments. Moreover, the deployment of robotic fleets raises new questions in the context of cyber-physical security. Since these systems rely on connectivity via the Internet and other networks, satellite links and artificial intelligence, issues arise that include safety and risk management of autonomous operations in complex marine environments. Although such systems reduce the dangers to humans in such operating environments, new risks inevitably arise, such as collisions with various elements present in the sea. From a management perspective, the high initial capital expenditure of AUVs and hybrid systems is an obstacle; however, life cycle cost analysis (LCA) shows that operational costs are significantly lower than those with a human crew.

Protecting the integrity of environmental data and ensuring that autonomous units cannot be hijacked are key security additional requirements that should be considered in potential integration. This clearly requires standardization of autonomous operations in order to clearly define the parameters of liability and insurance. However, this is beyond the scope of this paper, but certainly opens up the need for analysis and further research.
From a governance and security perspective, Croatia faces unique challenges due to its large maritime border, indented coastline, and intensive (seasonal) tourism. The creation of a robotic fleet in the national monitoring system would contribute to the safety and security of maritime navigation in the Adriatic, in particular by identifying underwater hazards in high-traffic corridors. Furthermore, the introduction of EU standards for autonomous underwater operations would enable better cross-border cooperation between Mediterranean Member States, ensuring a unified response to transboundary pollution.

CONCLUSION

It can be concluded that autonomous systems significantly contribute to a better and more qualitative approach when it comes to cleaning the oceans and marine ecosystems. The technology presented in the paper is not a futuristic vision, but represents a concrete solution to challenges that people have difficulty dealing with: for example, waste at inaccessible depths, microplastics scattered throughout the water column and ghost nets that "catch" marine life for years. Autonomous and robotic systems have various sensors and artificial intelligence algorithms at their disposal that are useful for identifying waste, independent of location and operating conditions, and can be used for coordinated actions. The paper presents the SeaClear system, which is an excellent example of how this technology can be applied in practice. However, it is important to emphasize that despite a number of advantages, such systems cannot save our seas and oceans by their actions alone.

To achieve this, an approach is needed that primarily includes reducing the use of plastic, greater responsibility in the separation, recycling and disposal of waste, with a clear development of technologies designed to detect microparticles that are already present and negatively affect the hydrosphere, with the establishment of procedures for action and cooperation with local communities. For a coastal country like Croatia, investing in these green and digital innovations is crucial for the long-term stability of the Adriatic ecosystem, which is an important part of the national economy. By aligning technological development with EU environmental goals, Croatia could position itself as a regional leader in environmental protection and management, as well as autonomous maritime safety. A smart future depends not only on advanced technology but also on thoughtful and strategic waste management.

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THE EVOLUTION OF ENVIRONMENTAL MANAGEMENT PARADIGMS

Abstract

The significance and methodological approaches to environmental management within the context of development are undergoing a profound transformation. Historically, particularly within Western civilization, there has existed an implicit tension between economic growth and development on one hand, and environmental conservation and ecological concerns on the other. In recent decades, as environmental management has emerged as a more explicit and pressing issue requiring governmental intervention, this dichotomy has gradually diminished, giving rise to more substantial discourse on the concept of sustainable development. Contemporary understandings of environmental management and sustainable development are informed by a diverse range of disciplinary perspectives. Concepts such as economic and technological feasibility, ecological necessity, and political viability are rapidly evolving. This paper delineates five fundamental paradigms of environmental management within the framework of development: frontier economics, deep ecology, environmental protection, resource management, and eco-development. Each paradigm is characterized by distinct interpretations of evidence, priorities, and challenges, and advocates divergent solutions, strategies, technologies, and roles for economic sectors, cultural values, governmental institutions, and ethical frameworks. Furthermore, each paradigm encompasses multiple schools of thought that may not always be fully aligned. These paradigms are interconnected and overlapping, having evolved from underlying societal assumptions regarding the relationship between humanity and the natural environment. As such, they should not be regarded as entirely discrete or isolated frameworks. The paper critically examines the distinctions, interrelations, and implications of these five paradigms for the future of environmental management in the development process.

Keywords: Environmental Management Paradigms, frontier economics, deep ecology, environmental protection, resource management, eco-development.

INTRODUCTION

Every aspect of human activity, whether economic or socio-cultural, occurs within distinct frameworks of interaction with the biosphere—essentially, the relationships between individuals or communities and the natural world. "Development," by its very nature, signifies a transformation in these interactions. For instance, agriculture serves as a form of environmental stewardship; however, the diverse agricultural practices employed often reflect fundamentally different perceptions of the relationship between humans and nature, including varying interpretations of what constitutes "environmental stewardship." As societies have evolved, so too has their relationship with the environment. At times, this evolution has resulted in practices that can be regarded as beneficial and sustainable for the ecosystem. Conversely, there have been instances where human exploitation of natural resources—through the manipulation of nature to enhance survival and living standards—has ultimately led to the degradation of local ecosystems, impairing their capacity to sustain future generations.

The way in which individuals perceive their relationship with the natural world is a fundamental aspect of any human development strategy. This perception forms the foundation of all disciplines involved in "environmental management," "economics," and "development," making its evolution critical to contemporary debates and the future implementation of "sustainable development." The field of environmental management is currently undergoing substantial changes, reflecting broader shifts in societal views regarding the interaction between human actions and the natural environment. The term

"nature" is intentionally used in this context to emphasize one dimension of this connection, in contrast to the term "environment," which has emerged from a specific viewpoint on the human-nature relationship. Essentially, it represents one of the conceptual frameworks currently undergoing transformation, reflecting an evolving understanding of nature itself.
Various approaches exist to conceptualize this essential connection and its implications for practical management across different social contexts. It is proposed that there are five core frameworks through which the relationship between humans and the environment can be understood, commonly referred to as "environmental management in development." Each framework is shaped by distinct beliefs about human behavior, the nature of the environment, and the dynamics between the two. These frameworks pose different questions, analyze varying forms of evidence, identify diverse threats or challenges to development, and advocate for divergent management strategies and solutions. Furthermore, each framework has its own set of limitations. The following discussion will highlight these distinctions for greater clarity.

However, it is important to note that these paradigms should not be regarded as entirely separate or autonomous entities. Given that certain characteristics overlap between two or more frameworks, some readers may perceive the differences between them as exaggerated. To some extent, this perception is accurate, reflecting the ongoing evolution of discourse around sustainable development and environmental management. Often, the consequences of shifting circumstances and emerging ideas in the field remain underexplored, with variations frequently subsumed under the dominant framework as mere "unconventional" ideas. Consequently, terms such as "environmentalism" and "environmental management" may seem ambiguous to those outside this field. Nevertheless, these concepts are far from monolithic, just as economics is often mistakenly viewed as a homogeneous discipline. This complexity makes the discussion surrounding the definition of "sustainable development" particularly compelling, underscoring the need for a more nuanced understanding and greater clarity.

METHODS

Certain methods are better suited to addressing specific problems or challenges, and all remain essential for the foreseeable future. However, what is notably shifting is the prominence or focus allocated to these various methods. Influenced in part by the limitations of previously dominant strategies, several new paradigms have emerged from earlier frameworks, inheriting many of their predecessor's characteristics while expanding their scope to encompass broader systems or more comprehensive boundaries. It is important to acknowledge that within each overarching paradigm, ongoing debates and diverse schools of thought continue to evolve.

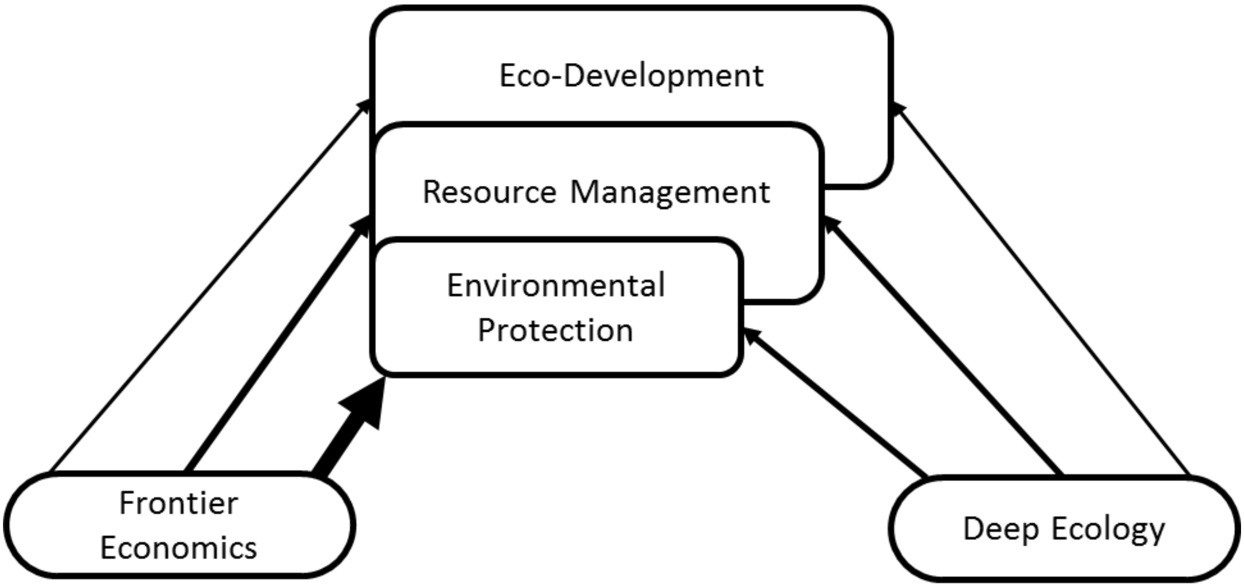
This paper aims to delineate the fundamental distinctions between these paradigms and begin to explore their implications: Frontier Economics, Deep Ecology, Environmental Protection, Resource Management, and Eco-Development. A descriptive comparative methodology is employed in this study to define five distinct approaches to environmental protection management. The authors will compare and contrast the strengths and weaknesses of these five paradigms, each of which serves as a foundation for the environmental protection management process.

RESULTS

Figure 1 provides a succinct overview of the distinctions between the various paradigms, emphasizing the dimensions previously outlined. However, presenting the five paradigms in a linear (horizontal) format may lead to a distorted perception of their "evolutionary" relationships. To address this, a two-dimensional diagram (Figure 1) has been included to offer greater clarity, although it remains an incomplete representation. Societies must critically examine the nature and significance of their relationships with the environment.

Furthermore, within the broader context of perceived dominant threats, it is possible to compile a detailed list of specific challenges or risks, along with a corresponding matrix that outlines the preferred "solutions" associated with each paradigm. Following this table, an in-depth discussion of each paradigm is provided, expanding upon the key ideas highlighted within the matrix.

Figure 1. Evolutionary Paradigms Diagram

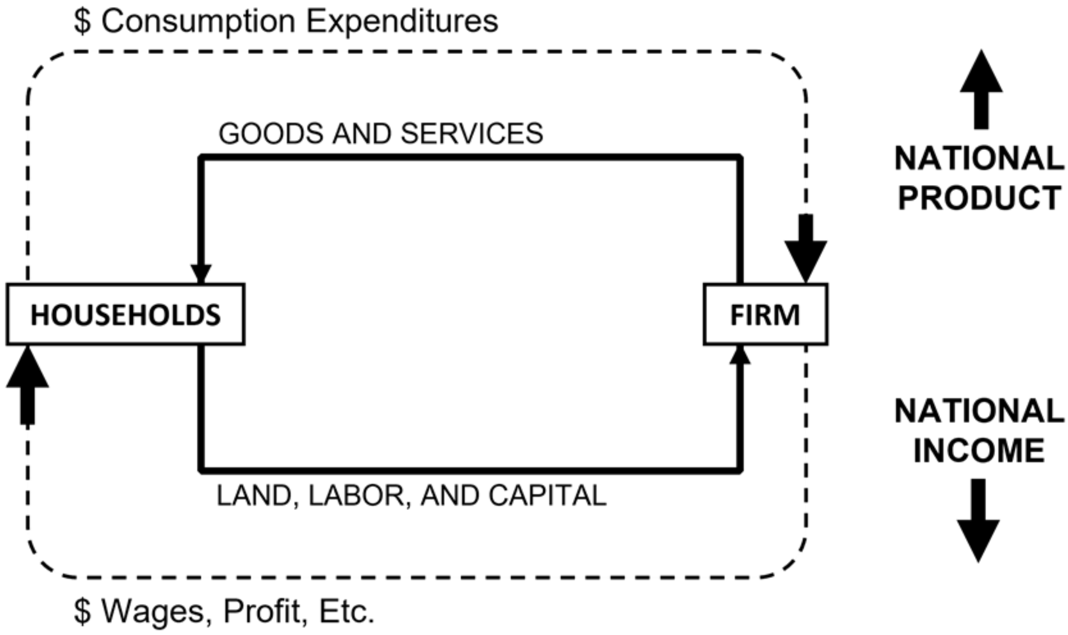


Source: [1]

Figure 1 aims to illustrate, in a simplified manner, the complex evolution of paradigms in several dimensions. It depicts the progression from one paradigm to the next in an upward trajectory over time, with the horizontal axis representing the placement of the top three paradigms on a continuum that ranges from the "diametrically opposed" poles of frontier economics to deep ecology. The dimensions of the boxes roughly correspond to the level of integration and inclusivity of social, ecological, and economic systems within the development framework and the organization of human societies.

The term **"Frontier Economics"** was coined by economist and systems theorist Kenneth Boulding to describe the dominant mindset in industrialized nations from the onset of the scientific revolution until the late 1960s. Central to this perspective is the view of nature as an infinite reservoir of physical assets, such as raw materials, energy sources, water, soil, and air, all of which are considered to be available for human use. Additionally, nature is regarded as an inexhaustible sink for the by-products of resource development and consumption, including pollution and other forms of environmental degradation. This cycle, in which resources flow from nature into the economic system and waste is subsequently expelled into the environment, was largely ignored in mainstream economic discourse, as nature was assumed to be limitless. In contrast, neoclassical economics focused primarily on the distribution of resources perceived to be finite. From this perspective, the biophysical environment is not seen as a significant entity requiring management, but rather as an external factor peripheral to economic concerns. As Lester Thurow noted in 1980, it is challenging to justify concerns about the depletion of natural resources using an economic framework.. [2-6]

Figure 2. Neoclassical Circular Flow Model of Economic Production



Source: [1]

Households provide land, natural resources, labor, and capital to firms, receiving factor payments in return, such as rent, wages, and profit. Firms then combine these factors of production to generate goods and services, which in turn yield consumption expenditures, investment, government spending, and net exports.

"Deep ecology" refers to a philosophical perspective that is often considered to stand in stark contrast to frontier economics, as viewed by proponents of both ideologies. It primarily emerges as a critique of many of the issues associated with the dominant economic paradigm. While it remains less widespread and not fully understood, this political movement is gradually gaining influence. It is essential to distinguish deep ecology from the scientific field of ecology. In its current form, deep ecology seeks to integrate various philosophical ideas—both traditional and contemporary—regarding the relationship between nature and human economic behavior. It places a particular emphasis on the ethical, social, and spiritual dimensions that are frequently overlooked within mainstream economic thought.

At present, deep ecology does not present a unified or cohesive philosophical position. Rather, it represents an intellectual current within the broader domain of "Green Politics," selectively drawing from a wide array of sources. These include contemporary systems ecology, wilderness conservation, 19th-century romanticism and transcendentalism, Eastern philosophies such as Taoism, and ethical principles related to justice and equity found in various religious traditions. Additionally, it incorporates elements of ecofeminism, pacifism, Jeffersonian ideals of decentralized and participatory governance, as well as certain social equality principles associated with socialism, often referred to as "social ecology." [7-9]

Figure 3. Dominant Economic Worldview vs. Deep Ecology Worldview

Dominant Economic Worldview	vs. Deep Ecology Worldview
Dominance over Nature Natural environment is a resource for humans Material/economic growth for growing human population Belief in ample resource reserves High technological progress and solutions Consumerism, Growth in consumption National/centralized community	Harmony with nature; symbiosis All nature has intrinsic worth; biospecies equality Simple material needs, serving a larger goal of self-realization Earth „supplies" limited Appropriate technology; non-dominating science Do with enough; recycling Minority traditions/bioregions

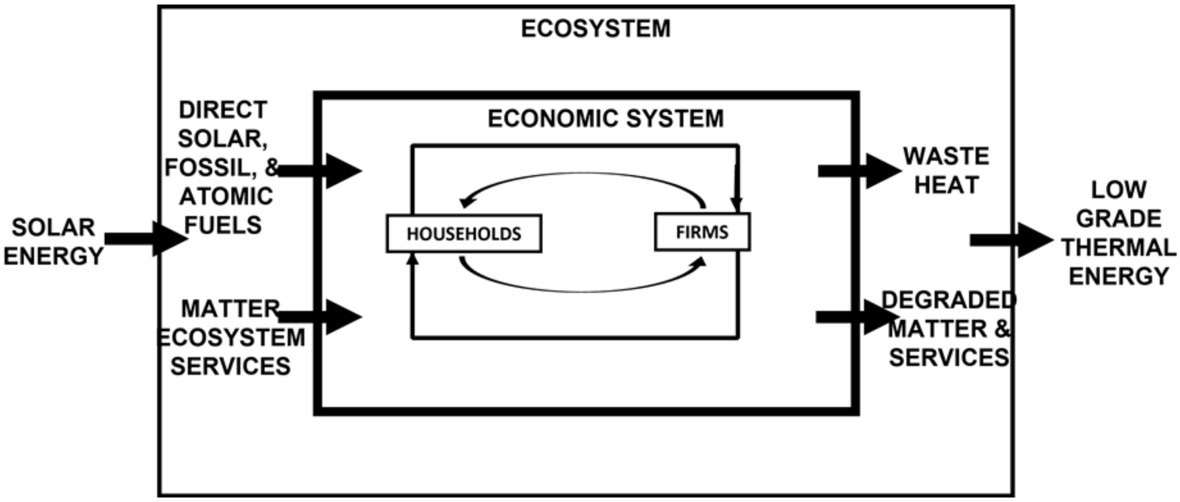
Source: [1]

In the 1960s, the dominance of the frontier economics model began to wane, particularly following the publication of Rachel Carson's groundbreaking work *Silent Spring* in 1962. By the end of the decade, pollution had emerged as a significant concern for developed nations. Researchers shifted their attention toward what they identified as "environmental problems," which were predominantly linked to pollution or the degradation of habitats and species. The recognition of pollution within the contentious framework of frontier economics contrasted sharply with the emerging principles of deep ecology, underscoring the necessity for compromises or trade-offs between economic growth and environmental preservation. The previously narrow perspective of "Ecology in Opposition to Economic Growth" gained renewed clarity during this period, paving the way for the promotion of the **"Environmental Protection"** paradigm.[10-11]

"Environmental impact statements" were introduced in various industrialized nations as a rational method to assess the benefits and drawbacks of development projects prior to their implementation. However, in practice, these statements were often incorporated only after key stages of project planning and design had already been completed, which led to environmental concerns being perceived as hindrances to development. Even in the most favorable scenarios, the process generally focuses on evaluating a limited set of alternative actions to identify the one with the least negative impact, rather than establishing fundamental "minimum standards" and then seeking solutions that align with those criteria. This marks the emergence of what could be described as a shift towards a "negative or defensive agenda" within environmental management strategies and practices, despite the fact that the underlying assumptions and values trace back much further in history. Ultimately, the approach remains predominantly anthropocentric, although some adjustments have been made in relation to critically endangered species and designated wilderness areas. However, it can be argued that the preservation of such regions still largely serves human aesthetic preferences.

Previous research has clearly demonstrated that the concept of **"Resource Management"** is gaining increasing prominence. This idea is central to numerous influential reports, including the Brundtland Commission's *Our Common Future*, the annual *State of the World* reports from the Worldwatch Institute, and the World Resources Institute's annual assessments. Resource management represents not only a significant departure from the traditional economic model but also a logical progression, positioning it as more "evolutionary" than "revolutionary." This approach advocates for the inclusion of all forms of capital—biophysical, human, infrastructural, and financial—when evaluating national accounts, productivity, and development strategies. It directly challenges frontier economic theories that disregard concerns over the depletion of natural resources. Within this framework, pollution may be viewed as a "negative resource," rather than merely an externality. Additionally, climate itself could be considered a resource in need of management. There is a growing recognition of the interconnectedness and varying significance of different resources, such as the crucial role of forests in regulating watersheds and climate, which, in turn, affect the productivity of hydropower, agriculture, and fisheries. [12-14]

Figure 3. Economic Production from a Biophysical Perspective



Source: [1]

Eco-Development represents a significant and ongoing shift in both perspective and action, one that is more profound than the previous two approaches. It can be understood as a response to the limitations inherent in those models. This approach seeks to fundamentally redefine the relationship between society and the natural world, aiming for a "positive sum game" through advanced forms of symbiosis, which contrasts with the simpler, nature-focused symbiosis promoted by deep ecologists. Eco-Development views nearly all developmental activities as mechanisms to manage this complex relationship. Terms such as environmental management, economic development, and socio-ecological development may, in essence, reflect different facets of the same overarching idea: the unified evolution of human society and nature. Consequently, the prefix "Eco-" integrates both "economic" and "ecological," reflecting their shared Greek origin, while the choice of "Development" over terms like "Growth," "Management," or "Protection" signifies a deliberate reorientation toward a higher level of integration among social, ecological, and economic factors in planning processes. [15-16]

DISCUSSION

The five paradigms previously outlined can generally be characterized by distinct interpretations of ecology, accompanied by varying degrees of inclusivity and practical application of those interpretations. These perspectives are situated within multiple contexts, including political, economic, biophysical, scientific and technological, philosophical, and social environments. Future trends may increasingly emphasize the importance of transforming worldviews, values, and, by extension, political frameworks.

Over the long term, the evolution of environmental management and development thinking—shaped by emerging conceptual frameworks from science, philosophy, and politics that significantly diverge from historically dominant ideas—could lead to innovative perspectives and unique opportunities for the interaction between humanity and the natural world. At present, these emerging trends are primarily philosophical, often grounded in ongoing debates surrounding scientific advancements and a shifting sociopolitical landscape.

Throughout this research, a recurring theme has emerged, suggesting that the evolution of environmental management reflects a broader shift in societal value systems. The degree to which humanity perceives itself as central in its relationship with the natural world serves as a key indicator of changes in these foundational values. Non-monetary values present a complex challenge, this may explain why economists have often refrained from addressing them, treating such values as constants. Nevertheless, it is clear that values play an essential role in the concept of development, and they are subject to change. The rise of influential "green" political movements in Europe, Australia, India, and Brazil, coupled with ongoing reform efforts in the Soviet Union and China, exemplify this shifting paradigm.

CONCLUSION

The summary presented in Figure 1 provides a cohesive overview of the five paradigms. It is essential to recognize that these paradigms are interconnected rather than entirely separate entities. In periods of significant transformation, the boundaries between these paradigms increasingly become blurred. No single paradigm offers a definitive solution to all environmental management or development challenges. As newer paradigms evolve, they often incorporate elements of the earlier ones.

This discussion involves two interrelated forms of evolution: the historical development of concepts and tools within the distinct paradigms, which are presented separately for clarity, and the historical shifts in their relative prominence. Rather than viewing paradigms as distinct "species," they can be conceptualized as separate "populations" that are evolving in response to changing "selective pressures" from various user groups and emerging challenges. Each paradigm reacts differently to new ideas, depending on the specific user group and the issues they prioritize. Moreover, these user groups themselves are evolving in relation to the paradigms they engage with and the challenges they identify, which, in turn, drives both the progression of the paradigms and their practical application.

Therefore, concepts of environmental management are undergoing change. The defensive (remedial) approach, due to its inability to address the detrimental effects of unchecked frontier economics and progress, has become self-defeating. In recent years, there has been a notable political shift towards a more neutral agenda, such as resource management and systems analysis. Despite this shift, there remains a prevailing belief that economic growth and environmental protection must inevitably be traded off. This assumption, however, is both detrimental and unnecessary. Approaches that fully integrate environmental management offer substantial economic and social benefits, dispelling the need for such trade-offs.

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THE IMPACT OF ARTIFICIAL INTELLIGENCE ON THE IMPROVEMENT OF OCCUPATIONAL SAFETY AND HEALTH: CHALLENGES, OPPORTUNITIES, AND REGULATORY FRAMEWORK

Abstract
Artificial intelligence is increasingly finding its application in the field of work and occupational safety and health. This paper analyzes the impact of artificial intelligence on the improvement of working conditions, the prevention of occupational injuries and diseases, and the enhancement of occupational safety and health management systems. Various possibilities for the application of artificial intelligence in occupational safety and health systems are examined, including its role in the automation of high-risk work processes, monitoring of the working environment, improvement of ergonomic and psychosocial working conditions. The paper highlights potential challenges related to the implementation of artificial intelligence in occupational safety and health, including issues of liability, employee data protection, ethical dilemmas, etc. A particular issue addressed is the need to adapt the existing regulatory framework. The conclusion is that artificial intelligence can play a significant role in improving occupational safety and health, but only if accompanied by adequate regulation, professional oversight, and responsible implementation.

Keywords: artificial intelligence, occupational safety and health, benefits, challenges, regulatory framework.

INTRODUCTION

Artificial intelligence, understood as software incorporating algorithmic models capable of performing tasks characteristic of intelligent beings—such as reasoning, meaning-making, generalization, and learning from prior experience—has found application in the development of numerous products and services, including autonomous vehicles, biometric identification systems, traffic management systems, as well as systems used in education and public administration, among others. More simply, it may be defined as the simulation of natural intelligence in machines that are programmed to learn and emulate human actions [1]. Some authors define artificial intelligence as novel information systems capable of autonomous learning and of undertaking various activities in a manner comparable to that of an intelligent human being [2].

Within the world of work, two distinct types of artificial intelligence applications in the workplace can be identified [3]. The first is oriented toward the automation of tasks performed by workers, while the second involves the use of AI-based analytics and algorithms to automate managerial functions—commonly referred to as "algorithmic management."

When artificial intelligence is employed to automate tasks, one of the primary concerns is the risk of large-scale job displacement. However, such an outcome is not inevitable, as technology can also be used to complement human labor when certain tasks are automated. Whether the adoption of technology leads to automation (job displacement) or augmentation (task complementarity) depends on several factors, including the centrality of the automated task within a given occupation, the manner in which technology is integrated into work processes, and the willingness of management to retain human workers to perform or oversee certain tasks despite their automation potential. It is important to acknowledge the inevitability of occupational transformation driven by artificial intelligence; accordingly, a workforce equipped with skills in machine learning, data science, and ethics is essential for harnessing the full potential of these technologies.

In addition to its potential effects on workers, the integration of artificial intelligence into the workplace may also have significant implications for organizational performance, including employee productivity, with spillover effects on broader economic outcomes. Consequently, unequal access to technology—arising from infrastructural bottlenecks, skills shortages, or cost barriers—may exacerbate existing productivity disparities between countries, as well as between large enterprises and small or micro-sized firms [3].

As artificial intelligence exerts a global influence on the world of work, it also has important implications for occupational safety and health. This paper examines how artificial intelligence may contribute to the improvement of working conditions, the prevention of occupational injuries and diseases, and the overall enhancement of workplace environments. Particular attention is devoted to the need for, and possibilities of, adapting the existing legislative framework to this emerging trend in occupational safety and health, especially given the European Union's ambition to become a global leader in establishing a safe environment for the use of artificial intelligence. In this context, it is imperative for the Republic of Serbia to follow these developments, which entails the establishment of an appropriate ethical and legal framework for the development and deployment of AI-based products and services.

ADVANTAGES AND CHALLENGES OF THE APPLICATION OF ARTIFICIAL INTELLIGENCE

When assessing the advantages and risks associated with the application of artificial intelligence across different segments of work, it is not straightforward to adopt a categorical position "for" or "against" its use. The impact of artificial intelligence is not inherently positive or negative; rather, it depends on the type of AI deployed, the manner of its use, and the specific legal, political, and institutional context in which a given system is implemented [4].

For instance, the digitalization of recruitment processes and the use of artificial intelligence enable the rapid and efficient processing of large volumes of data, the prediction of recruitment outcomes, and the effective matching of job seekers with suitable vacancies. At the same time, costs are reduced due to the automation of tasks previously performed by teams of employees within employers' organizations, public employment services, and private recruitment agencies [5]. An additional advantage lies in the reduction of errors that may occur in decision-making and in the execution of actions within recruitment procedures. However, algorithmic screening of job applications is not immune to risks, particularly the risk of discrimination. It is possible for algorithms to be based on data reflecting negative stereotypes and biases; similarly, in certain cases, algorithms may fail to account for factors relevant to preventing discrimination and ensuring equal treatment of candidates [5]. This implies that, in recruitment processes, algorithms may identify correlations not only between permissible criteria (such as skills and competencies), but also between permissible and impermissible grounds for differentiation among candidates [6].

Furthermore, digitalization and artificial intelligence have enabled the emergence of algorithmic management of employees. Although particularly prevalent in platform work [7,8], this phenomenon is also present in traditional forms of employment, especially with regard to task allocation, supervision of work, and the monitoring and evaluation of employee performance. This includes the use of systems that allow employers to track employees' location and movement, as well as the speed and efficiency of their work. Electronic monitoring is also applied to employees working at service counters and interacting with a large number of clients, particularly through the supervision of electronic communications conducted via company computers and telephones. For example, software such as Work Examiner enables comprehensive monitoring of virtually all employee activities conducted on workplace computers—from keyboard usage, internet browsing, and email communication to document downloads and printer usage—either with or without the employee's knowledge [4]. Such software may also capture screenshots in order to reproduce employees' activities. Additionally, it may facilitate monitoring through so-called sociometric badges, i.e., devices worn by employees to track their location and interactions with colleagues. These devices are equipped with microphones and voice-analysis programs capable of assessing workers' emotional states, without recording the content of conversations. This provides employers with the capacity to collect data for decision-making in personnel matters, with the aim of improving productivity, ensuring asset security, and enhancing employee safety. In this context, strict compliance with personal data protection regulations is essential.

Although the introduction of artificial intelligence systems into the workplace can enable employees to perform their tasks more easily, safely, and productively, it simultaneously opens the door to potential abuses of employers' supervisory, evaluative, and other managerial powers. The most significant risks relate to the infringement of the privacy of job applicants and employees, asymmetries of power between parties in recruitment processes, lack of transparency, algorithmic bias, and unclear rules regarding liability for violations of labor rights—particularly when employer decisions rely predominantly on data collected through digital monitoring systems. Another critical concern is the absence of meaningful human oversight over the entire process [9]. These risks may ultimately lead to violations of fundamental human rights, ranging from the right to dignity and personal integrity, freedom of expression, protection against discrimination, and the right to privacy, to core labor rights such as the right to occupational safety and health.

While digitalization and automation generally contribute to the protection of workers' health and safety—by relieving employees from repetitive, physically demanding, and hazardous tasks—they may also adversely affect workers' well-being and dignity. Artificial intelligence enables access to a wide range of personal data, including sensitive data. Similarly, work in collaborative systems, where employees and advanced robots jointly perform tasks, entails risks to employee health, particularly due to the fact that machines often determine the pace and intensity of work [9]. On the other hand, a further negative aspect is the limited opportunity for workers to develop their личности through work, especially where they are unable to fully utilize their acquired skills and knowledge, which may negatively impact their self-esteem and job satisfaction.

A further significant challenge concerns the provision of high-quality data for machine learning. Machine learning applications require the collection of large volumes of data; however, this is often accompanied by the inclusion of low-quality data, as well as excessive data collection. Such practices may conflict with one of the fundamental principles of personal data protection, namely data minimization [9].

REGULATORY FRAMEWORK

As previously noted, although there are numerous arguments in favor of the application of artificial intelligence—both generally and in the field of occupational safety and health—its deployment is also accompanied by certain risks. One of the most significant adverse effects concerns the potential infringement of fundamental human rights. In order to ensure legal certainty, effective enforcement of the law, and the protection of human rights, it is necessary for national legal systems to adopt specific regulations governing the use of artificial intelligence, including its application within the domain of occupational safety and health.

In this context, the European Union adopted the Artificial Intelligence Regulation in 2024, with certain provisions entering into force in 2025, others becoming applicable as of August 2026, and a smaller number of provisions scheduled for implementation in 2027 [10]. This represents the first comprehensive legal framework on artificial intelligence at the global level and serves as a guiding model for EU Member States, as well as for countries aspiring to membership, in adapting their legislation to ensure effective legal implementation, legal certainty, and the protection of fundamental rights. The Regulation aims to promote the development and uptake of safe and trustworthy AI systems within the European Union's single market, while simultaneously ensuring respect for fundamental rights and fostering investment and innovation in the field of artificial intelligence in Europe.

The Regulation distinguishes four categories of artificial intelligence systems based on the level of risk they pose: minimal risk, high risk, unacceptable risk, and specific transparency risk [10].

The vast majority of AI systems fall within the category of minimal risk, such as spam filters. These systems pose little to no risk to the rights or safety of individuals.

High-risk AI systems are subject to stringent regulatory requirements. Examples include systems used in critical infrastructure sectors such as water, gas, and electricity; medical devices; systems determining access to educational institutions or used in recruitment processes; and systems employed in border control. Furthermore, biometric identification, categorization, and emotion recognition systems are also considered high-risk.

AI systems presenting an unacceptable level of risk—those deemed to pose a clear threat to fundamental human rights—are prohibited. Examples include applications designed to manipulate human behavior in ways that circumvent users' free will, such as toys equipped with voice assistants that encourage harmful behavior in minors. In addition, certain uses of biometric systems are banned, including emotion

recognition systems in the workplace, as well as specific forms of biometric categorization and real-time remote biometric identification in publicly accessible spaces for law enforcement purposes.
The fourth category concerns systems associated with specific transparency risks. For example, when chatbots are used, users must be informed that they are interacting with a machine. All AI-generated content must be clearly labeled as such, and users must be notified when biometric categorization or emotion recognition systems are in use. Moreover, providers are required to design systems in such a way that synthetic audio, video, text, and image content is marked in a machine-readable format and can be identified as artificially generated or manipulated.
All of the aforementioned risks can be transposed to numerous situations within the workplace, where both labor rights and the right to occupational safety and health may be affected. The task of contemporary legal systems—both international and national—is to develop instruments capable of preventing the materialization of these risks or, where prevention is not possible, to ensure effective protection for workers whose rights have been violated. In this regard, particular importance is attached to the recognition of the worker's right not to be subject solely to automated decision-making.

In this context, it is also essential to recognize the right of workers, as well as their trade union representatives and other representatives—such as occupational safety and health representatives—to receive an explanation of algorithmic decisions that directly or indirectly affect them. This entails the right to an explanation of the parameters involved in machine-assisted decision-making processes, which remains a complex challenge due to the inherent opacity and unpredictability of machine learning systems [11].
Furthermore, it is of particular importance that legislators acknowledge the worker's right to digital disconnection, that is, the right of employees not to engage in work-related activities or communications outside working hours through digital devices. This right is already guaranteed in the legal systems of several EU Member States (including Belgium, Greece, Italy, Portugal, Slovakia, France, and Spain), while in other jurisdictions it is recognized as an integral component of the right to fair working conditions or the right to occupational safety and health [4].
Finally, the right to collective bargaining, as well as employees' rights to information and consultation, constitute important instruments for the protection of workers. These mechanisms contribute to building trust among employees, reducing uncertainties related to the use of artificial intelligence, and fostering a more positive attitude toward technological change.

INSTEAD OF A CONCLUSION – DEVELOPMENT PERSPECTIVES AND FUTURE IMPLICATIONS

Based on the conducted research, several conclusions may be drawn.
First, it is evident that the use of artificial intelligence in the world of work—particularly in the field of occupational safety and health—remains a relatively new topic, with a limited body of available scientific literature. The continued development of artificial intelligence systems will lead to their increasingly widespread use among employers, thereby amplifying their impact on occupational safety and health, both in positive and negative terms. In the future, artificial intelligence systems are likely to be systematically incorporated into risk assessment processes relating to occupational safety and health.
There are numerous positive implications of artificial intelligence for the world of work. Notably, a variety of intelligent occupational safety and health management systems are currently being developed. This development requires a broad range of professional skills, as well as specialists responsible for labeling, classifying, and validating the data used in specific artificial intelligence systems. Although precise data on the number of workers engaged in such activities are not available, estimates suggest that this figure reaches into the tens of millions [4]. These developments are expected to contribute to a reduction in workplace injuries and occupational diseases, increased efficiency in monitoring the implementation of safety measures, faster decision-making based on collected data, optimization of work processes, and the enhancement of preventive measures.
At the same time, there are numerous negative implications and challenges associated with the application of artificial intelligence. These include issues of liability for decisions made by AI systems, the increasingly prominent concerns regarding data protection and employee privacy, questions surrounding the ethical use of artificial intelligence, the prevention of digital discrimination and excessive employee surveillance, and the risks associated with over-automation, among others.

In light of the foregoing, there is a clear need for comprehensive legal regulation of the use of artificial intelligence systems in the world of work. At present, this area of law remains in its early stages of development. The European Union adopted its first comprehensive legal instrument on this subject in 2024, while national legal systems have yet to fully regulate this field. In the process of legislative development within EU Member States, national regulations must be aligned with the EU Regulation. Similarly, the Republic of Serbia should model its future regulatory framework on this Regulation.

Finally, it is important to return to the starting point. Regulating the use of artificial intelligence in the workplace necessarily entails understanding the causes of unpredictability inherent in machine learning systems—a highly complex task, particularly in light of their dynamic nature and capacity for autonomous learning. Such understanding is essential for establishing legal liability for damage caused to workers by algorithmic decision-making. The protection of human rights against the risks posed by AI-based technologies must remain a priority for both international organizations and national governments. In addition to the European Union, the Council of Europe has adopted a series of recommendations, declarations, and guidelines calling on Member States to take appropriate measures to regulate various aspects of artificial intelligence [12].

In conclusion, artificial intelligence represents a significant potential for improving occupational safety and health; however, this potential can only be realized through appropriate regulation, expert oversight, and responsible implementation.

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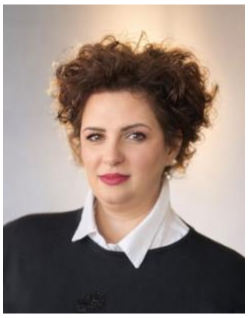

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Subject review

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TOWARDS AN INTEGRATED ENVIRONMENTAL FOOTPRINT ASSESSMENT OF AI INFRASTRUCTURE

Abstract
The rapid expansion of artificial intelligence (AI) systems has led to a significant increase in the scale and complexity of the underlying digital infrastructure, especially high-performance computing environments and large-scale distributed systems. Although AI is often considered a key technology for addressing environmental challenges, a growing body of evidence suggests that its application is associated with substantial environmental pressures across multiple resource dimensions. Existing research on the environmental impacts of AI is largely fragmented, with most studies focusing on isolated indicators such as energy consumption, carbon emissions or water use. Recent literature further highlights additional resource dimensions, including material intensity, e-waste generation and spatially uneven infrastructure burden. However, a coherent and integrated framework for assessing the overall environmental footprint of AI systems remains underdeveloped. This paper addresses this gap by developing a conceptual framework for integrated assessment of the environmental footprint of AI infrastructure. The proposed approach integrates findings from existing literature across several environmental dimensions, including energy demand, water use, emissions, and resource consumption, while emphasizing the need for a unified perspective capable of capturing cumulative and interactive impacts. Rather than attempting to provide definitive quantification, the study aims to structure the problem of environmental impact assessment in a systematic manner and to identify key groups of indicators that can support future empirical measurements and policy development. The framework contributes to ongoing efforts to standardize environmental impact assessment methodologies for digital technologies and highlights the importance of moving from single-metric assessments to multidimensional environmental accounting of AI systems.

Key words: environmental footprint, AI infrastructure, indicators, integrated framework, innovation.

INTRODUCTION

AI has rapidly evolved from a specialized research field to one of the dominant technological drivers of modern digital transformation. The rapid proliferation of generative AI systems, large-scale language models, and high-performance computing platforms has accelerated global demand for computing infrastructure, data processing capacity, and cloud-based services [1]. At the same time, AI is increasingly recognized as a strategic technology capable of supporting climate modeling, smart energy management, environmental monitoring, industrial system optimization, and broader sustainability-oriented decision-making [2,3,4]. Yet, despite the growing perception of AI as a technology that enables sustainability, there is still no clear scientific consensus on whether the overall environmental benefits of AI applications outweigh the environmental pressures created by the infrastructure required to develop and operate such systems. In this context, international initiatives such as the European Green Deal, Shaping Europe’s Digital Future, the OECD AI Framework and the proposed AI Law highlight the importance of aligning digital transformation with environmental sustainability goals.
However, despite the acknowledged benefits of AI deployment, increasing scientific and institutional attention has been focused on the environmental burden generated by AI infrastructure itself [5]. In contrast to traditional digital services, modern AI systems rely on extremely energy-intensive computing processes, including large-scale model training, continuous inference processes, GPU (graphics processing units) accelerated computing and hyperscale data centers operating under near-constant high utilization [6,7]. These processes require significant amounts of electricity, cooling capacity, water resources, raw materials and electronic components, creating multidimensional environmental pressures that extend beyond conventional carbon accounting [8,9,10].

LITERATURE REVIEW

Recent studies indicate that the environmental impacts of AI infrastructure are becoming increasingly significant at both global and regional levels. According to OECD and IEA analyses, the rapid growth of computing demand associated with AI could significantly increase electricity consumption in data centers in the coming years [11,12]. Existing research further suggests that the operational impacts of AI systems include not only greenhouse gas (GHG) emissions, but also direct and indirect water consumption, material intensity, land use pressures, e-waste generation and spatial concentration of infrastructure burdens [5,6]. The United Nations Environment Programme (UNEP) further warns that the environmental effects of AI remain largely invisible to end users despite the significant physical infrastructure required to maintain digital services. These environmental pressures are particularly visible in regions characterized by a high concentration of hyperscale data centers and intensive cloud-computing activity. Several regions characterized by a high concentration of hyperscale data centers, particularly the United States, parts of Europe, and East Asia, have experienced increasing pressure on power systems, cooling infrastructure, and local water resources due to the rapid expansion of digital infrastructure [6,8,9,11,12]. In several urban and regional areas, concerns have arisen about the increasing demand for electricity, localized water stress, land occupation, and infrastructure resilience associated with the development of large data centers. These challenges are especially pronounced because AI facilities often operate continuously with very high computing loads, resulting in continuously elevated energy and cooling demands compared to conventional digital infrastructures.
At the same time, the assessment of the environmental impact of AI systems remains methodologically fragmented. Most existing studies focus on isolated indicators, particularly energy consumption or carbon emissions, while significantly less attention is paid to an integrated assessment of cumulative environmental impacts [5,6,7,8,9,10]. Some studies examine operational electricity demand and associated GHG emissions, others focus on the water footprint of cooling systems, while new research addresses embodied impacts related to semiconductor manufacturing, hardware supply chains, and end-of-life e-waste management [6,7,8,9]. Consequently, the absence of a single assessment framework limits comparability across studies and complicates the development of evidence-based policies.

An additional challenge lies in the limited transparency of AI infrastructure operators regarding environmental performance metrics. Current sustainability reporting practices remain inconsistent, particularly with regard to AI-specific electricity consumption, operational water use, cooling efficiency, indirect environmental impacts, and life-cycle resource requirements [8,11]. While several international initiatives and standards, including IEEE P7100, recognize the importance of assessing the environmental performance of digital technologies, a comprehensive and standardized methodology for an integrated assessment of the AI footprint is still under development.
The OECD Framework for Measuring the Environmental Impact of AI emphasizes that future assessment approaches need to go beyond single operational indicators and include broader environmental dimensions, including direct and indirect impacts across the entire life cycle of AI systems [11]. Similarly, recent scientific literature highlights the need for integrated environmental accounting that is able to simultaneously take into account energy demand, water consumption, emissions, material consumption, infrastructure concentration and resource efficiency [5,6,7,8,9,10]. These recommendations are particularly relevant in the context of the global "green and digital twin transitions", where digital transformation and climate goals increasingly intersect.

In response to these challenges, this paper develops a conceptual framework for an integrated assessment of the environmental footprint of AI infrastructure. The proposed approach integrates existing scientific findings, policy frameworks, and sustainability assessment principles into a coherent analytical structure for evaluating the multiple environmental dimensions of AI infrastructure. Rather than focusing exclusively on a single impact category, the framework considers energy consumption, GHG emissions, water consumption, resource intensity, and broader environmental pressures associated with infrastructure as interdependent dimensions of assessing the sustainability of AI.
The study aims to contribute to ongoing efforts to standardize environmental impact assessment methodologies for AI systems and digital infrastructure by identifying key categories of indicators suitable for future empirical application and policy evaluation. Furthermore, the paper supports a broader shift from fragmented environmental reporting to integrated sustainability assessments that are

capable of capturing the cumulative environmental pressures associated with the continued expansion of AI infrastructure [1,5,11].

METHODS

Defining a comprehensive framework for assessing the environmental footprint of AI infrastructure poses a significant methodological challenge due to differences in system boundaries, environmental indicators, and assessment approaches used in existing studies. While some studies primarily focus on operational energy consumption and greenhouse gas emissions during training and inference, others extend the analysis to water consumption, infrastructure impacts, embodied emissions, and broader sustainability dimensions [5,6,7,8,9,10]. Previous research has consequently resulted in fragmented approaches to environmental assessment, characterized by inconsistencies in life cycle coverage, indicator selection, methodological assumptions, and principles for assessing environmental performance [10,11]. To identify dominant methodological approaches, research gaps, and opportunities for developing a more comprehensive environmental assessment framework, this study applies a structured comparative analysis of scientific literature, institutional reports, standards, and regulatory frameworks related to the environmental sustainability of AI.
The comparative methodological review included scientific papers, institutional reports, standards, and regulatory documents that address the environmental impacts of AI systems, data centers, and AI digital infrastructure. The analyzed sources were comparatively evaluated according to their research focus, methodological approach, environmental indicators, life cycle coverage, and identified methodological limitations relevant to developing a more integrated environmental footprint assessment framework for AI systems. A comparative overview of the analyzed methodological approaches and their key characteristics identified in the reviewed literature is presented in Table 1.

Table 1. Comparative overview of methodological approaches for environmental footprint assessment of AI systems and infrastructure

Author	Main Focus	Methodological Approach	Main Indicators	Life Cycle Coverage	Specific Contribution	Identified Limitations
Angrisani et al. (2026)	Environmental sustainability measurement of AI	GUM-based user-centered measurement framework	Energy, uncertainty, sustainability indicators	Operational phase	Introduces structured measurement uncertainty framework	Limited life cycle integration
Rohde et al. (2024)	Sustainable AI criteria and indicators	Sustainability-oriented indicator framework	Sustainability criteria, environmental indicators	Partial AI life cycle	Broadens sustainability perspective beyond carbon	Limited operational quantification
Hlabisa (2025)	Ecological limits of AI systems	Systems ecology perspective	Energy, water, materials, land use	Broad AI ecosystem	Holistic ecological interpretation of AI infrastructure	Conceptual rather than operational
Barnett-Itzhaki (2026)	Water footprint of AI	Water governance and footprint analysis	Water consumption, cooling demand	Data center operations	Emphasizes water sustainability dimension	Limited integration with carbon metrics
Vries-Gao (2026)	Carbon and water footprint of data centers	Data center environmental assessment	CO_2e, water footprint	Infrastructure and operations	Connects AI expansion with data center sustainability	Focused mainly on infrastructure
Siddik et al. (2021)	Environmental impacts of data centers	Environmental footprint analysis	Energy, emissions, infrastructure impacts	Data center systems	Quantifies infrastructure-related burdens	Limited AI-specific analysis
Lambert & Luccioni (2026)	Life cycle review of AI environmental impacts	AI-oriented life cycle assessment review	Energy, CO_2e, water, embodied impacts	Full AI life cycle	Most comprehensive AI life cycle synthesis	Lack of standardized reporting methodology

OECD (2022)	Environmental impacts of AI compute	Policy-oriented measurement framework	Energy, compute, emissions	AI computation and applications	Establishes policy-level AI footprint framework	Limited operational measurement guidance
IEA (2024)	Electricity demand and forecasting	Energy systems analysis	Electricity demand, energy mix	Energy infrastructure	Provides macro-level energy context for AI growth	Not AI-specific
IEEE P7100	Environmental impact measurement of AI systems	Standardization framework	Environmental impact indicators	AI systems	Standardization-oriented AI sustainability framework	Still under development

Source: Authors, 2026

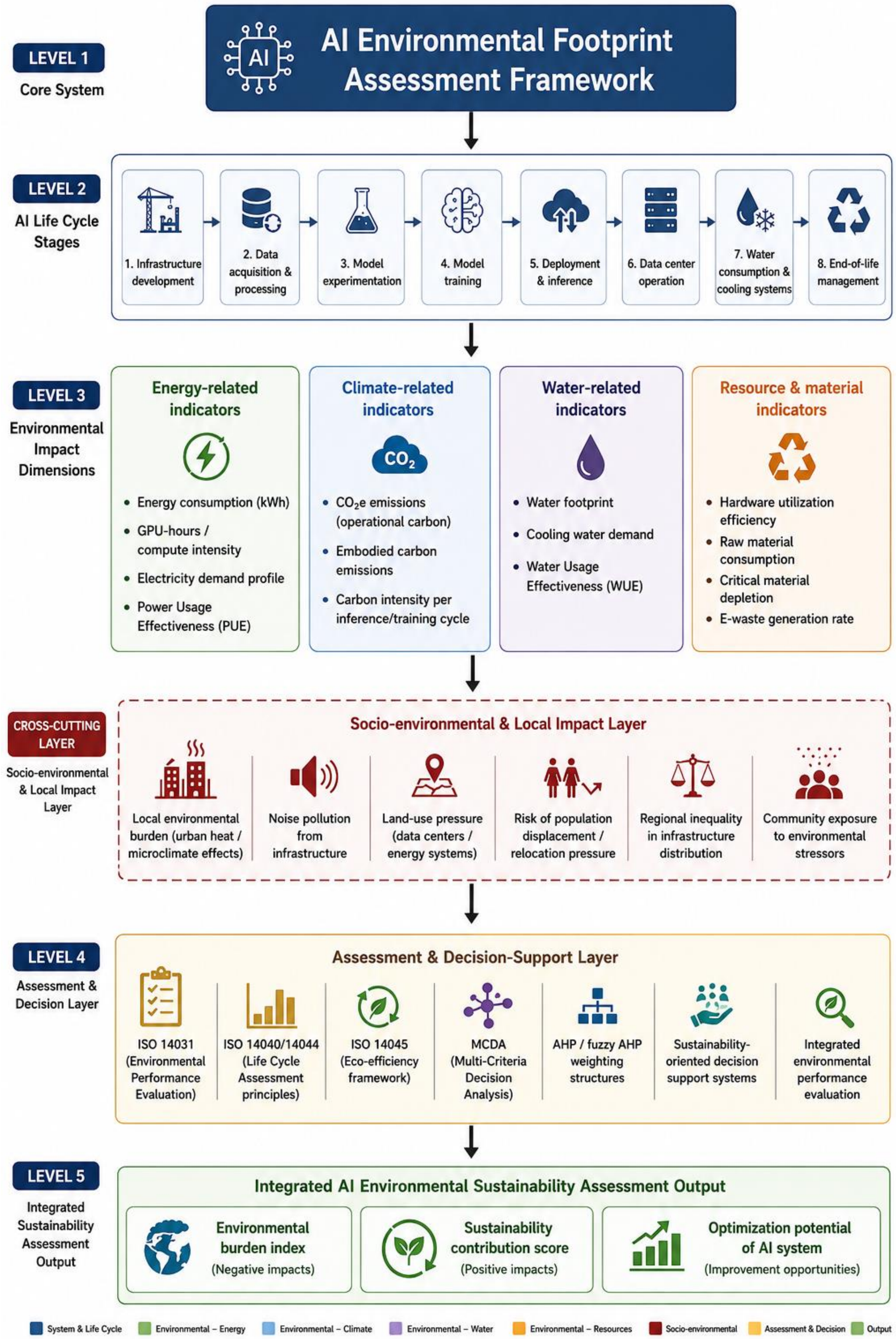
The comparative review indicates that no single existing approach currently integrates operational, infrastructural, water-related, and life cycle environmental dimensions of AI within a unified indicator-based assessment framework. In response to these identified methodological gaps, the proposed methodological framework is based on the integration of life cycle assessment principles, environmental performance assessment concepts, and multi-criteria decision-making (MCDA) logic to support the development of a more comprehensive framework for assessing the environmental footprint of AI infrastructure. Particular emphasis is placed on identifying and hierarchically structuring environmental innovation indicators applicable across different AI life cycle stages, including infrastructure development, data center operation, model experimentation, training, deployment, water consumption, and end-of-life management [13]. The methodological basis of the proposed framework is aligned with internationally recognized environmental management and assessment standards, primarily ISO 14031, the principles of ISO 14040and ISO 14044, as well as the concepts of eco-efficiency in accordance with ISO 14045. In addition, the research includes elements of MCDA in environmental assessment and hierarchical decision-making structuring approaches commonly applied in environmental management and sustainability assessment models [2,3,4]. Although ISO 14031 was not originally developed for AI systems, its indicator-oriented environmental performance assessment framework provides an appropriate methodological basis for structuring environmental assessment in AI-related contexts. Previous research has demonstrated the applicability of ISO 14031 principles in the development of integrated environmental performance assessment models based on indicator systems and hierarchical assessment structures [3].

Accordingly, this research conceptually proposes a hierarchical and indicator-based framework to support future environmental impact assessment of AI based on MCDA and the Analytical Hierarchy Process (AHP). The aim is not limited to quantifying the negative environmental burdens of AI infrastructure itself, but also to create a methodological basis for assessing the broader environmental implications of AI applications, including its potential contribution to environmental protection, optimization, and sustainability-oriented decision-support and environmental innovation management. Given the methodological complexity, limited transparency of AI systems, and the absence of standardized environmental reporting practices, the proposed framework should be understood as a conceptual and preliminary methodological basis for future quantitative modeling, weighting procedures, and operational assessment of the environmental performance of AI systems and infrastructure.

RESULTS AND DISCUSSION

Based on a comparative methodological review and identified limitations of existing approaches, this research proposes a conceptual hierarchical framework for assessing the environmental footprint of AI systems and infrastructure. The framework integrates life cycle assessment principles, environmental performance assessment concepts, and multi-criteria decision-making logic to support a more comprehensive and structured assessment of the environmental impacts of AI. The proposed framework is structured hierarchically and consists of several interconnected levels, including AI life cycle stages, environmental impact categories, environmental performance indicators, and decision support assessment components. In contrast to existing approaches that focus predominantly on operational energy consumption and carbon emissions, the proposed framework includes a broader set of environmental dimensions relevant to AI infrastructure and applications. The conceptual structure of the proposed framework and the relationships between the main components of the assessment are shown in Figure 1.

Figure 1. Conceptual framework for integrated environmental footprint assessment of AI infrastructure



Source: Authors, 2026

The first level of the proposed framework defines the central objective of the assessment process, namely the integrated assessment of the ecological footprint and sustainability of AI systems and infrastructure. At this level, the framework conceptually establishes the overall boundaries of the assessment and connects the operational, infrastructural, and sustainability-oriented dimensions of the environmental impact of AI into a single methodological framework.
The second level presents the stages of the AI life cycle identified through a comparative review of existing literature and methodological approaches. In contrast to studies limited primarily to model training and operational power consumption, the proposed framework adopts a broader life cycle perspective that includes infrastructure development, data collection and processing, model experimentation, training, deployment and inference, data center operation, water consumption and cooling systems, and end-of-life management. Structuring the framework across lifecycle stages allows for a more systematic identification of environmental impacts generated during the development and operation of AI systems and infrastructure.

The third level includes environmental impact dimensions and corresponding groups of indicators applicable to different phases of the AI lifecycle. The proposed structure includes energy-related indicators (e.g. energy consumption, graphics card operating hours, power demand profiles, PUE), climate-related indicators (e.g. operational and embodied CO_2e emissions, carbon intensity), water-related indicators (e.g. water footprint, cooling demand, water use efficiency – WUE), and resource and material-related indicators (e.g. hardware use efficiency, raw material consumption, critical material depletion, and e-waste generation). In contrast to the predominantly carbon-centric approaches identified in the literature reviewed, the proposed framework supports a multidimensional environmental impact assessment framework capable of integrating operational, infrastructure and resource-related environmental impacts.
In addition to conventional environmental indicators, the framework introduces a cross-sectoral socio-ecological and local impact layer, intended to capture the broader environmental and social implications associated with the development and operation of AI infrastructure. This layer includes local environmental pressures such as urban heat and microclimate effects, infrastructure-related noise, land-use pressures associated with data centers and energy systems, population displacement risks and spatial pressure, regional inequalities in infrastructure distribution and potential community exposure to environmental stressors. The inclusion of this layer extends the assessment beyond purely technical carbon-based indicators and supports a more holistic interpretation of the sustainability impacts of AI in local and regional environmental contexts.

The fourth layer is the assessment and decision support layer, which integrates environmental management standards, life cycle assessment principles and multi-criteria decision-making concepts into the proposed framework. ISO 14031 provides a methodological basis for assessing environmental performance through indicator-based assessment, while ISO 14040 and 14044contribute to the basic principles of life cycle assessment. In addition, ISO 14045 introduces eco-efficiency considerations relevant to linking environmental impacts to functional and operational performance. The framework further includes the concepts of MCDA logic and AHP as potential future tools for hierarchical structuring, weighting, prioritizing, and comparative assessment of environmental indicators and AI sustainability performance. The integration of these approaches enables the development of structured decision support mechanisms for future quantitative environmental assessment models in line with the ISO 56001.
The fifth level represents the integrated sustainability assessment output of the proposed framework. At this level, environmental indicators and assessment components are conceptually aggregated into broader sustainability-oriented assessment results, including an environmental burden index, a sustainability contribution score, and an AI system optimization potential. In addition to identifying negative environmental impacts associated with AI infrastructure, the framework also aims to support the assessment of potential positive contributions of AI applications to environmental protection, resource optimization, energy efficiency improvement, and sustainability-oriented decision-making processes. The proposed framework addresses several methodological limitations identified in previous studies related to the assessment of the environmental impact of AI. Existing approaches have predominantly focused on operational energy consumption and carbon emissions, while significantly fewer studies integrate broader life cycle impacts, water-related pressures, infrastructure effects and socio-ecological dimensions within a single assessment framework. By integrating the principles of life

cycle assessment, the concepts of environmental performance assessment and the hierarchical structuring of indicators, the proposed framework contributes to a more comprehensive and standardized methodological basis for assessing the environmental footprint of AI.

CONCLUSION

In response to the identified methodological limitations of existing approaches, this research proposed a conceptual hierarchical framework for an integrated assessment of the environmental footprint of AI systems and infrastructure, based on standardized life cycle assessment principles, environmental performance assessment concepts, and multi-criteria decision-making logic. The proposed approach allows for the structuring of environmental indicators across multiple stages of the AI life cycle and supports a broader understanding of the sustainability impacts of AI through the integration of energy, climate, water, resource, and socio-ecological dimensions.

The research further emphasizes that future environmental assessment of AI should not be limited solely to identifying negative environmental burdens. AI systems are increasingly showing significant potential to contribute to environmental protection and sustainability-oriented management through applications such as water distribution system optimization and water loss reduction, smart energy management, predictive maintenance of infrastructure systems, industrial process optimization, environmental monitoring, climate risk analysis, traffic optimization, waste management, and sustainability-oriented decision support. Accordingly, future methodological approaches should aim to assess both the environmental costs and potential environmental benefits of AI applications in an integrated and balanced manner.

The results of this research point to the need to develop more sophisticated environmental metrics, integrated sustainability indices, and hierarchical indicator systems capable of capturing the multidimensional and dynamic nature of AI's environmental impacts. Particular attention should be paid to the future operationalization of environmental indicators, weighting procedures, benchmarking methodologies and standardized reporting protocols applicable to different AI systems, infrastructures and operational contexts.

Furthermore, future research and regulatory initiatives should move beyond the exclusively user-oriented and ethical dimensions of AI governance towards a stronger consideration of sustainability impacts at the infrastructure, ecological and system levels. This includes the development of standardized environmental reporting requirements, harmonized methodological guidelines and sustainability-oriented regulatory frameworks, aligned with international environmental management standards and broader sustainable development goals. In this context, the proposed framework can serve as a conceptual starting point for the future development of standardized methodologies, operational assessment tools, and integrated sustainability assessment models for AI systems and infrastructure.

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