SYSTEM SAFETY: HUMAN - TECHNICAL FACILITY – ENVIRONMENT
7(1), 2025, pp. 184-193

THE IMPACT OF TECHNOLOGICAL INNOVATIONS IN THE USE OF PLANT PROTECTION PRODUCTS ON ENVIRONMENTAL AND WORKER SAFETY

DOI: 10.2478/czoto-2025-0018
Received: 09/11/2025
Accepted: 21/11/2025

Maria Pilarczyk[1] – *orcid id: 0000-0001-7401-8885, e-mail: maria.pilarczyk@pcz.pl*
Rober Ulewicz[1] – *orcid id: 0000-0002-5694-4284, e-mail: robert.ulewicz@pcz.pl*
[1] Faculty of Management, Częstochowa University of Technology, **Poland**

Abstract: The increasing use of plant protection products in modern agriculture requires careful management to minimize risks to human health and the environment. This study evaluated the impact of innovative technologies for applying plant protection products, including modern drones (UAVs), compared to traditional field sprayers, on occupational safety and environmental protection. The FMEA (Failure Mode and Effects Analysis) method was used to identify and assess hazards through the Risk Priority Number (RPN) indicator. The results showed that conventional sprayers pose higher chemical and contact risks for operators due to direct handling of large quantities of pesticides. Drones significantly reduce operator exposure but introduce new technical and organizational hazards, such as equipment malfunctions, flight control issues, or adverse weather conditions. Key preventive measures include the use of personal protective equipment, adherence to safety procedures, regular calibration and technical inspections, and monitoring of environmental conditions. The findings indicate that combining modern technologies with strict safety procedures can effectively reduce chemical exposure and environmental impact while addressing new risks associated with UAV use.
Keywords: technological innovations, UAVs, field sprayers, plant protection products, occupational safety

1. INTRODUCTION

Pesticides remain an integral component of modern agriculture, as they play a crucial role in crop protection and pest management. However, their use must be carefully managed to minimize risks to human health and environmental integrity (Tudi et al., 2021). Improper application of these substances can lead to increased exposure and elevate the likelihood of adverse effects (Kuster et al., 2024). Occupationally exposed individuals include farm and greenhouse workers, where pesticides are routinely applied. The environmental impact of pesticides may manifest as contamination of water, soil, and air due to surface runoff, leaching, or spray drift, as well as detrimental effects on non-target organisms (Damalas & Eleftherohorinos, 2011).

In recent years, agriculture has undergone a significant technological transformation. The adoption of precision spray management systems allows for accurate chemical dosing, thereby reducing environmental impacts, limiting pollutant emissions to soil and water, and decreasing the carbon footprint of agricultural production (Papadopoulos et al., 2024; Fountas et al., 2020; Verdouw et al., 2019).
Digital agricultural technologies offer substantial economic and environmental benefits. Field mapping systems and automated machine controls can reduce fertilizer use by up to 80%, while variable-rate application technologies for fertilizers and pesticides decrease usage by 60% and 80%, respectively, simultaneously enhancing crop yields by over 60%. Smart machinery and robotic systems can reduce manual labor by up to 97% and cut fuel consumption by approximately half, while farm management systems improve operational efficiency by 10–15% and lower production costs (Papadopoulos et al., 2024; Andújar et al., 2019; Maghsoudi et al., 2015; Tullberg, 2014).
Furthermore, digital agricultural technologies promote sustainable development. Variable-rate application systems enable water savings in orchards and vineyards of 20–50% and reduce greenhouse gas emissions, while improving production efficiency and protecting natural ecosystems (Papadopoulos et al., 2024).
Technological advancements also have significant implications for occupational safety in agriculture. Conventional practices, such as mineral fertilization or pesticide spraying, pose health risks to workers, bystanders, and the surrounding environment. Gao et al. (2025) demonstrated that the use of drones for pesticide application significantly reduces dermal exposure for both operators and bystanders compared to traditional backpack or field sprayers. Exposure decreases with distance from treated areas and, even in orchards under higher wind conditions, remains substantially lower than with conventional methods. These findings indicate that drones mitigate spray drift and minimize risks to human health and the environment. Currently, farms employ both traditional field sprayers and modern drones (UAVs), which differ in application methods, efficiency, and risk profiles. Such technologies help limit workers' direct contact with chemicals, reduce accident risks, and enhance environmental safety (Felkers et al., 2024; Bonds et al., 2024).
The present study aims to analyze the impact of modern technologies used in crop protection applications, with a particular focus on comparing drones (UAVs) and traditional field sprayers regarding environmental contamination and the safety of farmers and agricultural workers. Specifically, the study evaluates how drone-based spraying can reduce pesticide usage and mitigate occupational hazards in agricultural settings.

2. METHODOLOGY OF RESEARCH

To assess risk, the FMEA (Failure Mode and Effects Analysis) method was applied, allowing a comprehensive identification and evaluation of hazards associated with the operation of agricultural machinery and drones (UAVs), considering occupational safety, environmental protection, and machine technology. The results of FMEA enable the comparison of risks between different technologies, optimization of chemical application procedures, and identification of process elements requiring special attention, in accordance with the established RPN threshold (Wolniak, 2019). By the way, the methods of modeling these phenomena are very advanced and use numerous achievements of engineering sciences (Pietraszek et al., 2016; Radek et al., 2020).

For each identified hazard, the following parameters were determined: likelihood of occurrence (L), severity (S), and difficulty of detection (D). Based on these parameters, the Risk Priority Number (RPN) was calculated using the standard formula:

$$RPN = L \times S \times D \quad (1)$$

FMEA Rating Scale:

Likelihood of Occurrence (L)

1–2 – Very unlikely (once in many years, exceptional situation)

3–4 – Unlikely (occurs occasionally, once every few years)

5–6 – Moderately likely (may occur once a year or more frequently under intensive use)

7–8 – Likely (occurs regularly during spraying season under typical operation)

9–10 – Very likely (almost certain, occurs regularly)

Severity (S)

1–2 – Negligible impact (minor irritation, no losses, easily corrected malfunction)

3–4 – Minor impact (temporary health symptoms, minor environmental damage)

5–6 – Moderate impact (temporary inability to work, damage to machine component, localized environmental contamination)

7–8 – Serious impact (severe poisoning, hospitalization, significant environmental contamination, costly repairs)

9–10 – Catastrophic impact (permanent health damage, death, severe environmental degradation, total loss of equipment)

Difficulty of Detection (D)

1–2 – Very easy to detect (hazard obvious, clearly visible, immediately signaled)

3–4 – Easy to detect (usually noticed by the operator or during routine inspection)

5–6 – Moderately difficult to detect (warning signs may allow early detection, but not always; events detected only partially aftereffects appear)

7–8 – Difficult to detect (no clear warning signs; hazard usually identified only after an incident or damage occurs)

9–10 – Practically undetectable (no way to identify the hazard before damage occurs; detection possible only after the fact)

In the analysis, an acceptable RPN threshold of 160 was adopted. This means that any hazard with an RPN value above this threshold is considered high risk and requires immediate and strategic corrective actions aimed at effectively reducing potential hazards.

3. RESULTS

The FMEA-based analysis enabled the identification of key hazards associated with occupational safety and environmental protection during the use of field sprayers and UAV drones. The findings indicate that while both conventional field sprayers (Table 1) and modern drones (Table 2) present certain risks, the magnitude and nature of these hazards differ markedly between the two technologies.

Table 1
Hazard Risk Levels of Field Sprayers (FMEA Method)

Hazard ID	Description of Hazard	Probability of failure (1-10)	Potential Impact (1-10)	Detection Difficulty (1-10)	RPN
Z1	Dermal exposure to the working fluid during field sprayer operation	7	7	4	196

Z2	Inhalation of vapors during tank filling and cleaning	7	8	5	280
Z3	Chemical drift (wind or incorrect spray settings)	6	6	5	180
Z4	Collision or mechanical injury	5	7	4	140
Z5	Environmental contamination (leaks or improper cleaning)	6	6	5	180
Z6	Poor maintenance / outdated UAV components	6	6	5	180
Z7	Non-compliance with safety procedures	8	7	6	336
Z8	Adverse weather conditions (high wind, rain, extreme temperatures)	5	7	4	140
Z9	Incorrect UAV calibration (spray rate, altitude, speed)	6	6	7	252

High-Risk Hazards (RPN > 160):

Z7: Non-compliance with safety procedures (RPN = 336)

This hazard was identified as the highest risk in the entire process, mainly because at high ambient temperatures, the omission of certain personal protective equipment (PPE), such as coveralls, is very common. This increases both the likelihood of contact with chemicals and the difficulty of detecting the hazard. Lack of protection raises the employee's exposure to toxic substances (pesticides) through the skin and respiratory system. Potential consequences include severe poisoning requiring hospitalization or long-term health problems, (see also Szczyrba & Szataniak, 2024).

Z2: Inhalation of vapors during tank filling and cleaning (RPN = 280)

This hazard carries high risk due to direct inhalation of concentrated chemical vapors released during pesticide pouring or tank rinsing. The risk is exacerbated by the lack of adequate respiratory protection. Vapors can directly affect the respiratory and nervous systems, leading to poisoning symptoms such as dizziness, nausea, difficulty breathing, or organ damage.

Z9: Incorrect UAV calibration (RPN = 252)

Errors in working pressure settings, worn or inappropriate nozzles, and excessive tractor speed are common. These often result from time constraints, insufficient operator knowledge, or lack of routine equipment checks before operation. Calibration errors are difficult to detect immediately and can lead to financial losses (low treatment efficiency – wasted pesticides, crop damage) and environmental impacts (increased chemical drift, contaminating neighboring crops and surrounding environment).

Z1: Dermal exposure to working fluid during field sprayer operation (RPN = 196)

Primary causes include sprayer leaks (worn seals, cracked hoses) and splashes during tank filling or nozzle cleaning. Skin contact is highly likely during normal operation. Prolonged or repeated contact can lead to irritation, allergic reactions, or continuous absorption of chemicals, potentially causing poisoning.

Z3, Z5, Z6: Chemical drift, Environmental contamination, Poor maintenance (RPN = 180)

These hazards form a group with elevated risk due to factors such as outdated equipment, lack of routine inspections, and suboptimal work procedures. The consequences are serious and affect the environment, including groundwater and soil contamination.

Lower-Risk Hazards (RPN ≤ 160):

Z4: Mechanical injuries and *Z8: Adverse working conditions*, although assessed as lower risk, still require attention. Mechanical accidents (Z4) can have serious consequences but are relatively preventable through careful attention during work. Adverse conditions are often beyond the worker's direct control, but stopping spraying during unfavorable weather is feasible.

The use of UAV drones in field operations introduces new challenges regarding the safety of workers, bystanders, and environmental protection. The risk of various hazards arises from both the technology itself and the working conditions, making their identification and assessment a crucial part of safety management.

Table 2.
Assessment of Hazard Risk Levels – Drone (UAV) Using the FMEA Method

Hazard ID	Description of Hazard	Probability of failure (1-10)	Potential Impact (1-10)	Detection Difficulty (1-10)	RPN
D1	Dermal exposure to the working fluid (e.g., during UAV tank filling or maintenance)	5	6	4	120
D2	Inhalation of vapors during UAV tank filling	6	7	5	210
D3	Chemical drift due to incorrect UAV settings or wind influence	6	6	5	180
D4	Operator or bystander injury (rotor strike, UAV fall)	4	7	5	140
D5	Environmental contamination (liquid runoff, improper UAV landing with chemicals, poor field mapping)	5	7	5	175
D6	UAV technical failure (battery, electronics, motor) leading to an accident	5	7	6	210
D7	Non-compliance with safety procedures (lack of safety zones, no flight monitoring, absence of PPE)	6	7	6	252
D8	Adverse flight conditions (wind, low visibility)	6	6	5	180
D9	Incorrect spray calibration and settings (chemical type, dosage, flight altitude)	5	6	5	150

High-Risk Hazards (RPN > 160):

D7: Non-compliance with safety procedures (RPN = 252)

This hazard represents the highest risk during UAV spraying. Modern technology can create a false sense of security, leading to typical errors such as the absence of safety zones, loss of continuous UAV control, or omission of PPE during tank filling. The combination of chemical and mechanical hazards may result in serious injuries to the operator or bystanders, as well as exposure to chemical vapors.

D2: Inhalation of vapors during UAV tank filling (RPN = 210)

Although less frequent, UAV tank filling is just as hazardous as field sprayers. The risk arises from direct inhalation of concentrated chemical vapors, often in field conditions. Vapors can directly affect the respiratory and nervous systems, potentially causing acute poisoning with symptoms such as dizziness, nausea, and breathing difficulties.

D6: UAV technical failure (RPN = 210)

Main causes include battery failure (sudden power loss), onboard electronics malfunction (GPS, control system), or motor damage. An in-flight failure can result in uncontrolled UAV crashes onto people, animals, buildings, or traffic, causing severe property damage and serious bodily injuries. Detection difficulty is high because impending battery or software failures are often undetectable by the operator.

D3: Chemical drift and D8: Adverse flight conditions (RPN = 180)

These hazards are closely linked. Drift (D3) is caused by incorrect spray parameter settings (e.g., improper droplet setting speed) and flights under unsuitable wind conditions (D8). Starting a flight under strong wind or low visibility is a common operator error. Consequences include reduced treatment efficacy and environmental contamination. Chemicals may be carried to neighboring crops, water bodies, or non-agricultural areas, resulting in financial and ecological losses.

D5: Environmental contamination (RPN = 175)

The risk stems from improper UAV landing with residual tank liquids and errors in field mapping (e.g., omission of buffer zones near watercourses), leading to unintended spraying of other areas. This may result in direct soil and water contamination.

Lower-Risk Hazards (RPN ≤ 160):

D1: Dermal exposure to the working fluid (e.g., during UAV tank filling or maintenance) (RPN = 120)

This hazard is significantly reduced compared to field sprayers. The small tank size and remote application make direct skin contact unlikely, which is a key safety advantage of UAV technology.

D4: Operator or bystander injury (rotor strike, UAV fall) (RPN = 140)

The probability of direct contact with rotors is relatively low if proper distance is maintained, but potential consequences are severe.

D9: Incorrect spray calibration and settings (chemical type, dosage, flight altitude) (RPN = 150)

Dosage errors mainly affect treatment efficacy but are less hazardous than equipment failures.

4. DISCUSSION

A comparative risk analysis between conventional field sprayers and UAV drones reveals significant differences in the nature of hazards. For field sprayers, the highest RPN values are associated with non-compliance with safety procedures, inhalation of chemical vapors, and incorrect equipment calibration. These hazards result from direct operator contact with the working fluid, large fluid volumes, and physical handling of the machinery, increasing both the likelihood of exposure and the potential health and environmental consequences (Felkers et al., 2024).

Comparative analysis of pesticide operator exposure shows clear differences between traditional spraying methods and UAV applications. Studies conducted in the Fakous Province in Egypt (Elhalwagy et al., 2010) indicate that operators using conventional sprayers experience high levels of chemical exposure, particularly on the head, body, and legs. This exposure led to biochemical changes, including reduced acetylcholinesterase (AChE) activity, decreased glutathione (GSH) levels, and increased oxidative stress markers (MDA), demonstrating real health risks from chronic pesticide contact.

In UAV applications, chemical risks are significantly reduced due to small tank sizes and remote operation; however, new hazards arise from technical failures, flight control, and weather conditions. Felkers et al. (2024) found that the main exposure for UAV operators occurs during the mixing of concentrated pesticide formulations, whereas transferring the diluted solution to the UAV involves minimal pesticide contact.

Additional confirmation of the importance of the mixing and loading (M&L) phase as the primary source of UAV operator exposure comes from Felkers et al. (2024). Their study showed that the highest chemical exposure occurs during mixing of concentrated pesticides, while transferring the diluted solution to the UAV results in minimal contact. Exposure distribution analysis indicated that the hands account for 50–75% of total exposure, emphasizing the necessity of chemical-resistant gloves. Using a single layer of protective clothing in combination with gloves significantly reduces operator contact with chemicals. These results support a “stratified exposure” strategy, separating the handling of concentrated formulations and the transfer of diluted solutions, allowing for more precise risk assessment and selection of appropriate personal protective equipment (PPE). These data clearly show that UAVs substantially reduce direct operator contact with pesticides while still requiring adherence to basic safety procedures. Embedding Lean-oriented work design and behaviour-focused interventions can further raise procedural compliance and reduce residual risk (de Sá et al., 2025). Extending this with a user-centred prioritization of operator needs (e.g., comfort and usability of PPE, clarity of checklists and alerts) can further increase procedural compliance (Szczyrba & Szataniak, 2023).

Further support comes from Kuster et al. (2023), who conducted field experiments on UAV pesticide application in rice crops. They found that the highest operator exposure occurred during mixing and loading (M&L). The median potential dermal exposure for workers performing M&L was 9.886 mg/kg of handled substance, while for UAV pilots it was almost 25 times lower (0.400 mg/kg). The use of certified protective clothing reduced exposure by approximately 21%, and the addition of chemical-resistant gloves reduced it by 98% (to 0.173 mg/kg). Comparisons with backpack sprayer models showed that UAVs reduce operator exposure by 90–99%, clearly confirming the safety advantage of UAV technology over conventional methods.

The importance of PPE is further confirmed by AOEM data covering over 500 professional operators across 10 European countries. Wearing chemical-resistant gloves and protective clothing reduces operator exposure by over 90% in all mixing, loading, and application scenarios, provided proper use and adherence to safety procedures (Felkers et al., 2024). These findings emphasize that appropriate protective clothing remains critical in both conventional spraying systems and UAV applications.

Implementing a “stratified exposure” strategy, which separates the mixing of concentrated formulations from the loading of solutions into UAVs, allows for more precise risk assessment and selection of PPE (Felkers et al., 2024). Introducing UAVs into agriculture reduces direct operator contact with pesticides, limits environmental chemical load, and supports sustainable plant protection practices (Tudi et al., 2021; Kuster et al., 2023). However, despite reduced chemical risk, UAV applications still involve technical and organizational hazards, such as equipment failures, flight control, and weather conditions,

which must be addressed in safety procedures and operator training (Felkers et al., 2024; Bonds et al., 2024; Safaeinejad et al., 2025).
An important complement to risk analysis in UAV use is research on pesticide drift. Monitoring in Korea (Kim et al., 2023) showed that UAV-sprayed aerosols can settle on non-target crops, and their levels depend on multiple environmental and organizational factors. The highest residues were detected on leafy vegetables (e.g., scallions), while cereals and legumes, such as soybean or maize, exhibited the lowest pesticide accumulation. These results suggest that planning crop structures around UAV-treated fields can be a practical tool to reduce drift. Kim et al. (2023) demonstrated that buffer strips and windbreaks (e.g., maize crops) reduced airborne pesticide deposition by up to 100%, confirming the effectiveness of natural barriers in limiting environmental exposure. The study also found that although some sample residues exceeded permissible limits, the percentage of acceptable daily intake was only 0–0.81%, indicating low consumer risk. In discussions of UAV safety, it is therefore important to emphasize that drones reduce direct operator contact with pesticides but require additional procedures for environmental risk management. Considering factors such as crop morphology, the presence of protective strips, and meteorological conditions should be an integral part of good agricultural practices and UAV-related regulations (Kim et al., 2023).
Table 3 presents a summary of preventive recommendations aimed at reducing occupational and environmental risks during the use of field sprayers and UAVs. It includes both personal protective measures and practices minimizing the likelihood of hazards.

Table 3.
Preventive Recommendations for Operators of Field Sprayers and UAV Drones

Hazard	RPN	Risk Level	Preventive Recommendations
Z7 / D7 – Non-compliance with safety procedures	336 / 252	High	Strict use of PPE; mandatory safety training; establishment of safety zones; verification of procedures before work.
Z2 / D2 – Inhalation of vapors during tank filling and cleaning	280 / 210	High	Use of respirators with filters; closed filling systems; minimization of chemical exposure; monitoring of weather conditions.
T9 / D9 – Incorrect spray calibration	252 / 150	High / Medium	Regular calibration of sprayers and UAV settings; operator training; control of nozzles, pressure, flight altitude, and chemical dosage.
Z1 / D1 – Dermal exposure to the working fluid	196 / 120	High / Low	Use of waterproof protective clothing and gloves; regular equipment leak checks; safe filling and cleaning procedures.
Z3 / D3 – Chemical drift	180 / 180	High	Stop application during strong winds; proper nozzle and spray speed settings; weather monitoring; maintain buffer zones.
Z5 / D5 – Environmental contamination	180 / 175	High	Wash equipment in designated chemical neutralization areas; observe buffer zones; verify spraying plan and field mapping.

Z6 / D6 – Poor maintenance / UAV technical failure	180 / 210	High	Regular technical inspections; immediate replacement of damaged components; emergency procedures for UAVs; battery and electronics checks.
Z4 / D4 – Mechanical injuries	140 / 140	Medium	Exercise caution when handling equipment; training on safe equipment operation.
Z8 / D8 – Adverse working / flight conditions	140 / 180	Medium / High	Monitor weather conditions; suspend application during strong winds, low visibility, or high temperatures.

Analysis of Table 3 highlights that implementing the recommended preventive measures – such as proper PPE use, equipment maintenance, and environmental monitoring – effectively mitigates both chemical and mechanical risks for operators. These strategies ensure safer operation of field sprayers and UAV drones while minimizing potential environmental impact, consistent with safety culture effects on procedural compliance (Raditsela et al., 2025).

5. CONCLUSIONS

The use of modern technologies in agriculture, including UAV drones, reduces chemical risks for workers and limits negative environmental impacts compared to traditional field sprayers, which pose higher contact and chemical exposure risks. At the same time, new technologies introduce technical and organizational hazards, such as equipment failures, flight control issues, and adverse weather conditions. In both cases, consistent use of personal protective equipment, adherence to safety procedures, monitoring of working conditions, and regular equipment calibration and maintenance are essential to minimize risks to operators and the environment.

REFERENCES

Andújar, D., Moreno, H., Bengochea-Guevara, J. M., de Castro, A., & Ribeiro, A., 2019. Aerial imagery or on-ground detection? An economic analysis for vineyard crops. *Computers and Electronics in Agriculture*, 157, 398–407.

Bonds, J. A., Pai, N., Hovinga, S., Stump, K., Haynie, R., Flack, S., & Bui, T., 2024. Spray drift, operator exposure, crop residue and efficacy: early indications for equivalency of uncrewed aerial spray systems with conventional application techniques. *Journal of the ASABE*, 67, 27–41.

Damalas, C. A., & Eleftherohorinos, I. G., 2011. Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, 8(5), 1402–1419. DOI: 10.3390/ijerph8051402

Elhalwagy, M. E. A., Farid, H. E. A., Gh, F. A. A., Ammar, A. E., & Kotb, G. A. M., 2010. Risk assessment induced by knapsack or conventional motor sprayer on pesticides applicators and farm workers in cotton season. *Environmental Toxicology and Pharmacology*, 30(2), 110–115. DOI: 10.1016/j.etap.2010.04.004

Felkers, E., Kuster, C. J., Hamacher, G., Anft, T., & Kohle, M., 2024. Pesticide exposure of operators during mixing and loading a drone: Towards a stratified exposure assessment. *Pest Management Science*, Advance online publication. DOI: 10.1002/ps.8574

Fountas, S., Espejo-Garcia, B., Kasimati, A., Mylonas, N., & Darra, N., 2020. The future of digital agriculture: Technologies and opportunities. *IT Professional*, 22(1), 24–28.

Gao, B., Sasturain, J., Wiemann, C., Hewitt, N. J., Gan, W. J., Wang, G., Lan, Y., & Blaschke, U., 2025. Measurement of bystander dermal exposure resulting from drift after drone application under three crop treatment scenarios. *ACS Agricultural Science & Technology*, 5, 542–551.
Kim, C. J., Yuan, X., Kim, M., Kyung, K. S., & Noh, H. H., 2023. Monitoring and risk analysis of residual pesticides drifted by unmanned aerial spraying. *Scientific Reports*, 13(1), 9975. DOI: 10.1038/s41598-023-36822-w
Kuster, C. J., Kluxen, F. M., Felkers, E., Morgan, N., Hewitt, N. J., & Durand-Reville, J., 2024. Efficiency of working coveralls and chemical resistant gloves in reducing operator exposure to pesticides. *Journal of Consumer Protection and Food Safety*, 19, 1–10.
Kuster, C. J., Kohler, M., Hovinga, S., Timmermann, C., Hamacher, G., Buerling, K., Chen, L., Hewitt, N. J., & Anft, T., 2023. Pesticide exposure of operators from drone application: A field study with comparative analysis to handheld data from exposure models. *ACS Agricultural Science & Technology*, 3, 1125–1130. DOI: 10.1021/acsagscitech.3c00253
Maghsoudi, H., Minaei, S., Ghobadian, B., & Masoudi, H., 2015. Ultrasonic sensing of pistachio canopy for low-volume precision spraying. *Computers and Electronics in Agriculture*, 112, 149–160.
Papadopoulos, G., Arduini, S., Uyar, H., Psiroukis, V., Kasimati, A., & Fountas, S., 2024. Economic and environmental benefits of digital agricultural technologies in crop production: A review. *Smart Agricultural Technology*, 8, 100441. DOI: 10.1016/j.saat.2024.100441
Pietraszek, J., Dwornicka, R., Szczotok, A., 2016. The bootstrap approach to the statistical significance of parameters in the fixed effects model. In *Proceedings of the 7th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS Congress 2016)*, pp.6061-6068. DOI: 10.7712/100016.2240.9206
Radek, N., Pietraszek, J., Radek, M., Paraska, O., 2020. The influence of plasma cutting parameters on the geometric structure of cut surfaces. *Materials Res. Proc.*, 17, 132-137. DOI: 10.21741/9781644901038-20
Raditsela, R., Sharp, K.L. & Bevan-Dye, A.L.. 2025. Safety culture in focus: comparing employee perceptions across small and medium-sized manufacturing SMEs in South Africa. Production Engineering Archives, 31(2), 238-246. DOI: 10.30657/pea.2025.31.24
Sá, J.C., Oliveira, A., Hines, P., Mourão, F., McDermott, O., Marques, P.A., Zouari, A., Pathania, A. & Ulewicz, R. 2025. The effects of Lean and people's behaviours on Occupational Safety. Production Engineering Archives, 31(1), 1-14. https://doi.org/10.30657/pea.2025.31.1
Safaeinejad, M., Ghasemi-Nejad Raeini, M., & Taki, M., 2025. Reducing energy and environmental footprint in agriculture: A study on drone spraying vs. conventional methods. *PLoS One*, 20(6), e0323779. DOI: 10.1371/journal.pone.0323779
Szczyrba, A., & Szataniak, E. 2024. Integrated approach to occupational safety in the production of ready-to-eat meals and canned meat: Challenges and solutions. System Safety: Human – Technical Facility – Environment, 6(1), 175–183. https://doi.org/10.2478/czoto-2024-0019
Szczyrba, A., & Szataniak, M. (2023). Decoding consumer preferences in food packaging with the Kano model. System Safety: Human – Technical Facility – Environment, 5(1), 83–92. https://doi.org/10.2478/czoto-2023-0010
Tudi, M., Ruan, D., Wang, L., Lyu, J., Sadler, R., Connell, C., Chu, C., & Phung, D. T., 2021. Agriculture development, pesticide application and its impact on the environment. *International Journal of Environmental Research and Public Health*, 18, 1112.
Tullberg, J. N., 2014. CTF and global warming. In *Proceedings of the 5th Australian Controlled Traffic and Precision Agriculture Conference*, p. 214.
Verdouw, C., Sundmaeker, H., Tekinerdogan, B., Conzon, D., & Montanaro, T., 2019. Architecture framework of IoT-based food and farm systems: A multiple case study. *Computers and Electronics in Agriculture*, 165, 104939.
Wolniak, R., 2019. Problems of use of FMEA method in industrial enterprise. *Production Engineering Archives*, 23, 12–17. DOI: 10.30657/pea.2019.23.02