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Occupational health and safety in the age of automated engineering solutions in agriculture

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Abstract. The rapid implementation of automated engineering solutions in agriculture has significantly transformed occupational health and safety conditions. The purpose of this study was to analyse the impact of automation on occupational safety in the agricultural sector, identify emerging risks, and develop practical approaches to safety management. The research was based on a comprehensive methodological framework combining system analysis, comparative legal analysis, risk classification, and cases described in scientific literature involving automated systems. National regulatory frameworks were examined alongside international standards to assess their adequacy in addressing the challenges associated with agricultural automation. The results demonstrated that automation does not eliminate occupational risks but leads to their transformation, forming a multidimensional risk system in which traditional hazards are supplemented by new categories, including risks related to human–machine interaction, cybersecurity, and increased psychophysiological load. It was established that the transition from manual labour to supervisory and analytical functions reduces direct physical risks while increasing dependence on system reliability, data accuracy, and decision-making processes. The study also revealed significant regulatory gaps, particularly in liability distribution, software reliability, and safety requirements for autonomous systems. In addition, the results confirmed the transformation of labour functions, characterised by increased demand for digital competencies and the need for structured training and certification systems. The practical significance of the study lies in the development of applied safety management approaches, including scenario-based risk assessment, implementation of digital monitoring systems, and continuous personnel training. The application of these measures contributes to reducing occupational injuries, minimising downtime, improving process controllability, and enhancing the overall efficiency of agricultural enterprises. However, their effectiveness depends on overcoming regulatory, organisational, and financial constraints

Keywords: human-machine interaction; autonomous agricultural systems; industrial cybersecurity; precision farming technologies; risk transformation; robotics

Introduction

The integration of automated engineering solutions into the agricultural sector fundamentally transformed not only production processes but also the nature of occupational risks. Unlike traditional mechanisation,

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which primarily altered physical workloads, modern automation introduced complex interactions between humans, autonomous machines, and digital infrastructures. This created a qualitatively new risk environment characterised by unpredictability, system interdependence, and increased reliance on software-controlled decision-making. This trend is also supported by a study by Z. Zhai *et al*. (2020) on decision support systems in Agriculture 4.0, which demonstrated that the increasing reliance on data-driven platforms enhances decision-making efficiency but simultaneously introduces new dependencies on data quality, system integration, and algorithmic reliability.

Under such conditions, occupational health and safety could no longer be limited to conventional hazard prevention approaches focused on mechanical or chemical factors but required a systemic model capable of addressing hybrid risks emerging at the intersection of human factors, robotics, and digital technologies. This challenge became particularly acute in contexts where external destabilising factors, such as military threats or labour shortages, accelerated the adoption of automation without the simultaneous development of adequate regulatory and safety frameworks.

Scientific research increasingly focused on various aspects of automation in agriculture and its implications for safety and labour transformation. J. Lincoln *et al*. (2025) investigated occupational safety challenges related to robotics and autonomous machines in agriculture and concluded that traditional safety models were insufficient for managing risks associated with human-robot interaction, particularly during maintenance and non-routine operations. Similarly, J.C. Mayoral Baños *et al*. (2023) developed a risk management framework for safe robotic navigation in agricultural environments, emphasising the importance of integrating human detection systems and fail-safe mechanisms to prevent collisions. Their findings highlighted that technological reliability alone did not guarantee safety without proper system design and operational protocols. In the context of technological development, S. Hossain *et al*. (2025) analysed autonomous navigation systems in agricultural machinery and demonstrated that environmental factors such as dust, uneven terrain, and sensor limitations significantly affected system performance, thereby increasing the likelihood of operational errors. At the same time, J. Lowenberg-DeBoer *et al*. (2021) examined the regulatory impact on autonomous agricultural equipment in Europe and concluded that legal uncertainty regarding liability distribution among stakeholders represented a major barrier to the safe implementation of such technologies. This indicated that safety issues extended beyond technical aspects and required institutional and legal solutions.

The transformation of agricultural production through digitalisation was also explored by V. Tankosić *et al*. (2024), who emphasised that Agriculture 4.0 technologies, including IoT and data-driven platforms, significantly improve operational efficiency while simultaneously introducing new categories of risks related to system reliability, data quality, and cybersecurity vulnerabilities. Similarly, K.G. Liakos *et al*. (2018) highlighted that the application of machine learning in agriculture enables advanced predictive analytics and optimisation of production processes, but increases dependence on data accuracy and model reliability, which may introduce additional operational risks. This perspective is further supported by S. Ballingall *et al*. (2023), who analysed safety standards for autonomous systems and demonstrated that cybersecurity becomes an essential component of operational safety, particularly in systems based on artificial intelligence and remote control technologies. From a labour perspective, automation does not eliminate jobs but transforms them, increasing demand for specialists capable of combining technical, analytical, and managerial competencies. At the same time, this shift creates new psychophysiological risks associated with increased cognitive load and responsibility (World Economic Forum, 2023).

L. Benos *et al*. (2023) demonstrated that the increasing integration of human–robot interaction systems in agriculture requires a transition from traditional reactive safety approaches toward more proactive risk management strategies based on continuous monitoring, operator supervision, and the implementation of structured safety protocols. In addition, A. Bechar & C. Vigneault (2016) analysed the fundamental concepts and components of agricultural robots, emphasising that their operational efficiency depends on the integration of mechanical systems, sensors, and control algorithms, which simultaneously creates multiple points of potential failure and risk. Despite the significant contributions of these studies, several important aspects remained insufficiently explored. Existing research tended to analyse technological, legal, or social factors separately, without considering their interaction within a unified risk system. In addition, the specific conditions of countries experiencing external stressors, such as armed conflict or large-scale labour shortages, were rarely incorporated into safety models, although these factors significantly influenced both the pace of automation and the nature of risks. Furthermore, there was a lack of comprehensive approaches that integrated cybersecurity, human–machine interaction, and regulatory frameworks into a single occupational safety management concept adapted to agricultural systems.

These research gaps determined the relevance of this study. The aim of the study was to provide a comprehensive analysis of the impact of automated engineering solutions and robotics on the occupational health and safety system in the agricultural sector, to identify emerging and transformed risks, and to develop practical, regulation-oriented recommendations for effective safety management under conditions of digitalisation and external challenges. To achieve this aim, the study addressed several interrelated objectives, including the analysis of traditional and emerging occupational risks in agriculture, the examination of trends in the implementation of automated and robotic systems, the classification of new risk categories associated with human–machine interaction, the comparative assessment of national and international regulatory frameworks, and the evaluation of labour market transformations and training requirements in the context of agricultural digitalisation.

Materials and Methods

The study was conducted as an independent research work and was not carried out within the framework of a specific funded scientific project. It was based on a comprehensive methodological framework that integrated analytical, comparative, and prognostic approaches to assess the impact of automated engineering solutions on occupational health and safety in the agricultural sector. The study relied on a combination of regulatory, scientific, and empirical data sources, which ensured the reliability and multidimensional nature of the analysis. The material base of the research included current national legislative and regulatory documents of Ukraine, in particular The Labour Code of Ukraine (1971), which established general occupational safety requirements for production processes and equipment, as well as DSTU 2293:2014 (2014), which defined the fundamental terminology related to occupational health and safety, including the concepts of risk, hazard, and safety management systems. These documents were used to evaluate the existing regulatory framework and to identify its limitations in the context of the implementation of automated technologies. In addition, international standards were analysed, including ISO 45001:2018 (2018), which provided a framework for occupational health and safety management systems, ISO 18497:2018 (2018), which specified safety requirements for highly automated agricultural machines, and UL 4600 (2020), which addressed safety evaluation principles for autonomous systems. These standards were selected due to their direct relevance to automation and robotics and were used as benchmarks for comparative analysis.

The methodological approach of the study was grounded in system analysis, which allowed occupational safety to be considered as a complex and dynamic system influenced by technological, organisational, and external factors. This method was applied to identify cause-and-effect relationships between the introduction of automation technologies and the transformation of occupational risks. Its selection was justified by the need to assess interdependencies between human factors, technical systems, and regulatory mechanisms within a unified analytical framework. Comparative legal analysis was employed to evaluate discrepancies between national legislation and international standards regulating the safety of automated and autonomous systems. This method enabled the identification of regulatory gaps, particularly in the areas of liability distribution, human–machine interaction, and cybersecurity. Its application was justified by the necessity to assess the degree of alignment of the national regulatory framework with contemporary technological developments. The method of classification and systematisation was applied to structure occupational risks into traditional and emerging categories. Traditional risks included physical, chemical, and biological hazards, while emerging risks were associated with human–machine interaction, cybersecurity threats, and increased psychophysiological load. This method ensured a consistent conceptual framework for risk identification and facilitated further analytical interpretation.

Empirical analysis was conducted through the examination of documented incidents involving automated and robotic systems in agricultural environments. Three representative cases were selected for analysis based on their relevance to the key categories of occupational risks associated with agricultural automation. The first case concerned human–robot interaction and operator supervision in agricultural tasks, highlighting challenges related to communication, safety protocols, and human presence detection (Benos *et al.*, 2023). The second case focused on autonomous navigation in a real agricultural environment and examined the influence of sensor performance and environmental conditions on navigation accuracy and system reliability (Fujinaga, 2025). The third case addressed safety, operational constraints, and risk factors associated with the deployment of autonomous agricultural systems, including issues related to human detection, collision prevention, and regulatory requirements (Spagnuolo *et al.*, 2025). These cases were selected because they represent complementary technological, environmental, and human-related dimensions of occupational risks in automated agricultural systems. The analysed cases included examples of human–robot interaction failures, such as unintended collisions caused by sensor misidentification, accidents during maintenance and testing procedures, and malfunctions of autonomous navigation systems under adverse environmental conditions. The identification of patterns was carried out using qualitative comparative analysis, which involved the systematic comparison of incident characteristics, including causal factors, operational conditions, and the presence or absence of safety protocols. This approach made it possible to identify recurring risk factors, such as insufficient personnel training, inadequate system design, and the lack of standardised safety procedures. In addition, forecasting methods were applied to assess trends in the transformation of the labour market and qualification requirements in the context of agricultural digitalisation. This involved the analytical review of current technological trends, scientific literature, and international reports to identify stable development patterns and potential future scenarios. The application of forecasting methods was justified by the rapid evolution of automation technologies and the need to anticipate emerging occupational risks. The research procedure was implemented through several sequential stages. Initially, traditional occupational risks in agriculture were identified based on regulatory documents and scientific literature. Subsequently, emerging risks associated with automation and robotics were analysed and classified. This was followed by a comparative assessment of regulatory frameworks to identify inconsistencies and gaps. Finally, the analytical findings were used to formulate recommendations aimed at improving occupational safety management in the context of automated agricultural systems.

Results and Discussion

Activities in the agricultural sector were traditionally associated with a wide range of occupational risks, including physical, chemical, and biological hazards. Physical risks arose from the operation of heavy machinery, such as tractors and harvesters, where workers were exposed to moving parts, rollovers, and mechanical injuries. Chemical risks were related to the use of pesticides, herbicides, and fertilisers, which could cause poisoning and occupational diseases, while biological risks included exposure to zoonotic infections. However, the introduction of automated engineering solutions did not eliminate these risks but fundamentally transformed their structure and interrelationships.

The transformation of risks was characterised by a clear cause-and-effect relationship between the implementation of automation technologies and changes in the role of workers within production systems. As automation replaced direct manual operations, workers transitioned from physically intensive tasks to supervisory and analytical functions. This transition altered the structure of occupational risks. Instead of being primarily exposed to direct mechanical hazards associated with operating machinery, workers became responsible for monitoring system performance, interpreting sensor information, supervising autonomous operations, and making corrective decisions when abnormal situations occurred. As a result, occupational safety increasingly depended on the quality of human–machine interaction, the reliability of communication channels, and the operator's ability to correctly interpret system feedback. In human-robot interaction environments, operators often perform supervisory functions remotely, requiring continuous situational awareness and timely intervention in the event of sensor errors, navigation failures, or unexpected system behaviour (Benos *et al.*, 2023). Consequently, the likelihood of direct physical injuries may decrease, while the importance of cognitive workload, decision-making quality, and system transparency increases. This shift reduced exposure to traditional mechanical hazards; however, it simultaneously increased dependence on the reliability and stability of digital systems and autonomous equipment. The use of autonomous machinery may reduce the likelihood of operator-related accidents by minimising direct human involvement in hazardous operations; however, it introduces new categories of risks associated with sensor failures, incorrect object recognition, communication disruptions, and unpredictable system behaviour. Perception-related failures, including sensor malfunctions and missed detections, are among the most frequently reported causes of operational errors in agricultural robotic systems. At the same time, navigation accuracy in such systems may vary within ±0.05 m depending on sensor performance, while communication latency in human–machine interaction systems can reach approximately 15-20 ms, which may affect system responsiveness under variable environmental conditions (Zhivkov *et al.,* 2023; Fujinaga, 2025). Thus, the reduction of direct physical risks resulted in the emergence of indirect, technologically mediated hazards, which required new approaches to risk assessment and management. This shift occurred because the increasing complexity and autonomy of technological systems reduced direct human involvement while simultaneously increasing dependence on system reliability, sensor accuracy, and real-time data processing, which, in turn, increased the probability of system-related errors and delayed responses. In the case of autonomous agricultural machinery, operators may perform remote supervision of field operations, which reduces the risk of direct physical injury but increases the likelihood of incidents related to communication delays, software failures, and incorrect sensor data interpretation under variable environmental conditions (Zhivkov *et al.*, 2023; Spagnuolo *et al.,* 2025).

The empirical analysis of documented incidents involving automated and robotic systems revealed several recurring patterns. Three representative cases were analysed to identify the principal sources of occupational risks in automated agricultural systems. The first case, based on the review of human–robot interaction applications in agriculture, highlighted challenges related to operator supervision, communication reliability, and the implementation of safety protocols in collabourative work environments (Benos *et al.*, 2023). The second case concerned autonomous navigation of an agricultural robot operating in a real cultivation environment, where navigation performance depended on LiDAR-based perception and the ability to maintain a positional accuracy of approximately ±0.05 m under changing environmental conditions (Fujinaga, 2025).

The third case focused on agricultural robotic systems operating in complex field environments and identified critical challenges associated with human detection, obstacle recognition, collision prevention, and regulatory compliance requirements (Spagnuolo *et al.*, 2025). The review emphasised that autonomous agricultural robots frequently operate in dynamic environments characterised by the simultaneous presence of workers, machinery, crops, and unexpected obstacles. Under such conditions, the effectiveness of safety functions depends on the reliability of perception systems, obstacle detection algorithms, and fail-safe mechanisms. The study further highlighted that operational safety cannot be ensured solely through technical performance, as safe deployment also requires appropriate regulatory frameworks, operator training, and compliance with established safety procedures. These findings support the results of the present study, which indicate that occupational risks in automated agricultural systems emerge through the interaction of technological, environmental, and organisational factors.

Collectively, these cases demonstrated that technical failures, perception errors, communication limitations, and insufficient safety measures represent the most common sources of operational risk in agricultural automation. The analysed cases demonstrated that incidents involving autonomous agricultural machinery were most frequently associated with sensor failures, communication disruptions, and incorrect object recognition under variable environmental conditions (Benos *et al.*, 2023; Spagnuolo *et al.*, 2025). In a number of cases, unsafe situations occurred during maintenance operations or in scenarios where the presence of a human operator was not correctly detected by the system, leading to near-miss events and potential collisions. These findings indicate that operational risks in automated agricultural systems are strongly dependent on system reliability, environmental adaptability, and the effectiveness of human detection mechanisms.

For example, T. Fujinaga (2025) reported the operation of an autonomous agricultural robot in a real strawberry production environment, where navigation accuracy depended on LiDAR-based perception and stable interpretation of environmental features. The robot maintained a distance accuracy of approximately ±0.05 m relative to cultivation beds; however, the study emphasised that sensor limitations and environmental variability could affect localisation accuracy and navigation stability. Such limitations are particularly important in agricultural environments where uneven terrain, vegetation density, and changing lighting conditions may reduce perception accuracy and increase the need for operator intervention. Similarly, studies reviewed by L. Benos *et al.* (2023) highlighted that communication quality, operator supervision, and the effectiveness of safety protocols are critical factors influencing the safe operation of collabourative agricultural robotic systems.

The qualitative comparative analysis made it possible to identify common patterns and differences in the causes of incidents across various operational contexts. The comparison was performed across three principal groups of factors: technical factors (sensor performance, software reliability, communication stability), environmental factors (terrain variability, obstacles, weather conditions, and changes in operating environments), and human-related factors (operator supervision, decision-making, and compliance with safety procedures). This classification made it possible to evaluate not only the direct causes of incidents but also the interactions between different categories of risk factors. It was established that the most significant causal factors included insufficient reliability of sensor systems, limited adaptability of autonomous equipment to changing environmental conditions, and the absence or incomplete implementation of safety protocols during maintenance and non-standard operations. Incidents occurring under standard operating conditions were primarily associated with technical failures, whereas incidents in complex or unpredictable environments were more likely to involve a combination of technical, environmental, and human-related factors. For example, a sensor malfunction occurring under controlled operating conditions may result only in a temporary reduction in navigation accuracy. However, the same malfunction in a dynamic agricultural environment characterised by uneven terrain, variable lighting conditions, or the presence of workers may significantly increase the probability of unsafe situations and require immediate operator intervention. Similarly, the consequences of communication disruptions depend on the operator's ability to recognise abnormal system behaviour and apply appropriate safety procedures. These observations indicate that incident outcomes are determined not by isolated technical failures but by the interaction of technical, environmental, and human-related factors (Benos *et al.*, 2023; Fujinaga, 2025; Spagnuolo *et al.*, 2025). This indicates that occupational risks in automated agricultural systems are systemic in nature and arise from the interaction of multiple interdependent variables rather than from isolated causes.

The comparative analysis revealed a clear differentiation of risk factors depending on operating conditions, with technical factors prevailing under controlled environments, while environmental and human-related factors became dominant in variable and unpredictable conditions. In the context of armed conflict, these transformations were further intensified. Traditional risks were compounded by external threats, including landmines and unexploded ordnance, as well as labour shortages caused by mobilisation and migration. These factors accelerated the adoption of automation technologies, which in turn increased the importance of managing complex, dynamic, and interdependent risks. As a result, occupational safety in agriculture evolved into a multidimensional system in which traditional, technological, and external risks coexisted and interacted, forming a unified risk environment (Pietrantoni *et al.,* 2024; Yang *et al.,* 2025). Automation in the agro-industrial complex includes several interconnected technological domains (Spagnuolo *et al.*, 2025). Intelligent management systems based on precision agriculture technologies enable real-time monitoring of soil conditions, crop status, and equipment performance, which improves decision-making and operational efficiency. At the same time, this increases dependence on data accuracy, system reliability, and cybersecurity. Autonomous ground machinery performs hazardous and labour-intensive tasks, reducing direct human exposure; however, it introduces risks related to machine autonomy, navigation errors, and interaction within shared workspaces. Unmanned aerial vehicles are used for monitoring and targeted application of crop protection products, which reduces chemical exposure but introduces additional risks associated with flight safety, communication failures, and regulatory constraints. These findings are consistent with the results of the present study.

The comparative analysis of regulatory frameworks, presented in Table 1, demonstrated that the national system of occupational safety regulation was primarily focused on traditional hazards, whereas international standards increasingly addressed challenges related to automation, robotics, and cybersecurity. In particular, international standards emphasised the implementation of human detection systems, fail-safe mechanisms, and risk-oriented design approaches for autonomous machines, while national regulations lacked specific provisions regarding liability distribution, software reliability, and human–machine interaction. This discrepancy created a regulatory gap that complicated the safe implementation of automated technologies and limited the effectiveness of existing safety management systems. A more detailed comparison indicates that national regulatory documents are primarily oriented toward general occupational safety requirements and the operation of conventional equipment. For example, The Labour Code of Ukraine (1971) establishes general obligations regarding workplace safety and the use of production equipment, while DSTU 2293:2014 (2014) standardises fundamental occupational safety terminology, including the concepts of risk and hazardous factors. However, these documents do not provide specific requirements for autonomous decision-making systems, human-machine interaction, software reliability, or cybersecurity. In contrast, ISO 18497:2018 (2018) contains dedicated provisions related to the safe operation of autonomous agricultural machinery, including human detection and collision prevention mechanisms. Similarly, UL 4600 (2020) and UL 4740 (2024) focus on safety assurance for autonomous systems through risk assessment procedures, cybersecurity requirements, and the verification of critical system components. Consequently, international standards provide more detailed mechanisms for addressing automation-specific risks, whereas the national framework remains focused on general occupational safety principles.

Table 1. Overview of regulatory acts and standards

Name of the act/standard	Type	Scope	Key provisions	Status in Ukraine
The Labour Code of Ukraine	Law	General occupational safety	Requirements for the design, manufacture, and commissioning of production equipment	Mandatory
DSTU 2293:2014 "Occupational Safety. Terms and Definitions of Basic Concepts"	Standard	Occupational safety terminology	Standardisation of terms "risk", "hazardous factor", "occupational safety"	Mandatory (recommended for use)
Temporary Procedure for the Use of Airspace	Regulatory Act	Use of drones	Prohibition of flights over certain objects, requirement for authorisation	Mandatory, but creates bureaucratic barriers
ISO 18497	Standard	Agri-robot safety	Safety requirements, human detection, collision prevention	Recommended
UL 4600, UL 4740	Standards	Autonomous systems safety	Risk assessment, cybersecurity, component testing	Recommended, but not integrated into the national legal framework

Source: compiled based on The Labour Code of Ukraine (1971), DSTU 2293:2014 (2014), ISO 18497:2018 (2018), UL 4600 (2020), UL 4740 (2024)

At the regulatory level, the results indicated the need for the development of targeted policy instruments aimed at bridging the gap between national legislation and international standards. This included the adaptation of ISO-based safety requirements for autonomous agricultural systems, the introduction of certification frameworks for digital and robotic equipment, and the establishment of clear liability models for human-machine interaction scenarios. The implementation of these measures required the development of practical regulatory tools, such as standardised risk assessment methodologies, guidelines for the certification of autonomous systems, and the integration of cybersecurity requirements into occupational safety regulations. The necessity of these instruments is directly linked to the risk categories identified during the empirical and comparative analyses. For example, certification procedures for autonomous agricultural equipment can help address risks associated with software failures, sensor malfunctions, and unreliable system behaviour by establishing minimum safety and performance requirements before deployment. Standardised risk assessment methodologies are particularly important for evaluating human–machine interaction scenarios, including situations involving remote supervision, operator intervention, and collabourative work environments. Likewise, the integration of cybersecurity requirements into occupational safety regulations is essential because communication disruptions, unauthorised system access, or data integrity failures may affect the reliability and safety of autonomous operations. These measures therefore provide regulatory mechanisms for mitigating the technological, environmental, and human-related risks identified in the study (ISO 18497:2018, 2018; UL 4600, 2020; Spagnuolo *et al.*, 2025). The adoption of such instruments would have a direct impact on agricultural enterprises by increasing the predictability of regulatory requirements and facilitating the safe deployment of automated technologies.

The emergence of new categories of risks represented one of the key results of the study and reflected the systemic transformation of occupational safety under conditions of automation. Risks related to human-machine interaction arose due to the absence of clearly defined physical and functional boundaries between workers and autonomous systems, which increased the probability of collisions, unsafe proximity, and unintended system responses. These risks became particularly significant during maintenance, calibration, and non-standard operations, where safety protocols were often insufficiently developed or inconsistently applied. Cybersecurity risks were associated with the integration of digital platforms, remote control systems, and data exchange networks into agricultural production processes. Unauthorised access, software failures, or disruptions in communication channels could result in uncontrolled equipment behaviour, which directly affected operational safety and increased the likelihood of hazardous situations. Thus, the growing dependence on digital infrastructure led to the emergence of a new category of technologically mediated risks requiring specialised control mechanisms.

Psychophysiological risks were linked to the increased cognitive load imposed on workers, who were required to monitor complex systems, analyse large volumes of data, and make decisions under conditions of uncertainty and time constraints. This shift in functional responsibilities contributed to fatigue, reduced attention, and a higher probability of human error. Consequently, automation not only reduced physical strain but also redistributed risk toward cognitive and psychological domains. These categories of risks formed an interconnected and hierarchical system in which human–machine interaction risks, cybersecurity threats, and psychophysiological factors were interdependent and could amplify each other, creating complex multi-layered risk scenarios. The transformation of professional roles and qualification requirements, presented in Table 2, confirmed a shift from physically oriented occupations to roles requiring digital competencies, analytical skills, and the ability to effectively interact with automated systems. This transition reduced exposure to traditional physical hazards; however, it simultaneously increased exposure to cognitive and technological risks. In addition, the absence of a unified certification system for operators of automated equipment created additional safety challenges related to insufficient training, inconsistent qualification levels, and variability in operational practices. These factors limited the effectiveness of safety management and increased the likelihood of incidents in automated agricultural environments.

Table 2. Changes in qualification requirements and skills of agricultural workers

Traditional roles	New roles	Required competencies	Main risks
Tractor operator / combine harvester operator	Autonomous equipment operator, Agronomist-analyst	Physical endurance and practical skills, knowledge of mechanisms, practical experience	Physical injuries, fatigue, exposure to vibration and noise
Field agronomist	Unmanned aerial vehicle operator, Precision agriculture specialist	Technological literacy, data analysis, software management	Cyber risks, psychophysiological load, fatigue
Technician / repair specialist	Mechatronics and robotics specialist	Knowledge of hydraulics, electricity, and mechanical systems	Physical injuries, overexertion, risk of electric shock
Manual labour worker	Weeding robot operator	Robot interaction, monitoring, and control	Collision risks, lack of clear interaction protocols

Source: compiled based on the analysis of V. Tankosić *et al.* (2024), J. Lincoln *et al.* (2025), S. Hossain *et al.* (2025)

The forecasting analysis enabled the formulation of three distinct development scenarios for occupational risks in agricultural automation, reflecting different levels of technological adoption and regulatory maturity. The scenarios were differentiated according to three principal criteria: the rate of technology adoption, the degree of regulatory development, and the level of organisational preparedness, including personnel training and safety management practices. These criteria were selected because the results of the empirical, comparative, and regulatory analyses indicated that they exert the strongest influence on the emergence and management of occupational risks in automated agricultural systems. In a baseline scenario, automated technologies are introduced gradually and under relatively controlled conditions, allowing organisations sufficient time to adapt operating procedures and train personnel. As a result, traditional physical risks are progressively reduced, while technological and cognitive risks increase at a manageable rate. In an accelerated automation scenario, driven by labour shortages, economic pressures, or technological incentives, autonomous systems are implemented faster than organisations can adapt regulatory procedures, training programs, and safety protocols. Under such conditions, the probability of incidents associated with software reliability, operator errors, communication failures, and inadequate risk management increases. In a regulated development scenario, technological deployment is accompanied by certification procedures, personnel training programs, internal safety protocols, and the harmonisation of national legislation with international standards. Under these conditions, the risks associated with autonomous systems become more predictable and controllable, contributing to improved system reliability and enhanced occupational safety outcomes. These scenarios demonstrate that the evolution of occupational risks in agriculture is directly dependent on the pace of technological adoption, the level of regulatory development, and the effectiveness of organisational safety measures. This conclusion is consistent with the empirical findings of the study, which demonstrated that occupational risks are influenced not only by technological factors but also by the adequacy of regulatory frameworks and the preparedness of organisations to manage human–machine interaction and autonomous system operation (Benos *et al.*, 2023; Spagnuolo *et al.*, 2025).

The generalised results of the applied methods indicate that the transformation of occupational risks in agricultural automation follows a consistent and interconnected pattern. The system analysis demonstrated that the implementation of automated technologies changes the role of workers and shifts the structure of occupational risks from direct mechanical hazards toward technology-dependent risks associated with autonomous systems, sensor reliability, software performance, and human–machine interaction. The analysis of documented incidents revealed recurring patterns related to perception errors, communication disruptions, and limitations of safety mechanisms. The qualitative comparative analysis further showed that the consequences of such failures depend not only on technical conditions but also on environmental variability and human-related factors, including operator supervision and compliance with safety procedures. The comparative assessment of regulatory frameworks indicated that existing national regulations only partially address automation-specific risks, while international standards provide more comprehensive approaches to risk management, human detection, and collision prevention. Finally, the forecasting analysis demonstrated that the future evolution of occupational risks depends on the interaction between technological adoption, regulatory development, and organisational preparedness. Collectively, these findings confirm that occupational risks in automated agricultural systems are not isolated phenomena but emerge through the interaction of technological reliability, environmental conditions, and human-related factors. This conclusion provides a structured basis for the development of integrated occupational risk management strategies in agricultural automation (Benos *et al.*, 2023; Fujinaga, 2025; Spagnuolo *et al.*, 2025).

The practical implementation of automated technologies required the development of structured safety management mechanisms at the enterprise level. Risk assessment procedures were adapted to include scenario-based analysis, the identification of human–machine interaction zones, and the evaluation of system reliability under variable environmental conditions. In practice, this was implemented through the integration of digital monitoring systems, automated risk analysis tools, and adaptive safety management protocols that enabled real-time identification and mitigation of potential hazards. Internal regulations defined operational protocols, including emergency response procedures, maintenance safety requirements, and safe operating modes for autonomous equipment. The implementation of digital monitoring systems enabled real-time tracking of equipment performance and worker activities, which facilitated the early detection of hazardous situations and supported more informed and timely decision-making. For employers, the implementation of automated technologies required the establishment of standardised safety management frameworks. These included clearly defined internal regulations, structured operational procedures, and the use of advanced digital tools for monitoring and control. Digital systems, such as real-time monitoring platforms and predictive analytics tools, enabled continuous assessment of operational conditions and supported proactive risk management. In addition, the effective use of automated systems required the implementation of structured training and certification programs, including simulation-based training and periodic qualification assessment of personnel working with autonomous equipment.

The application of these measures can positively influence the operational efficiency of agricultural enterprises by reducing the frequency of disruptions associated with human error, equipment malfunction, and delayed responses to abnormal operating conditions. Digital monitoring and control systems provide continuous information on machine status, navigation performance, and operational parameters, allowing operators to identify anomalies at an early stage and implement corrective actions before failures escalate into accidents or prolonged downtime. In addition, automated systems can reduce the need for direct human involvement in hazardous or repetitive tasks, thereby decreasing exposure to occupational risks and improving the continuity of field operations. Evidence from recent studies indicates that the implementation of robotic and automated technologies may contribute to measurable operational improvements. For example, agricultural automation has been associated with reductions in manual labour requirements of up to 58%, decreases in labour costs of approximately 22.5%, and reductions in pesticide exposure risks of up to 45% in selected agricultural applications (Anastasiou *et al.*, 2025). Furthermore, automated monitoring and control technologies improve process transparency, support more efficient resource allocation, and facilitate data-driven operational decision-making, which contributes to enhanced productivity and operational stability (Spagnuolo *et al.*, 2025). These findings indicate that the efficiency gains associated with automation result not only from technological improvements themselves but also from enhanced process control, reduced operational uncertainty, and more effective allocation of labour and technical resources.

However, the implementation of such technologies was constrained by regulatory barriers, high initial investment costs, and the lack of standardised training and certification systems. These barriers included regulatory uncertainty, limited harmonization with international standards, high capital investment requirements, and insufficient availability of qualified personnel. Furthermore, small and medium-sized enterprises faced additional constraints related to limited access to digital infrastructure and financial resources. These limitations had to be considered when developing strategies for the safe and effective integration of automation into agricultural production systems. Generalised implementation scenarios indicated that effective occupational safety management in automated agriculture required coordinated interaction between equipment manufacturers, agricultural enterprises, and regulatory authorities. Manufacturers integrated advanced safety features, including sensor redundancy, human detection systems, and fail-safe mechanisms, into system design. Agricultural enterprises implemented comprehensive risk assessment procedures, digital monitoring tools, and continuous personnel training and certification programs. Regulatory authorities ensured the harmonisation of national legislation with international standards and developed practical guidelines for certification, risk assessment, and safety validation of automated systems. The alignment of these elements enabled not only the reduction of occupational risks but also the improvement of operational efficiency, system controllability, and the overall sustainability of agricultural production.

The results of this study demonstrated that the implementation of automated engineering solutions in agriculture led to a transformation of occupational risks, shifting from traditional physical hazards to complex system-based risks associated with human–machine interaction, digitalisation, and cognitive load. These findings were further analysed in the context of recent scientific literature. L. Benos *et al.* (2023) conducted a systematic review of human–robot interaction in agriculture, focusing on safety incidents and operational conditions. They found that the lack of clearly defined interaction zones between humans and robotic systems significantly increases the likelihood of accidents, particularly during maintenance and non-standard operations. These findings are consistent with the results of the present study, which also identified human-machine interaction as a critical risk factor. The study supports this conclusion and further emphasises that in agricultural environments, characterised by variability and low standardisation, these risks are amplified. L. Pietrantoni *et al.* (2024) investigated the integration of collabourative robots in agriculture and other industries, with particular attention to human factors and safety. Their study demonstrated that increased automation is associated with higher levels of cognitive load and psychological stress among operators. These findings align with the present study, which identified psychophysiological risks as a key component of modern occupational safety. However, while L. Pietrantoni *et al.* (2024) primarily examined structured environments, the results of this study indicate that in agricultural contexts, environmental variability further intensifies these effects. Therefore, the conclusions of L. Pietrantoni *et al.* (2024) are supported and further extended by incorporating the influence of external conditions. M. Spagnuolo *et al.* (2025) conducted a technical review of agricultural robotics, focusing on sustainability and operational challenges. They found that automation improves productivity and reduces labour intensity, but introduces new risks related to system reliability and environmental interaction. These findings are strongly consistent with the present study. However, the obtained results expand this perspective by demonstrating that these risks form an interconnected system influenced by technological, organisational, and regulatory factors.

In their study, Y. Yang *et al.* (2025) analysed the application of blockchain and IoT technologies in agriculture, focusing on data management and system security. They found that digitalisation enhances transparency and operational efficiency but creates vulnerabilities related to cybersecurity and data integrity. These findings are consistent with the present study, which identified cybersecurity risks as an essential component of occupational safety. This conclusion is supported, and it is further emphasised that failures in digital systems can directly translate into physical safety risks in automated environments. A.J. Moshayedi *et al.* (2024) examined the role of robotics in transforming agricultural practices. Their study showed that robots reduce human exposure to hazardous tasks but introduce uncertainties related to system autonomy and decision-making processes. These findings align with the present study. However, this conclusion is extended by demonstrating that such uncertainties are exacerbated by environmental variability, including terrain complexity and sensor limitations. A.A. Mirani *et al.* (2021) reviewed the application of machine learning in agriculture, focusing on predictive analytics and decision-support systems. They found that data-driven technologies improve efficiency and decision-making accuracy. These findings partially correspond with the present study. While the benefits of such systems are acknowledged, the results of this study indicate that excessive reliance on algorithmic decision-making may introduce additional risks related to data inaccuracies and model bias. Therefore, these conclusions are partially supported, while emphasising the need for human oversight.

E. Anastasiou *et al.* (2025) reported that the implementation of agricultural automation and robotic technologies can contribute to reductions in manual labour requirements, lower labour costs, and decreased exposure to occupational hazards in selected agricultural applications. These findings are consistent with the results of the present study, which also identified the potential of automation to improve operational efficiency and reduce workers' exposure to hazardous tasks. However, the results of this study additionally demonstrate that the successful realisation of these benefits depends on the reliability of autonomous systems, the adequacy of safety protocols, and the effectiveness of regulatory and organisational measures governing their deployment. J. Ingram *et al.* (2022) analysed the development of digital agriculture and identified key research priorities, including system integration, data governance, and user adaptation. They found that increasing digitalisation enhances decision-making capabilities but also introduces systemic dependencies on data quality and infrastructure reliability. These findings align with the present study. This conclusion is supported, and it is further demonstrated that such dependencies create new categories of risks associated with system failures and data inconsistencies E. Anastasiou *et al.* (2025) conducted a systematic analysis of robotics and extended reality applications in agriculture. Their study showed that these technologies significantly improve operational efficiency and reduce manual labour, but require advanced safety frameworks to ensure reliable human-machine interaction. These findings are consistent with the present study. This conclusion is supported, and it is further emphasised that the lack of standardised safety protocols remains a critical limitation.

In their research, M.R. Endsley (2021) conducted a systematic review of objective measures of situation awareness, comparing methods used to assess human cognitive performance in complex systems. The study demonstrated that increased system complexity and information density reduce situational awareness and increase the likelihood of decision-making errors. These findings are consistent with the present study, which identified psychophysiological risks associated with monitoring automated systems. However, while M.R. Endsley (2021) focused on controlled environments, the present study demonstrates that in agricultural contexts, environmental variability further exacerbates cognitive load. Therefore, these conclusions are supported, with an emphasis on their amplified impact in real-world agricultural systems. Overall, the analysis of recent studies confirms that automation in agriculture does not eliminate occupational risks but redistributes them across technological, cognitive, and organisational domains. The present study contributes to the existing body of knowledge by demonstrating that these risks form a multidimensional and interconnected system influenced by environmental conditions, regulatory frameworks, and human competencies. This integrated perspective provides a more comprehensive understanding of occupational safety in automated agricultural systems and highlights the need for systemic and adaptive risk management approaches.

Conclusions

The study established that the implementation of automated engineering solutions in agriculture does not eliminate occupational risks but leads to their structural transformation. Traditional physical, chemical, and biological hazards are reduced in terms of direct human exposure; however, they are replaced by technologically mediated risks associated with system reliability, human–machine interaction, and digital infrastructure. As a result, occupational safety in the agricultural sector evolves into a multidimensional system characterised by the interaction of conventional, technological, and external risk factors.

A key driver of this transformation is the change in the role of workers within production processes. The transition from manual labour to supervisory and analytical functions decreases the likelihood of mechanical injuries but increases dependence on automated systems and the quality of decision-making. This shift contributes to the emergence of new categories of risks, including interaction-related hazards, cybersecurity threats, and increased psychophysiological load caused by the need to process complex information in real time. The results also demonstrate the existence of a significant gap between national regulatory frameworks and international safety requirements for automated and autonomous systems. This gap limits the effectiveness of safety management and complicates the implementation of advanced technologies. At the same time, the study confirms that effective risk management requires the integration of scenario-based risk assessment, digital monitoring systems, and structured training and certification programs for personnel. Overall, the findings indicated that ensuring occupational safety in the conditions of agricultural automation requires a systemic approach that combines technological, organisational, and regulatory solutions. Such an approach enables not only the reduction of occupational risks but also supports the sustainable and efficient development of agricultural production systems. From a practical perspective, the implementation of these measures contributes to improved operational performance, including reduced injury rates, minimised downtime, and enhanced process controllability. However, the effectiveness of such approaches depends on overcoming regulatory, financial, and organisational barriers, particularly in the context of limited resources and insufficient standardisation.

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Conflict of Interest

None.

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Охорона праці в добу автоматизованих інженерних рішень в агросекторі

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Анотація. Стрімке впровадження автоматизованих інженерних рішень в аграрному секторі суттєво трансформувало умови охорони праці. Метою цього дослідження було проаналізувати вплив автоматизації на безпеку праці в сільському господарстві, ідентифікувати нові ризики та розробити прикладні підходи до управління безпекою. Дослідження ґрунтувалося на комплексному методологічному підході, що поєднував системний аналіз, порівняльно-правовий аналіз, класифікацію ризиків та емпіричний аналіз інцидентів, пов’язаних із застосуванням автоматизованих систем. Національні нормативно-правові акти розглядалися у порівнянні з міжнародними стандартами з метою оцінки їх відповідності викликам автоматизації аграрного виробництва. Результати дослідження показали, що автоматизація не усуває професійні ризики, а призводить до їх трансформації, формуючи багатовимірну систему ризиків, у якій традиційні небезпеки доповнюються новими категоріями, зокрема ризиками взаємодії «людина-машина», кіберзагрозами та зростанням психофізіологічного навантаження. Встановлено, що перехід від фізичної праці до наглядових і аналітичних функцій зменшує безпосередній вплив механічних ризиків, водночас підвищуючи залежність від надійності систем, точності даних і якості прийняття рішень. Також виявлено суттєві регуляторні прогалини, зокрема щодо розподілу відповідальності, надійності програмного забезпечення та вимог безпеки для автономних систем. Крім того, підтверджено трансформацію трудових функцій, що характеризується зростанням потреби у цифрових компетентностях і необхідністю впровадження структурованих систем навчання та сертифікації персоналу. Практична значущість дослідження полягає у розробленні прикладних підходів до управління охороною праці, зокрема на основі сценарного оцінювання ризиків, впровадження цифрових систем моніторингу та безперервного навчання персоналу. Застосування цих заходів сприяє зниженню рівня виробничого травматизму, мінімізації простоїв, підвищенню керованості виробничих процесів та загальної ефективності діяльності аграрних підприємств, водночас ефективність їх реалізації залежить від подолання регуляторних, організаційних і фінансових обмежень

Ключові слова: людино-машинна взаємодія; автономні аграрні системи; промислова кібербезпека; точне землеробство; трансформація ризиків; робототехніка