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AGRICULTURE 4.0 – MODERN TECHNOLOGIES IN OCCUPATIONAL HEALTH AND SAFETY MANAGEMENT

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Purpose: The aim of the article is to identify and assess the impact of modern technologies on risk management in the area of occupational safety within the context of Agriculture 4.0.
Design/methodology/approach: Critical Literature Review. Analysis of international literature from major databases and Polish literature related to the researched topic.
Findings: Occupational Health and Safety Management in the context of Agriculture 4.0 requires the integration of advanced technologies, such as Artificial Intelligence (AI), Big Data, the Internet of Things (IoT), nanotechnology, drones, and biotechnology, which can significantly increase production efficiency and improve workplace safety. However, the implementation of these innovations faces challenges, including high investment costs, the need for employee training, and the adaptation of occupational health and safety regulations to new technologies. A comprehensive approach to risk management is crucial to optimally harness the potential of these technologies while ensuring an appropriate level of safety. Current safety regulations are insufficient for new, automated systems.
Originality/value: An innovative approach to occupational health and safety management in the context of Agriculture 4.0.
Keywords: Agriculture 4.0, modern technologies, occupational safety, barriers.
Category of the paper: literature review.

1. Introduction

According to the UN report, the current global population has exceeded 8 billion, and projections indicate that it will rise to 8.5 billion by 2030 and reach 9.7 billion by 2050. By 2100, this number could reach as high as 11 billion. In light of these challenges, one of the most important tasks for agriculture in the 21st century is to ensure an adequate food supply for the growing population. It is estimated that agricultural production must increase by 60% to meet this challenge, while simultaneously minimizing negative environmental impacts (Berckmans, 2017; Ofosu et al., 2020; Pittelkow et al., 2015).

Agriculture, as the largest industrial sector in the world, employs over a billion people and generates annual revenues exceeding $10 trillion (FAO, 2023). Unfortunately, this sector is characterized by a high risk of workplace accidents, making it one of the most dangerous areas of employment. Data from Eurostat (2022) indicates that agriculture accounts for 11.6% of all fatal workplace accidents in the European Union. In Poland, in 2021, there were 12,088 reported accidents, of which 11,597 were related to agricultural work, representing a 16.5% increase compared to 2020, when there were 10,974 incidents (KRUS, 2022).

Managing occupational safety in agriculture is particularly complex due to specific risks such as operating heavy machinery, exposure to hazardous chemicals, exposure to extreme weather conditions, and ergonomic hazards arising from prolonged physical labor. As noted by Tiwari et al. (2002) and Suutarinen (2004), “human error” is one of the main causes of accidents in this sector. The complexity of agricultural work and the unpredictability of environmental factors increase the likelihood of accidents, rendering traditional risk management methods based on inspections and personal monitoring insufficient. Therefore, it is necessary to implement effective preventive measures and adapt legal regulations to changing working conditions.

In the context of Agriculture 4.0, modern technologies such as artificial intelligence, Big Data, the Internet of Things (IoT), nanotechnology, drones, and biotechnology can significantly improve workplace safety and production efficiency (Johnsson, 2023; Patel et al., 2021; Vlăduț et al., 2024; Wolniak, 2023; Wolniak, Grebski, 2023; Wolniak et al., 2020). Agriculture 4.0 is revolutionizing modern agricultural production by introducing a range of advanced technologies that enable precise management of crops and livestock. A key role in this transformation is played by the Internet of Things (IoT), which allows for real-time monitoring of environmental parameters such as soil moisture, temperature, and the health status of plants and animals (Namana et al., 2022). By utilizing IoT sensors, it is possible to collect vast amounts of data from farms, opening new possibilities for process automation. For instance, soil moisture sensors integrated with irrigation systems can automatically trigger watering when the soil requires it, promoting water savings and optimal resource utilization (Farooq et al., 2019). When combined with drip irrigation systems, this approach minimizes water waste, which is crucial in light of changing climatic conditions (Spadoni et al., 2020).

Not only soil parameters, but also the NDVI (Normalized Difference Vegetation Index) based on satellite image analysis enables farmers to monitor plant health accurately (Huang et al., 2021). With NDVI, it is possible to track soil condition, nutrient levels, and crop performance, allowing for more informed and sustainable fertilizer application (Sharma et al., 2022). The data collected, both from sensors and satellites, are then transmitted to cloud computing, where they are stored and analyzed (Conti et al., 2023). In this context, cloud computing becomes a central point that connects all elements of modern farming. Farmers, thanks to quick access to data from anywhere, can make more informed decisions regarding crop management, fertilization, irrigation, and plant protection (Zalewski, 2000).

The mentioned data, which are collected in vast quantities, are processed using artificial intelligence (AI) and machine learning algorithms (Tse et al., 2017). AI not only allows for the analysis of current data but also enables the prediction of yields and the diagnosis of plant diseases based on images from drones or sensors (Kartikeyan, Shrivastava, 2021). Precision pest management is also made possible through AI with the help of IoT systems supported by drones that monitor crops, applying pesticides only where necessary (Abdulridha et al., 2020). This reduces production costs while minimizing the negative environmental impact (Mishra et al., 2022). According to the European Commission report (EC, 2017), one of the EU's goals is to comprehensively connect farmers with the digital economy to succeed in sustainable agriculture (Trendov et al., 2019). Implementing innovative production strategies based on smart management systems, as indicated by Vågsholm et al. (2020), has the potential to significantly increase agricultural productivity in a short time while reducing environmental impact.

An inseparable element of Agriculture 4.0 is also robotics, which automates harvesting and plant care processes. Robots, such as those produced by Abundant Robotics, can independently harvest ripe fruits like apples, increasing efficiency and eliminating the need for manual harvesting (Osten-Sacken, 2008, Yi et al., 2021). Meanwhile, Nexus La Chevre robots specialize in mechanical weed control, allowing for reduced use of chemical plant protection products (Filho et al., 2020). All these technologies would not function without effective analysis of vast amounts of data. Big Data collects information gathered by IoT, drones, machines, and satellites (Rodrigues et al., 2021). Analyzing historical and current data is very important for decision-making in modern agriculture, allowing for the identification of trends and forecasting future production needs.

The global market value of Agriculture 4.0 was around $7 billion in 2020, with Europe accounting for 30% (Variant Market Research, 2024). Digital technologies not only increase efficiency but also contribute to the reduction of greenhouse gas emissions and the decrease in pesticide use. Studies show that the implementation of Agriculture 4.0 solutions can reduce production costs by 13% per hectare and the use of water, fuel, fertilizers, and pesticides by 30%. Additionally, a 15% reduction in the carbon footprint has been observed in crops, which positively impacts environmental sustainability (Osservatori.net, 2024). The application of innovative technological solutions not only improves workplace safety but also reduces the risk of occupational diseases.

Despite the potential of technologies used in Agriculture 4.0 to reduce workplace accidents and occupational diseases, their implementation still faces numerous obstacles, especially in smaller farms. Makinde et al. (2022) identified several major barriers, including high implementation costs, limited technology usability, and lack of awareness of available solutions. Farmers often assess whether a particular technology meets their needs and is practical. If the benefits of its implementation are minimal or inadequate to the specifics of their work, they may reject it, even if its application could potentially improve production efficiency or workplace safety.

In light of the growing population and the challenges associated with food production, it becomes essential to implement modern technologies that can contribute to increasing production efficiency and improving workplace safety. Therefore, the aim of this study is to identify and assess the impact of modern technologies on risk management in the area of workplace safety in the context of Agriculture 4.0.

2. Agriculture 4.0 technologies and their role in improving workplace safety

The introduction of Agriculture 4.0 technologies brings benefits such as increased work efficiency and improved, faster decision-making based on real-time data (Mahmud et al., 2021). Automation of processes, robotics, and monitoring systems significantly optimize work organization on farms, reducing the need for labor-intensive and repetitive tasks. As noted by Mahmud et al. (2021) and Bujak (2012), modern machinery also replaces physical labor, which minimizes the risk of occupational diseases. In livestock farms, automation of feeding and watering processes reduces the need for workers to manually perform these tasks. In traditional livestock farms, employees must perform labor-intensive tasks daily, such as preparing and delivering feed to animals. The introduction of automated systems eliminates this necessity, resulting in reduced physical strain on employees while also lowering production costs. With automated solutions, the feeding and watering processes can occur with greater precision and without the need for constant supervision, as well as at any time of day, leading to savings in time and resources. Manual feeding and watering of animals pose numerous risks for workers, including the possibility of workplace accidents. Animals, especially in large herds, can exhibit unpredictable behavior, which, combined with the need to feed and water them, can lead to injuries and accidents. Workers are at risk of being struck, kicked, or involved in accidents related to machine operation. Automatic feeding and watering systems eliminate these hazards, as animals receive food from machines that operate based on programmed schedules and sensors, reducing worker contact with potentially dangerous situations. Thanks to automated systems, farmers and livestock farm workers can focus on other, more demanding tasks that have not yet been automated. This allows for more efficient time management, improved animal care quality, and greater focus on other tasks (Rodrigues et al., 2021). Drones equipped with cameras can not only locate and count animals but also herd them. Virtually created fences allow for keeping animals in a specific area without the need for physical barriers, relying on sound signals and gentle electric impulses (Herlin et al., 2021; Vlăduț et al., 2024). Such solutions significantly impact the improvement of workplace safety on farms. First, with the help of drones, employees can monitor and manage animals from a greater distance, reducing the risk of direct contact with large, unpredictable animals. This limits the number of accidents related to animal handling (e.g., crushes, kicks, etc.). Workers no longer need to install or repair physical barriers, which reduces the risk of injuries associated with working in unfavorable weather conditions or on dangerous terrain. Additionally, systems based on sound signals and gentle electric impulses are safe for both animals and humans, minimizing the need for more aggressive herding methods.

Advanced devices, such as sensors, detectors, and unmanned aerial vehicles (drones), play a crucial role in modern agriculture, particularly in the context of Agriculture 4.0, in monitoring working conditions and improving production efficiency. These technologies enable real-time data collection, allowing for immediate responses to changes and potential threats on farms (Namana et al., 2022; Xie et al., 2022). Sensors and detectors installed in agricultural machinery, as well as those embedded in workers' clothing, allow for the collection of data on working conditions in real-time. This enables not only monitoring the technical condition of machines but also ongoing analysis of parameters affecting workers' health and safety. Sensors can detect levels of noise, vibrations, or emissions, allowing for immediate adjustments to working conditions to avoid health hazards (Salgado-Salazar et al., 2018; Vlăduț et al., 2024; Xie et al., 2022; Zhang et al., 2020).

Precise monitoring of production processes, such as soil moisture, fertilization levels, temperature, or sunlight exposure, allows for quicker responses to changing weather conditions. This, in turn, enables optimization of actions such as irrigation or fertilization tailored to the specific needs of plants. With this data, farmers can better control product quality, resulting in higher yields and better production outcomes (Conti et al., 2023; Farooq et al., 2019; Zhang et al., 2020).

One of the most promising applications of technology in Agriculture 4.0 is the use of aerial vehicles (drones) in field crops. Drones can be equipped with advanced sensors that allow for precise monitoring of plant health and detection of weeds. Utilizing drones for field monitoring enables faster and more accurate identification of problem areas, such as the presence of weeds that can reduce yields (Rodrigues et al., 2021). Instead of broadly applying herbicides across an entire field, drones can be used for precise application of herbicides only in areas where problems actually exist. This type of technology minimizes the use of chemicals, positively impacting the environment and the health of workers. Furthermore, production costs decrease as herbicides are applied more efficiently and in smaller quantities (Farooq et al., 2019; Vlăduț et al., 2024; Zhang et al., 2020).

Drones are also used for spreading mineral fertilizers. Thanks to precise dosage, mineral fertilizers are applied exactly where reinforcement is needed, significantly reducing excessive fertilizer use, which positively affects the farm's financial performance and decreases environmental harm (Conti et al., 2023). Advanced technologies such as drones and monitoring systems also contribute to reducing direct worker contact with chemicals such as pesticides or herbicides. In traditional agriculture, the use of these substances involves manually spreading them across fields, exposing workers to harmful fumes and contact with potentially toxic or harmful substances (Xie et al., 2022). The implementation of drones and automated systems allows for the remote distribution of fertilizers and plant protection products, reducing workers' exposure to danger. Additionally, sensors can monitor exposure levels to harmful substances such as pesticides, enabling quicker responses in the event of a detected threat. If sensors record dangerous levels of chemicals, alarm systems can immediately alert workers to take preventive actions, reducing the risk of accidents and health problems (Conti et al., 2023; Farooq et al., 2019; Filho et al., 2020; Patel et al., 2021; Rodrigues et al., 2021; Vlăduț et al., 2024; Zhang et al., 2020).

Innovations in technology, such as sensors that monitor operator fatigue, play a crucial role in improving workplace safety. These systems can detect signs of fatigue, reducing the risk of accidents and errors during work. In emergency situations, these systems can alert the machine operator, suggesting a break to prevent accidents related to excessive fatigue. Modern machines equipped with sensor and camera systems can also monitor the area around the vehicle, preventing collisions with people or obstacles. These machines can automatically stop or adjust their operation if a threat is detected, for instance, near power lines, thus reducing the risk of accidents (Aiello et al., 2022; Vlăduț et al., 2024; Zhang et al., 2020). Furthermore, continuous monitoring of the technical condition of machines allows for early detection of potential failures and prevents their consequences.

3. Challenges and barriers in the implementation of Agriculture 4.0

The implementation of technological advancements in agriculture brings many benefits, but it is also associated with certain challenges and problems. Agriculture 4.0, despite its significant potential, faces numerous barriers to development that limit its adoption by farmers. Among the main obstacles are the lack of infrastructure, the complexity of technology, insufficient digital skills among farmers and agricultural workers, and the lack of data reliability related to cybersecurity. Additionally, the need for substantial investments in equipment and technology also poses a serious issue (Kamienski et al., 2019; Pogorelskaia et al., 2020; Scuderi et al., 2022). High costs of equipment and software discourage farmers from investing in new technologies. The prices of devices for Agriculture 4.0 can range from $750 to $1250 per hectare, which is an insurmountable barrier for many farms. Robotic milking systems, which have become popular in cattle breeding, require significant financial outlays, and their profitability depends on efficiency and production scale (Borusiewicz et al., 2023). Adapting barns to work with robots often necessitates substantial changes, such as remodeling spaces, installing new plumbing and electrical systems, and adjusting stalls for cows or building new milking stations.

Credit constraints also significantly impact the implementation of Agriculture 4.0, especially for smaller farms that encounter difficulties in obtaining funding necessary to purchase modern technologies (Vollaro et al., 2019). Governments often offer financial support (e.g., subsidies, preferential loans) to facilitate farmers' investments in innovations. The lack of such solutions can delay the implementation of Agriculture 4.0, especially in low-income countries. Credit limitations are a barrier to the development of modern agriculture, making it essential to introduce more accessible and flexible financing options.

According to research conducted by Long et al. (2016), many believe that the digital divide restricts the use of new technologies in agriculture, hampering innovation and access to global markets. Smaller farms, with areas below 10 hectares, rarely implement Agriculture 4.0 solutions—only 25% of them do so. In contrast, larger farms exceeding 100 hectares have an adoption rate of 65% (Kernecker et al., 2020).

Another barrier is farmers' concerns regarding the use of smart technologies. Research conducted in Italy by Scuderi et al. (2022) reveals that the cultural attitude of farmers toward innovation, combined with a limited understanding of the benefits of implementing Agriculture 4.0, hinders the adoption of modern solutions. Furthermore, they note that the small size of farms complicates investments in new technologies. An analysis conducted in the Bologna province indicates that structural factors and farm specialization still play a significant role in the process of adopting new technologies (Vollaro et al., 2019). Veltheim and Heise (2021) identified major barriers to the adoption of autonomous field robots (AFR) in German agriculture. The primary obstacles included a lack of knowledge and experience, operational complexity, low reliability, operational requirements, and compatibility issues with technology. Many digital applications aimed at farmers exist on the market. Unfortunately, many of them are developed by programmers without collaboration with agronomy experts, resulting in their low practical utility (Wawer, 2019).

Critical infrastructure in many countries is insufficient, which lowers the potential for utilizing modern technologies in agriculture. Better internet connectivity is required to remotely collect and process data from distributed crop fields. Furthermore, changing environmental conditions, such as humidity, dust, extreme temperatures, and vibrations, can affect the operation of sensors and intelligent systems (Symeonaki et al., 2020).

The traditional nature of agriculture and the conservative approach of older generations of farmers toward modern technologies also represent a significant barrier. Younger generations are more open to innovations, but there remains a need for training in ICT so that all farmers can fully exploit the potential of Agriculture 4.0 (Pogorelskaia et al., 2020). Research findings have shown that significant barriers to adoption include a lack of mobile internet coverage, inadequacy of farmers' phones to meet app requirements, and the complexity of operating these tools. These obstacles significantly limited the effective introduction of mobile applications in agricultural practice (Michels et al., 2020).

It is also important to mention the lack of trust among farmers in digital technology providers and concerns regarding data privacy. According to research by Jakku et al. (2019), farmers are reluctant to share their data, which limits the potential for analysis and the application of modern solutions in agriculture. In the context of digitization in agriculture, ownership rights to the collected data are a concern. Currently, contracts are structured such that farmers lose rights to the collected data, benefiting only corporations. Therefore, many farmers are skeptical about the advantages of using data collections on platforms (Big Data services) (Isitor, Stanier, 2016; Wiseman et al., 2019).

According to Kamienski et al. (2019), the four main challenges for IoT in agriculture are: adaptability of systems to local conditions, effective implementation based on reliable infrastructure, scalability depending on farm size, and system complexity, where the choice between simple and more advanced solutions is crucial.

4. Risk management in Agriculture 4.0

Risk management in the context of Agriculture 4.0 plays a crucial role in ensuring production efficiency, protecting worker health, and ensuring safety in operations. The dynamic development of technologies such as the Internet of Things (IoT), artificial intelligence (AI), and complex monitoring systems is transforming the agricultural sector. Modern, automated production systems bring new types of risks that must be addressed (Abdulridha et al., 2020; Araújo et al., 2023; Deutsch et al., 2018; Domingues et al., 2022; Kartikeyan, Shrivastava, 2021).

To ensure safe working conditions, it is essential to focus on four main areas of risk management. The first is the use of real-time data to identify hazards. Thanks to modern technologies, such as IoT sensors, farmers can monitor working conditions and the performance of machines. Collected data on noise levels, vibrations, temperature, humidity, and air quality are crucial for protecting the health of machine operators and making important decisions regarding work organization (Abdulridha et al., 2020; Boursianis et al., 2020; Deutsch et al., 2018; Domingues et al., 2022; Kartikeyan, Shrivastava, 2021).

The second essential element is the implementation of effective alarm systems. Integrated monitoring systems enable rapid response to potential hazards, such as adverse conditions or machine failures. These systems automatically send notifications to operators, informing them of risks and recommending preventive actions. For example, if sensors detect excessive noise or vibrations, the system can alert operators about the need to take appropriate measures or halt operations, significantly reducing the number of accidents and improving workplace safety (Rose et al., 2021).

Early detection of threats is another important aspect of risk management. Modern technologies allow for monitoring various work parameters, such as operator fatigue. For instance, if sensors indicate that a worker is fatigued, the system can automatically recommend a break, minimizing the risk of accidents and increasing work comfort (Abbasi et al., 2022; Tzachor et al., 2022).

Continuous monitoring of working conditions and employee health is the fourth very important element of risk management. The use of advanced sensors to analyze temperature, humidity, and air quality allows for ongoing assessment of conditions in the farm's breeding facilities. Regular monitoring of these parameters contributes to improving work comfort and reducing the risk of health issues, such as heat stroke or respiratory diseases (Xie et al., 2022).

Risk management in Agriculture 4.0 is a complex process that combines modern technologies with workplace safety management practices. By utilizing real-time data, effective alarm systems, early threat detection, and continuous monitoring of conditions, farmers can significantly enhance workplace safety and the efficiency of their operations. The introduction of technological innovations not only protects workers' health but also supports the sustainable development of the agricultural sector, which is crucial in light of the challenges facing modern agriculture, such as climate change, increasing food demand, and the need to protect natural resources (Filho et al., 2020; Zhang et al., 2020).

5. Work safety management in Agriculture 4.0 in selected EU countries

No country or international organization systematically collects data on the application of automated digital technologies in agriculture (Lowenberg-DeBoer, 2022; Zhang et al., 2020). It is estimated that about 70% of farms in the USA use digital technologies in management, while in the European Union, this percentage is only around 20% (Wawer, 2023). In the context of Agriculture 4.0, EU countries adopt various strategies for implementing and managing work safety. These differences are largely determined by local conditions, legal regulations, and the level of technological development, which affects the effectiveness of safety solutions in the agricultural sector. Common EU regulations, such as directives on occupational safety and health, provide a foundation for national legislations, but each country adapts them to its own conditions and level of technological advancement. The directions for the development of Agriculture 4.0 are outlined in strategic international documents, especially those from the European Union, such as the Strategic Plan for the Common Agricultural Policy for 2023-2027 and the strategies of the European Green Deal. National documents are also important, including Poland’s Strategy for Sustainable Rural Development, Agriculture, and Fisheries until 2030 and the National Strategic Plan for CAP for 2023-2027.

Many EU countries are focusing on the digitalization of agriculture and the use of modern technologies to increase efficiency and work safety in agriculture. In Poland, there has been a noticeable increase in interest in implementing Agriculture 4.0 technologies in recent years, which also encompasses aspects of work safety. The implementation of monitoring systems, such as IoT sensors and data management software, aims not only to enhance production efficiency but also to improve working conditions. Farmers are starting to utilize analytical solutions that identify health hazards, such as noise and vibrations, and optimize working conditions on farms. Investments in monitoring technologies contribute to reducing accidents and occupational diseases (Stępień et al., 2023; Wawer, 2023). Reports by Wawer (2019) and Kordowska et al. (2023) highlight significant opportunities for the development of Polish agriculture through the implementation of Smart Farming solutions. However, to harness this potential, close cooperation among technology producers, agricultural advisors, and farmers themselves is necessary. Only collaboration among these entities can create conditions for the rapid implementation of innovations and enhance the competitiveness of Polish agriculture.

The implementation of Agriculture 4.0 technologies in EU countries, such as France, Germany, the Netherlands, and Spain, is associated not only with improving production efficiency but also with challenges related to work safety. Modern technologies, such as autonomous machines, GPS tools, and farm management information systems (FMIS), have the potential to significantly reduce hazards associated with agricultural work, but their implementation faces several barriers that affect effective work safety management.

In Poland, as in other EU countries, the agricultural sector is undergoing a digital transformation, which requires adjusting work safety management systems to new realities. However, the development of Agriculture 4.0 encounters numerous barriers, such as the diverse spatial structure of farms, limited use of the sector's internal potential, low levels of economic diversification in rural areas, and traditional operating models. Additionally, collaboration and activity among producer groups are insufficient (Kiniorska et al., 2021; Ślusarz, 2015). Despite this, interest among Polish farmers in modern technologies is rapidly increasing, as demonstrated by the application process for the "Support for Agriculture 4.0 under the KPO", launched by the Agency for Restructuring and Modernization of Agriculture. The application process, which was expected to last a month, ended after just three days because the amount requested by farmers exceeded 150% of the planned budget of 164 million PLN. Farmers are particularly interested in solutions that improve fertilization efficiency, weed control, soil cultivation support systems, automatic machine guidance, and telemetry. The introduction of these solutions will increase work safety in agriculture.

Technologies such as Internet of Things (IoT) sensors, remote imaging, and big data analytics are seen as key to improving agricultural production efficiency while simultaneously enhancing work safety. Both in the USA and Germany, these technologies are gradually being implemented in agriculture, although their full utilization requires further infrastructure development. In Germany, some rural areas still lack access to sufficiently fast internet connections, limiting the possibilities for digital agriculture. Despite this, Germany is one of the leaders in technological innovation in agriculture in the EU (Bernhardt et al., 2021). In this country, advanced work safety management systems are being implemented, which include process automation and monitoring of working conditions. These systems aid in the early detection of health hazards, contributing to improved worker safety. However, further development of digital infrastructure in rural areas in Germany requires state intervention and political support. Privatization of infrastructure has led to the concentration of investments in urban areas, creating a need for additional actions to support agriculture in rural areas. A strong point is that technologies like LPWAN (Low-Power Wide-Area Networks) are being developed in Germany, offering low bandwidth but being more energy-efficient and better suited to agricultural needs (e.g., soil monitoring). Nevertheless, coverage for these networks is only 70%, and their development is mainly organized by civic networks rather than commercial ones (Bernhardt et al., 2021). Additionally, Germany has strict regulations regarding work safety, which supports the implementation of modern solutions.

Italy is focusing on innovations in the agricultural sector, particularly regarding risk management associated with work safety. Work safety management in the context of Agriculture 4.0 relies on the use of modern technologies, such as mobile applications, drones, sensors for data collection and automatic data acquisition, robots, and autonomous machines. Many Italian farms utilize monitoring technologies that allow for the identification of hazards, such as exposure to harmful chemicals. Research conducted by Caffaro et al. (2020) indicates that key factors influencing the adoption of these technologies are their practical utility and access to relevant information. Moreover, Italian regulations require farmers to conduct training on work safety and to use modern health protection methods (Caffaro et al., 2020; Scuderi et al., 2022; Vecchio et al., 2020).

Sweden, as one of the countries where innovations in agriculture are closely linked to a high level of health and work safety protection, is introducing advanced systems for monitoring risks related to working conditions, stress levels, and worker fatigue. There is an increasing use of robots and automation for heavy, routine tasks, which reduces the physical burden on workers. Swedish regulations on occupational safety and health are among the most stringent in the world, including for the agricultural sector. There is a strong emphasis on social responsibility, which influences the development of innovative technological solutions. Sweden’s investment in research and development of new agricultural technologies aims to improve efficiency, product quality, and working conditions in the sector (Bjerke, Johansson, 2022; Drottberger, Langendahl, 2023).

In France, the implementation of Agriculture 4.0 technologies focuses on process automation and monitoring working conditions. French farms increasingly use digital systems for data management, allowing for real-time tracking of worker health and working conditions. The French government also promotes educational initiatives aimed at raising farmers’ awareness of work safety principles and ergonomics (Bellon-Maurel et al., 2023).

Spain, like Sweden, actively invests in modern technologies in agriculture. The use of sensors to monitor air quality and noise levels is becoming increasingly common in Spanish farms. Investments in these technologies are supported by both the public and private sectors, facilitating the implementation of new solutions. The Spanish government promotes the development of technology in agriculture through various programs and grants. The country also emphasizes education in workplace ergonomics, which translates into improved employment conditions (Sadjadi, Fernández, 2023).

The Netherlands is known for innovative agricultural practices and is introducing advanced technologies in work safety management. The country uses monitoring systems that allow for close control of working conditions and worker health. Dutch farms utilize real-time data, enabling quick responses to hazards such as weather changes or equipment failures. The Netherlands also focuses on educating farmers about work safety and promotes ergonomic solutions in farms (Puente-Rodríguez et al., 2022).

6. Discussion of results

Mahmud et al. (2021) and Bujak (2012) emphasize that process automation, particularly in animal husbandry, significantly reduces the physical burden on workers and minimizes occupational hazards. Their studies confirm findings that automated feeding and watering systems for animals reduce direct contact with them, lowering the risk of injuries caused by unpredictable animal behavior. These observations align with the results of Rodrigues et al. (2021), who highlight that automation allows workers to focus on more complex tasks while reducing the intensity of labor, which ultimately improves workplace safety.

In their research, Herlina et al. (2021) and Vlăduț et al. (2024) analyzed how drones and monitoring technologies contribute to improving safety in agriculture. These technologies enable farmers to remotely monitor animals, reducing the likelihood of accidents related to handling them. For example, drones can guide animals on pastures using sound signals, minimizing the need for physical contact. This is consistent with the findings of Namany et al. (2022) and Xie et al. (2022), whose research shows that real-time monitoring with drone's aids in better decision-making, thereby increasing overall farm safety.

The studies by Salgado-Salazar et al. (2018) and Zhang et al. (2020) emphasize that the use of sensors and detectors plays a crucial role in improving workplace safety by monitoring environmental conditions and the health of workers. These devices detect harmful levels of noise, vibrations, or emissions of hazardous gases, allowing for the immediate adjustment of working conditions and preventing health hazards. Contemporary studies confirm that real-time data collection facilitates preventive actions in response to potential dangers in the work environment.

Risk management is a crucial aspect highlighted by Abdulridha et al. (2020) and Araújo et al. (2023), who emphasize the role of real-time data in identifying hazards on farms. Current studies underline that effective alarm systems and early detection mechanisms can mitigate risks associated with equipment failures and unfavorable working conditions. Continuous monitoring of factors such as operator fatigue provides additional evidence that the use of Agriculture 4.0 technologies can improve both safety and efficiency in agriculture.

Conversely, the studies by Kamienski et al. (2019) and Pogorelskaia et al. (2020) revealed barriers to the implementation of Agriculture 4.0 technologies, which limit the widespread use of these solutions. Despite the obvious advantages, high costs and a lack of digital skills among farmers restrict the widespread adoption of these technologies. The research by Vollaro et al. (2019) indicates that smaller farms often struggle with the introduction of such innovations due to financial constraints and insufficient infrastructure. These barriers hinder the implementation of innovations, despite their potential benefits. Understanding these challenges is crucial for developing strategies to increase the adoption of technologies that improve workplace safety.

Effective implementation of 4.0 technologies in agriculture requires a comprehensive approach. In addition to investing in training and infrastructure, appropriate legal frameworks and financial support for all farmers are essential. Collaboration between various sectors and the active role of advisors are crucial for the success of this transformation.

7. Research limitations and future directions in Agriculture 4.0

Research on Agriculture 4.0 faces numerous limitations that significantly impact its effectiveness and practical implementation. Many data-driven technological solutions are still in the testing phase, which hinders their widespread application in real agricultural conditions. There is a limited availability of comprehensive and reliable data, making it difficult to conduct thorough analyses that would allow for assessing the effectiveness of new technologies under diverse socio-economic, geographical, cultural, and environmental conditions in different regions of the country and the world (Zhang et al., 2020).

Another research challenge is the high variability of local conditions, such as climate, microclimate, soils, terrain, and biological factors, which can significantly influence research outcomes. Depending on the region, various crop species and livestock breeds may respond differently to new technologies and changing environmental conditions, which can lead to divergent results in different locations (Ahrari et al., 2024). This means that results obtained in one region are not always directly transferable to others, limiting the development of universal technological solutions.

The development of Agriculture 4.0 is also dependent on political and legal factors. The availability of grants, tax incentives, and clear regulations regarding data sharing play a significant role in accelerating the implementation of new technologies. Without appropriate institutional support, many innovative solutions may not be effectively implemented.

Despite numerous benefits, the development of Agriculture 4.0 is hindered by several key factors. The lack of compatibility between different systems limits their effective utilization, and the high implementation costs, along with insufficient infrastructure, especially in rural areas, prevent many farmers from fully benefiting from modern technologies. As a result, this delays the process of digitizing agriculture and limits its development potential.

Additionally, small and medium-sized farms often face barriers to accessing modern technologies and knowledge, which may exacerbate inequalities in the level of technological advancement in Agriculture 4.0 (Kernecker et al., 2020).

To overcome these limitations, future research should focus on analyzing the impact of Agriculture 4.0 technologies in diverse conditions. A crucial aspect of this research should be the comparison of different regions, which will enable the identification of best practices and solutions that can be adapted to various environments.

Another direction for research should be the investigation of barriers to the adoption of Agriculture 4.0 technologies by farmers, including psychological, economic, and educational aspects. Understanding these barriers is vital for developing effective strategies to support farmers and provide them with education that will facilitate the adoption of new technologies.

It is also essential to examine the impact of Agriculture 4.0 on the natural environment and animal welfare. These studies should focus on sustainability, biodiversity, and the efficient use of natural resources. Evaluating the effects of modern technologies on ecosystems and animal welfare can provide valuable insights that will be crucial for the development of future resource management strategies (Xu et al., 2024).

A key research direction should also involve fostering collaboration between the scientific sector and industry. Such cooperation can contribute to a better understanding of practitioners' needs and accelerate the implementation of innovative solutions, which is critical for the success of Agriculture 4.0.

8. Conclusion

Managing safety and health in the context of Agriculture 4.0 is a complex process that requires consideration of modern technologies, risk management, and employee education. The implementation of innovative technological solutions, such as artificial intelligence (AI), Big Data, the Internet of Things (IoT), nanotechnology, drones, and biotechnology, can significantly enhance production efficiency and improve work safety. However, this process brings a range of challenges, such as high investment costs, the need to retrain employees, and the necessity to adapt to rapid technological changes. Agriculture 4.0 offers many benefits but leveraging them also comes with certain challenges. It is crucial to understand both the possibilities and limitations of these technologies to fully exploit their potential in modern agriculture. New technologies also require adjustments to occupational health and safety regulations to align with changing conditions. Current safety regulations are insufficient for new, automated systems.

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