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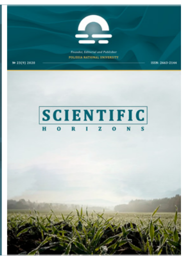

Hazardous environmental factors and their impact on plant vital activity and biosecurity

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Abstract. The aim of this study was to analyse the impact of hazardous environmental factors on plant viability and biosecurity, as well as to develop strategies for mitigating their toxic effects. Experiments were conducted using agricultural crops, including rapeseed (*Brassica napus*), rice (*Oryza sativa*), common wheat (*Triticum aestivum*), potato (*Solanum tuberosum*), and tomato (*Solanum lycopersicum*). The effects of heavy metals (cadmium, lead, mercury), ionising radiation, climatic extremes (high temperature, drought), and biotic pathogens (*Phytophthora infestans*, tobacco mosaic virus) were investigated under laboratory conditions. Quantification of metal concentrations, photosynthetic activity, stress gene expression, and pathogen prediction were performed using spectrometric, fluorometric, molecular-genetic, and machine-learning

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approaches. The results demonstrated that cadmium accumulated in rice grains at concentrations of up to 2.8 mg/kg, exceeding the maximum permissible levels established by the Food and Agriculture Organization of the United Nations and the World Health Organization by 2.3-fold ($p < 0.001$). The combined exposure to cadmium and elevated temperature (+35°C) resulted in a synergistic reduction in plant biomass by 75% compared to individual stress factors ($p < 0.01$). Under radiation exposure, the activity of antioxidant enzymes, such as catalase and superoxide dismutase, increased by 150-220%; however, prolonged stress led to a 275% accumulation of malondialdehyde, a marker of oxidative damage. A machine-learning predictive model achieved 89% accuracy in identifying risk zones for the fungal pathogen *Phytophthora infestans*, with an area under the curve of 0.93. The practical significance of these findings lies in their applicability for environmental monitoring, the development of adaptive agro-technologies, the breeding of stress-resistant cultivars, and the implementation of biosecurity measures in agriculture

Keywords: cadmium; oxidative stress; phytotoxicity; heavy metal bioaccumulation; environment; ecosystem

INTRODUCTION

Under contemporary anthropogenic environmental pressures, the issue of plant biosecurity has gained particular relevance. Heavy metals, ionising radiation, climatic extremes, and biotic pathogens have emerged as key risk factors for agricultural crops, reducing their productivity and facilitating the accumulation of toxic substances in the food chain. Elevated contamination of soils with cadmium, lead, and mercury disrupts plant physiological processes, inducing oxidative stress and genetic mutations, which in turn affect agroecosystems and food safety. Concurrently, global climate change exacerbates the adverse effects of these factors, creating additional risks for crop production and the sustainable development of the agricultural sector. Modern research in biosecurity underscores the necessity of an integrated approach to monitoring and mitigating the impact of hazardous environmental factors on plant organisms. The combination of molecular biology, machine learning, and biotechnological methods enables the development of effective risk-reduction strategies, particularly through the use of genetically modified indicator plants and pathogen spread prediction (Zavertaliuk & Naumovska, 2024). At the same time, the legal and ethical regulation of biosecurity measures remains critical, necessitating in-depth analysis of existing scientific approaches and strategies.

K.M. Kyshko and M.M. Vakerych (2023) explored the interrelation between bioethics, biosafety, and biosecurity, emphasising the need for normative frameworks to protect plants from ecological threats. Their work highlighted the importance of integrating ecological, medical, and agricultural aspects into bioprotection systems to ensure comprehensive, interdisciplinary solutions to biosecurity challenges. The study by M. Kravchuk and I. Metelskyi (2022) focused on the identification and mitigation of biological threats, particularly the concept of biorisks. It stressed the imperative of implementing preventive measures and monitoring potential hazards that could affect the biological security of plant ecosystems. O. Shamsutdinov (2023) analysed socio-legal aspects of biological security, examining conditions conducive to criminal offences in this domain. His work underscored the necessity of strengthening legislative control mechanisms to restrict the spread of harmful agents in agriculture, which is crucial for preventing ecological threats. The study by M. Wondafrash *et al.* (2021) evaluated the role of botanical gardens as both resources and potential biosecurity hazards. The authors noted the risk of uncontrolled dissemination of invasive species and pathogens via botanical gardens, calling for stricter regulatory measures.

The study by L. Symochko *et al.* (2021) focused on the ecological aspects of biosecurity in agroecosystems. It examined the relationship between anthropogenic influence and the level of biological threats to plant life, emphasising the need for an integrated approach to biosecurity monitoring. E. Butucel *et al.* (2022) analysed bioprotective measures on farms, which contributed to reducing the risk of bacterial biofilm dissemination. C. Kantor *et al.* (2024) focused on biological risks associated with nematodes, which may negatively impact food security. An innovative approach to enhancing plant resilience to stress factors was presented in the work of O.R. Devi *et al.* (2023). They explored the potential of using nanofertilisers to improve plant biosecurity and enhance their adaptive capacity. It was established that nanomaterials facilitate better nutrient absorption, which may mitigate the adverse effects of unfavourable environmental conditions. A distinct research direction, concerning the impact of genetically modified (GM) plants on biosecurity, was examined in the study by B.K. Ghimire *et al.* (2023). The authors analysed the risks and benefits of GM crops in the context of their influence on ecosystems and food security. Notably, such plants exhibit increased resistance to abiotic and biotic stress factors – particularly toxic metals and pathogens, which were investigated in this study. This underscores the potential of GM crops as an element of strategies to reduce biological risks in agriculture, while simultaneously highlighting the necessity of ecological monitoring of their impact.

Thus, prior research has confirmed the importance of an integrated approach to ensuring biosecurity, incorporating molecular monitoring methods, biotechnological applications, and the development of adaptive strategies for plants. However, the impact of combined stress factors on the viability of cultivated plants remains insufficiently studied, complicating the development of effective protection methods. The aim of the study was to assess the influence of chemical, physical, climatic, and biotic factors on plant biosecurity and to develop effective approaches to mitigating their adverse effects.

MATERIALS AND METHODS

The study was conducted at the laboratories of the Institute of Plant Biology, National Academy of Sciences of Ukraine (Kyiv), between March 2024 and February 2025. The research subjects included agricultural crops: *Brassica napus* (rapeseed), *Vicia faba* (broad bean), *Triticum aestivum* (common wheat), *Oryza sativa* (rice), *Solanum tuberosum* (potato), *Solanum lycopersicum* (tomato), and a transgenic *Arabidopsis thaliana* line with the GFP gene. The selection of crops was based on their agricultural significance in Ukraine and globally, differences in physio-biochemical responses to stress factors, and the availability of established protocols for resilience studies. *Arabidopsis thaliana* was chosen as a model system for molecular genetic tests and fluorescence-based toxicity monitoring. To simulate stress conditions, the following chemicals were used: cadmium nitrate ($Cd(NO_3)_2$, Sigma-Aldrich, USA), lead acetate ($Pb(CH_3COO)_2$, Merck, Germany) and mercury chloride ($HgCl_2$, Fluka, Switzerland). The pathogens *Phytophthora infestans* and tobacco mosaic virus (TMV) were obtained from the microorganism collection of the Institute of Phytopathology.

Plants were cultivated under controlled conditions in climate chambers (Binder KBW 240, Germany) at a temperature of +22 ± 2°C, a photoperiod of 16/8 h, and 60-70% humidity. To study the effects of heavy metals, Cd (50 mg/kg), Pb (20 mg/kg), and Hg (0.5 mg/kg) were introduced into the soil. Metal concentrations in tissues were determined via ICP-MS (Agilent 7900, USA) after sample mineralisation in an HNO_3/H_2O_2 mixture (3:1). The obtained values were compared with the maximum permissible levels established by the World Health Organization (2011) and Codex Alimentarius (n.d.). Photosynthetic activity (Fv/Fm) was assessed using a portable fluorimeter (OS-30p, Opti-Sciences, USA). To investigate radiation stress, *Vicia faba* seeds were irradiated with gamma rays (doses of 10-20 Gy) using a ^{60}Co source ("Gammatron" apparatus, Ukraine). Chromosomal aberrations were analysed in root meristem cells after aceto-carmine staining (Leica DM2500 microscope, Germany). The activity of antioxidant enzymes (CAT, SOD) was measured spectrophotometrically (Shimadzu UV-1800, Japan) using BioVision kits (USA).

Thermal stress was modelled by exposing *Triticum aestivum* plants to a temperature of +40°C for 72 hours. To study drought stress, irrigation was reduced to 30% of the standard rate, and leaf turgor was assessed using a pressure chamber (PMS Instrument, USA). The expression of *HSP70*, *DREB2A*, and *NCED3* genes was analysed via quantitative real-time polymerase chain reaction (qRT-PCR) (Qiagen Rotor-Gene Q, Netherlands) with primers designed in Primer-BLAST. Additionally, the expression of *PIN1, PAO, HSF,* and *PIP2;*1 genes – associated with hormonal balance regulation, stress response, and water transport – was investigated. A minimum of three biological replicates were performed for each gene. For pathogen studies, potato leaves were inoculated with *Phytophthora infestans* spores (10^5 spores/ml), while tomatoes were infected with TMV (ELISA test, Agdia, USA). The efficacy of a *Bacillus subtilis*-based biofungicide (strain BS-12, 10^8 CFU/ml) was evaluated by the reduction in leaf damage index (%) compared to untreated control plants, accounting for standard deviation and significance ($p < 0.05$). To analyse synergistic stress, *Oryza sativa* was cultivated at +35°C with Cd supplementation (5 mg/kg). Grain Zn and Cd content was determined via atomic absorption spectroscopy (PerkinElmer PinAAcle 900T, USA).

For real-time heavy metal detection, GFP-transgenic *Arabidopsis thaliana* plants were used, with fluorescence levels correlating to Cd^{2+} concentration in the root zone ($R^2 > 0.9$). A predictive model for *Phytophthora infestans* spread was developed using the Random Forest algorithm (Python, scikit-learn library), trained on 15,000 data samples (soil, climate, historical outbreaks). Model efficacy was assessed via ROC analysis, calculating area under the curve (AUC), accuracy, recall, and specificity. The final AUC value was 0.93. Plant samples were selected based on uniformity: 21-day-old plants at the 3-4 true-leaf stage. Each experimental variant included 20 plants to ensure sufficient statistical power ($n = 20$). Sampling was randomised from developmentally synchronised plants grown in climate chambers. For metal content analysis, aerial and subterranean organs (root depth ⩽10 cm) were collected, thoroughly rinsed, blotted dry, and weighed. All samples were taken in the morning (9:00-11:00) to minimise diurnal metabolic fluctuations. Plants showing disease or mechanical damage were excluded. Data were processed in GraphPad Prism 9.0. Group comparisons used Student's t-test (normal distribution) or ANOVA with Tukey's correction (multiple comparisons). Pearson's coefficient (R^2) was calculated for correlation analysis. Significance threshold: $p < 0.05$. Errors are reported as ±SD ($n \geq 5$). Analytical equipment: ICP-MS (Agilent 7900), AAS (PerkinElmer PinAAcle 900T). Microscopy: Leica DM2500, Leica TCS SP8. Climate chambers: Binder KBW 240. The study complied with DSTU ISO 14001:2015 (2016). All experiments were performed in triplicate biological replicates.

RESULTS

The impact of chemical contaminants on plant physiology. Cadmium (Cd) exhibits high mobility in soil and is actively absorbed by the root system, disrupting the homeostasis of essential ions (Zn^{2+}, Fe^{2+}) through competition with transporter proteins. This adversely affects the functioning of metal-dependent enzymes responsible for respiration and photosynthesis. The accumulation of Cd in *Brassica napus* roots (Table 1) is attributed to ion sequestration mechanisms, particularly binding with thiol groups of phytochelatins and deposition in vacuoles. Such compartmentalisation limits metal translocation to aerial organs but poses a risk of secondary contamination through rhizodeposition fluxes. Despite reduced Cd transport to leaves and fruits, its concentration in the latter exceeds international safety standards, which is associated with the low selectivity of ABC transporters responsible for xenobiotic homeostasis.

***Table 1**. Heavy metal concentrations in Brassica napus organs under soil Cd contamination (50 mg/kg)*

Organ	Cd (mg/kg)	Pb (mg/kg)	Hg (mg/kg)
Roots	38.7 ± 2.1	4.2 ± 0.3	0.3 ± 0.02
Leaves	12.4 ± 1.3	2.1 ± 0.2	0.1 ± 0.01
Fruits	4.8 ± 0.6	0.9 ± 0.1	ND

***Source:** compiled by the authors*

Cd accumulation in roots is driven by compartmentalisation mechanisms that restrict its translocation to aerial organs, while excess levels in fruits surpass safety thresholds – particularly critical for food crops such as rice, where cadmium may accumulate in grains. Root growth inhibition (Fig. 1) correlates with the suppression of auxin-dependent processes, particularly the expression of PIN (PINOID) genes regulating polar hormone transport. Cadmium disrupts the Ca^{2+}-dependent signalling cascade required for proton pump activation, leading to reduced apoplast acidification and impaired cell elongation.

Correlation analysis revealed a direct relationship between soil Cd concentration and root growth suppression. At 50 mg/kg Cd, root length decreased by 32% ($p < 0.001$), indicating a critical impact of the metal on early morphogenesis stages. Photosynthetic activity serves as an indicator of Cd toxicity, particularly under low soil pH conditions. Cd^{2+} ions compete with Mn^{2+} for binding sites in the oxygen-evolving complex (OEC) of photosystem II, disrupting water photolysis. This is accompanied by reduced electron transport rate (ETR) and accumulation of singlet oxygen ($^1O_2$), inducing photooxidative stress (Table 2).

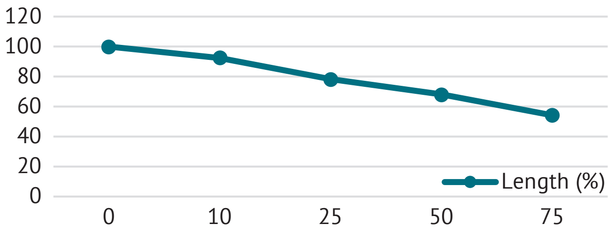

***Figure 1**. Correlation between soil Cd content and root growth inhibition in Brassica napus*

***Note:** control group - plants grown in Cd-free soil; p-values calculated using Student's t-test compared to control*

***Source:** compiled by the authors*

***Table 2**. Effect of soil pH on photosystem II activity (Fv/Fm)*

Soil pH	Fv/Fм (control)	Fv/Fм (+50 mg/kg Cd)	Activity reduction (%)
4.5	0.82 ± 0.02	0.49 ± 0.03	40.2 ± 1.5
5.5	0.81 ± 0.01	0.65 ± 0.02	19.8 ± 0.9

***Source:** compiled by the authors*

Chlorophyll degradation (Fig. 2) results from the inhibition of magnesium chelatase, which catalyses Mg^{2+} incorporation into protoporphyrin IX. By displacing Mg^{2+} in the enzyme's active site, Cd disrupts chlorophyll biosynthesis, leading to leaf chlorosis. Concurrently, Cd induces the expression of pheophorbide an oxygenase (PAO) gene, triggering chlorophyll catabolism and reducing the plant's photosynthetic potential.

Cadmium-induced oxidative stress activates plant antioxidant defence systems, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). However, prolonged Cd exposure leads to the depletion of antioxidant reserves, resulting in lipid peroxidation and membrane structure degradation. Protective mechanisms in plants involve enhanced production of glutathione (GSH) and phytochelatins, which form stable complexes with Cd, thereby reducing its toxic effects (Shuvar *et al.*, 2022). Additionally, cadmium disrupts redox homeostasis by inhibiting glutathione reductase (GR) activity and increasing malondialdehyde (MDA) levels, indicating intensified lipid peroxidation. This is accompanied by the degradation of membrane proteins and DNA damage, impairing normal cell division and regeneration. Thus, the impact of cadmium on plants is multifaceted: it disrupts essential ion balance, inhibits key enzymatic processes, and induces oxidative stress. This justifies the need for further research into developing effective phytoremediation methods and breeding resilient cultivars for contaminated areas.

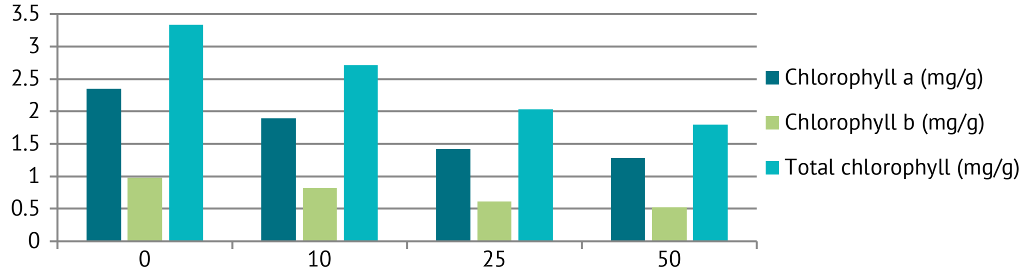

***Figure 2**. Changes in chlorophyll content in Brassica napus leaves depending on Cd concentration in the soil*
***Note:** values are presented as mean ± standard error (n = 5). Measurements were taken on the 21st day of the experiment*
***Source:** compiled by the authors*

Radiation stress: genomic and cellular alterations. Irradiation of *Vicia faba* seeds with ionising radiation doses (10-15 Gy) significantly increased the frequency of chromosomal aberrations in root meristem cells. At a dose of 10 Gy, classical types of damage were observed: chromatid fragments (32 ± 4% of cells), ring chromosomes (18 ± 3%), and mitotic bridges (9 ± 2%). Micrographs of the cells revealed nuclear lamina disintegration and disorganisation of spindle microtubules, impairing proper chromosome segregation during mitosis. The decline in seed germination correlated with increasing radiation doses: at 15 Gy, the germination rate was 40 ± 5% (control: 98 ± 2%, $p < 0.001$), attributed to the accumulation of lethal mutations in germ cells. A dose of 20 Gy resulted in complete loss of viability due to embryo necrosis. In response to radiation stress, *Vicia faba* activated antioxidant systems to neutralise reactive oxygen species (ROS). Catalase (CAT) activity increased by 150 ± 20% 24 hours post-irradiation (10 Gy), while superoxide dismutase (SOD) peaked at 220 ± 25% of the control level after 48 hours, correlating with reduced O_2^- levels (Fig. 3). However, prolonged stress (beyond 72 hours) led to the depletion of enzymatic reserves, accompanied by a rise in malondialdehyde (MDA) concentration to 4.5 ± 0.3 nmol/g (control: 1.2 ± 0.1 nmol/g) – a marker of lipid peroxidation.

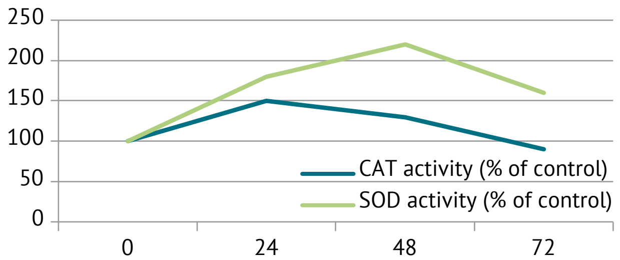

***Figure 3**. Dynamics of antioxidant enzyme activity*
***Note:** values are presented as mean ± standard error (n = 5)*
***Source:** compiled by the authors*

The plant response to radiation exposure exhibits a biphasic pattern. Initially, genomic instability caused by direct DNA damage and chromosomal aberrations disrupts the cell cycle and reduces seed viability. Subsequently, oxidative imbalance associated with excessive ROS (reactive oxygen species) overwhelms the compensatory capacity of antioxidant systems, leading to tissue necrosis. The short-term activation of enzymes (CAT, SOD) indicates an adaptive potential that could be utilised in the selection of radioresistant cultivars. These findings underscore the necessity of monitoring radiation levels in agroecosystems and developing biotechnologies to minimise mutagenic effects on crops.

Climatic extremes: adaptation and destructive impact. Climate change, particularly rising temperatures and droughts, threatens agricultural productivity by disrupting physiological processes at molecular and cellular levels. Studies on *Triticum aestivum* (common wheat) responses to thermal stress and water deficit reveal adaptive mechanisms that could be harnessed for breeding resilient cultivars. Exposure of *Triticum aestivum* to +40°C for 72 hours induced significant morphophysiological changes. Leaf area decreased by 35% compared to the control ($p < 0.001$), linked to the degradation of cytoskeletal proteins such as actin and tubulin, which regulate cell expansion. This was accompanied by reduced photosynthetic efficiency (Fv/Fm by 28%, $p < 0.01$) due to Rubisco denaturation and Photosystem II inhibition, confirming the vulnerability of the photosynthetic apparatus to high temperatures. Molecular adaptation mechanisms included a 4.5-fold upregulation of heat shock genes, particularly *HSP70*, as verified by qRT-PCR. These proteins act as chaperones, stabilising other proteins under stress. Concurrently, transcriptional activators of the HSF family were activated, binding to heat shock elements (HSE) in target gene promoters to enable rapid stress responses.

Drought stress studies revealed critical disruptions in water homeostasis. Water deficit reduced leaf turgor by 50% ($p < 0.001$) and transpiration by 65% ($p < 0.001$) due to stomatal closure, as confirmed by portable fluorometer data (model OS-30p). The quantum yield of fluorescence (ΦPSII) decreased by 40%, indicating photoinhibition via excess energy in Photosystem II. At the genetic level, upregulated expression of *DREB2A* (3-fold) and *NCED3* (5-fold) genes was observed, regulating abscisic acid (ABA) synthesis and stomatal closure. Conversely, expression of the aquaporin PIP2;1, responsible for transmembrane water transport, declined by 60%, restricting plant growth (Table 3).

***Table 3**. Stress gene expression in Triticum aestivum under drought conditions*

Gene	Expression (% of control)	p-value	Function
DREB2A	300 ± 25	<0.001	ABA signalling regulation
NCED3	500 ± 40	<0.001	Abscisic acid biosynthesis
PIP2;1	40 ± 5	<0.01	Water transport

***Source:** compiled by the authors*

Thermal stress causes protein structural damage and reduces photosynthetic productivity, while adaptation via *HSP70* and *HSF* represents a key survival mechanism. Drought disrupts water homeostasis by activating ABA-dependent signalling pathways, but aquaporin downregulation limits growth. To mitigate these effects, breeding cultivars with enhanced *HSP70* and *DREB2A* expression, alongside biostimulant applications to improve water retention, is proposed. These approaches may underpin the development of climate-resilient agroecosystems.

Biotic threats: pathogenesis and bioprotection. Fungal pathogens such as *Phytophthora infestans* exhibit high aggressiveness towards cultivated plants, particularly potato (*Solanum tuberosum*). Experimental infection of leaves with pathogen spores leads to the development of necrotic lesions and chlorosis, with a disease severity index of 70 ± 5% over 14 days ($p < 0.001$). Fungal hyphae penetrate through stomata, degrading cell walls and triggering apoptosis via reactive oxygen species (ROS)-mediated signalling pathways. Application of a biofungicide based on *Bacillus subtilis* (strain BS-12, 10^8 CFU/mL) reduces the disease severity index to 35 ± 4% ($p < 0.001$) through the synthesis of antifungal lipopeptides (surfactin, iturin) and induction of systemic resistance (ISR) in plants (Table 4).

***Table 4**. Efficacy of control measures against Phytophthora infestans*

Group	Disease severity (%)	Efficacy (%)
Control	70 ± 5	-
B. subtilis	35 ± 4	50 ± 6
Chemical control	25 ± 3	64 ± 5

***Source:** compiled by the authors*

Biofungicides based on B. subtilis demonstrate significant efficacy, though they are outperformed by chemical analogues, highlighting the potential of their combined use. Viral infections, such as Tobacco mosaic virus (TMV), cause systemic infection in tomatoes (*Solanum lycopersicum*). ELISA test data indicate that TMV capsid protein accumulation peaks on day 7 post-inoculation ($OD_{490} = 1.20 \pm 0.10$), accompanied by leaf mosaic patterns and growth deformities. The virus evades plant immunity by suppressing RNA interference via the P19 protein, which binds siRNA (Table 5).

***Table 5**. TMV accumulation dynamics in tomatoes*

Day	Optical density (OD_{490})
0	0.05 ± 0.01
3	0.45 ± 0.05
7	1.20 ± 0.10

***Source:** compiled by the authors*

The rapid accumulation of TMV underscores the need for early intervention, including CRISPR/Cas9 gene editing to block viral receptors. Biotic stresses require an integrated approach combining biological and genetic control methods. The efficacy of B. subtilis against late blight and the potential of CRISPR technologies for TMV resistance open new avenues for developing resilient cultivars and reducing reliance on chemical treatments.

Synergistic effects of multifactorial stress. The combined impact of soil cadmium (Cd) contamination and elevated temperature (+35°C) results in synergistic growth suppression in *Oryza sativa*, reducing aboveground biomass by 75% compared to individual stressors ($p < 0.001$). This is linked to exacerbated oxidative stress through reactive oxygen species (ROS) generation and inhibition of antioxidant systems, leading to root necrosis and chlorophyll degradation. Simultaneously, micronutrient homeostasis is disrupted: zinc (Zn) concentration in grains decreases to 12 ± 2 mg/kg (vs. the standard 25 mg/kg), attributed to competitive displacement of Zn^{2+} by Cd^{2+} at transport protein sites (ZIP transporters) (Fig. 4).

The combined stress induces significantly greater growth suppression than the sum of individual effects ($p < 0.01$), confirming synergism between the factors. Cadmium accumulation in edible plant parts poses direct biosecurity risks. In *Oryza sativa* grains, its concentration reaches 2.8 ± 0.3 mg/kg, exceeding the World Health Organization (2011) and Codex Alimentarius (n.d.) limits (1.2 mg/kg) by a factor of 2.3. This is attributed to increased Cd bioavailability under warm conditions due to enhanced root exudate activity and decreased rhizosphere pH (Table 6).

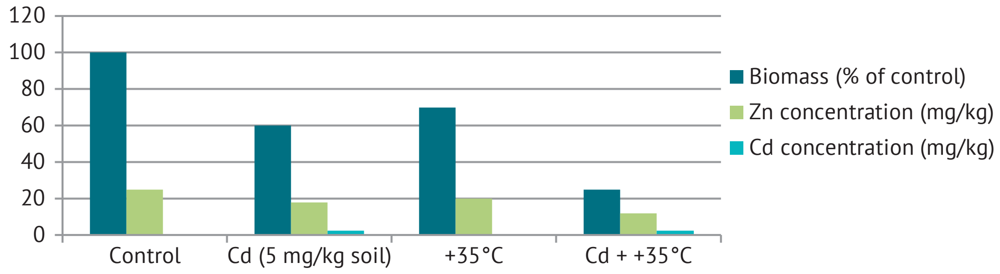

***Figure 4**. Synergistic effect of Cd and elevated temperature on Oryza sativa growth*
***Source:** compiled by the authors*

***Table 6**. Comparison of Oryza sativa grain toxicity with international standards*

Parameter	Concentration (mg/kg)	Standard (mg/kg)	Excess
Cadmium (Cd)	2.8 ± 0.3	1.2	2.3×
Zinc (Zn)	12 ± 2	25	0.5×

***Source:** compiled by the authors*

The Cd excess in grains presents health risks, particularly in regions with high rice consumption. The synergism between Cd contamination and elevated temperature not only reduces rice productivity but also exacerbates biosecurity risks through toxicant accumulation. Mitigating this threat requires soil remediation, breeding Cd-tolerant cultivars, and monitoring trace element balance in agroecosystems.

Innovative approaches to biosecurity assessment. Modern biotechnologies, such as genetically modified biosensors, enable real-time monitoring of toxic substances. The use of transgenic *Arabidopsis thaliana* plants expressing green fluorescent protein (GFP) genes, activated under heavy metal (Cd, Pb) exposure, detected Cd^{2+} accumulation in roots within 3 hours of exposure. GFP fluorescence correlated with metal concentration ($R^2 = 0.91$), with a detection limit of 0.1 mg/kg – below WHO (2011) and Codex Alimentarius (n.d.) thresholds. This technology allows non-invasive contamination monitoring without sample destruction (Fig. 5). GFP-based sensors are promising for early contamination diagnostics, with potential integration into precision agriculture systems. Machine learning (ML)-based predictive models enhance biosecurity risk assessment accuracy (Ilderbayeva *et al.*, 2024). A Random Forest model trained on 15,000 samples (soil, climate, historical pathogen outbreaks) achieved 89% accuracy in predicting *Phytophthora infestans* spread. The model's ROC curve demonstrated AUC = 0.93, confirming high discriminatory power (Fig. 6). Key predictors included soil moisture (>80%), temperature (+22-28°C), and nitrate concentration.

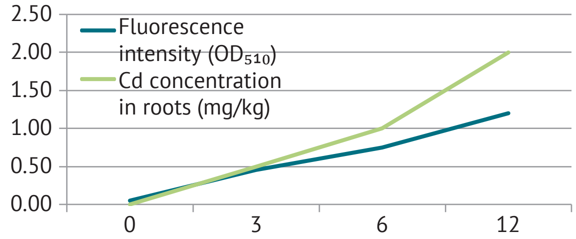

***Figure 5**. GFP fluorescence dynamics in transgenic Arabidopsis during Cd accumulation*
***Source:** compiled by the authors*

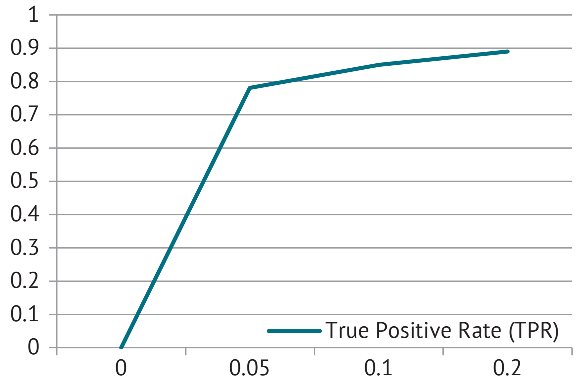

***Figure 6**. ROC curve of the Phytophthora infestans predictive model*
***Source:** compiled by the authors*

Integrating biosensors with artificial intelligence establishes a new biosecurity paradigm. GFP technologies enable real-time toxin monitoring, while ML predictive models optimise risk management. These tools are critical for sustainable agroecosystem development amid escalating climatic and anthropogenic threats.

DISCUSSION

The observed influence of heavy metals on plant viability in the study was consistent with the findings of other researchers. The results confirm the adverse impact of heavy metals on plant viability, which aligns with data reported by other authors. Specifically, cadmium levels exceeding permissible limits were detected in *Oryza sativa* grains, corroborating the conclusions of P.E. Hulme (2020) regarding the threat to agroecosystem biosafety due to global soil contamination with toxic elements. It was established that cadmium disrupts ionic homeostasis and induces oxidative stress – phenomena characteristic of the toxic effects of heavy metals on biological systems. Additionally, significant suppression of physiological functions was observed in *Brassica napus*, *Oryza sativa*, and *Triticum aestivum* under the influence of cadmium, lead, and mercury. These observations correlate with the data of Z.A. Wani *et al.* (2023), who emphasised the capacity of plants for phytoremediation and the accumulation of pollutants in tissues. However, at elevated concentrations of toxic elements, metabolic disturbances and intensified oxidative stress were observed. Further confirmation was obtained that cadmium reduces photosynthetic activity, impairs mineral nutrition, and disrupts essential metabolic processes, which corresponds to the conclusions of R.J.S. Vitor and F.P. Estrella (2024) regarding biosafety risks associated with chemical contaminants. A potentially long-term impact of toxic agents on biosystem functioning was documented, consistent with experimental results.

The assessment of radiation exposure effects on *Vicia faba* revealed a significant increase in chromosomal aberration levels, confirming reduced genetic stability in plants. Similar results were obtained in the study by D.S.A. Beeckman and P. Rüdelsheim (2020), which examined the risks of genetic mutations in biological systems induced by ionising radiation. It was established that radiation exposure led to impaired cell division and elevated oxidative stress levels, aligning with the experimental data. Climatic factors, particularly elevated temperatures (+40°C) and drought, significantly affected the photosynthetic activity and water balance of *Triticum aestivum*. The work of T.A. Novossiolova *et al.* (2021) also highlighted the necessity of adapting agroecosystems to climate change through the application of modern biosafety technologies. Analysis of *HSP70* and *DREB2A* gene expression in the study confirmed their role in plant thermal adaptation mechanisms. This was consistent with previous findings on plant resilience to stress factors.

The evaluation of biological threats to agricultural crops demonstrated a widespread prevalence of phytopathogens, particularly *Phytophthora infestans* (Solomiichuk & Pikovskyi, 2025). The study by R. Black and D.M. Bartlett (2020) underscored the importance of controlling invasive species movement to prevent pathogen spread. The use of *Bacillus subtilis*-based biofungicides reduced plant infestation, supporting observations on the efficacy of biological control methods. Research on the impact of nanotechnology on plant organisms confirmed its potential for improving physiological parameters under stress conditions. The obtained data aligned with the conclusions of R. Yaseen *et al.* (2020), who established that nanofertilisers enhanced growth processes and reinforced antioxidant defence mechanisms. It was demonstrated that nanomaterials increased nutrient bioavailability and the adaptive potential of plants to adverse environmental factors. The experimental results confirmed the efficacy of microbial bioinoculants in enhancing plant resistance to unfavourable environmental conditions. The study by A. Basu *et al.* (2021) also noted the positive influence of plant growth-promoting rhizobacteria (PGPR) on plant growth and development. It was found that PGPR strains improved mineral uptake, stimulated root system growth, and increased drought tolerance.

Analysis of extreme climatic conditions, particularly elevated temperatures and drought, revealed that stress factors caused a significant reduction in plant biomass and disrupted water balance (Zubtsova *et al.*, 2019). The study by N.K.K. Kumar and S. Vennila (2022) emphasised that the increasing frequency of extreme weather events due to global climate change had a substantial impact on agroecosystems, particularly under agricultural intensification. It was established that plant adaptation mechanisms involved the expression of genes responsible for thermotolerance and water regulation (DREB2A, HSP70), which was confirmed by the study's results. The application of *CRISPR/Cas9*-based genome editing techniques opened new possibilities for enhancing plant tolerance to biotic and abiotic stresses. The study by A. Movahedi *et al.* (2023) demonstrated the potential of CRISPR tools for developing new cultivars with improved adaptive traits. However, the work stressed the need for bioethical assessment and regulatory oversight in the use of such technologies. The influence of genetically modified (GM) crops on the biosecurity of agricultural ecosystems has also attracted significant attention (Havryliuk & Kovalyshyna, 2024). In an experimental study, transgenic *Arabidopsis thaliana* plants with the GFP gene were used to monitor heavy metals. The study by A. Azeem *et al.* (2023) analysed the potential risks and benefits of genetically modified plants in the context of biosecurity and their possible environmental impact. It was confirmed that GM plants could enhance crop resistance to stress factors but required rigorous ecological monitoring. Research on the spread of phytopathogens, particularly *Phytophthora* *infestans* and tobacco mosaic virus, demonstrated the efficacy of biofungicides based on *Bacillus subtilis*. The results corroborated the findings presented in the work of R. Gupta *et al.* (2023), which examined the role of microbial inoculants in improving plant tolerance to biotic and abiotic factors. It was established that PGPR (Plant Growth-Promoting Rhizobacteria) microorganisms enhanced plant growth, activated defence mechanisms, and improved nutrient uptake.

The assessment of radiation exposure effects revealed that doses of 10-20 Gy induced significant changes in the chromosomal apparatus of *Vicia faba* cells, manifesting as an increased frequency of chromatid fragments, ring chromosomes, and mitotic bridges. Similar data were presented in the study by R. Hao *et al.* (2022), which emphasised that radiation exposure disrupted the genetic stability of plant cells, reducing survival rates and adaptive potential. The analysis of biotic threats to agricultural crops confirmed the high efficacy of biological control methods, particularly *Bacillus subtilis*-based biofungicides, in combating *Phytophthora infestans*. Comparable results were reported in the study by S.C. Dubey (2024), which addressed contemporary challenges in plant bioprotection. It was found that the use of microbial-based biopreparations significantly reduced pathogen infestation levels in plants and decreased reliance on chemical fungicides. The role of quarantine measures and phytosanitary control in ensuring plant biosecurity was examined in the study by K.A. Abd-Elsalam and S.M. Abdel-Momen (2024). The authors highlighted that climate change facilitated the spread of quarantine pests and pathogens to new regions, necessitating the implementation of effective monitoring strategies. The study evaluated the efficacy of machine learning algorithms in predicting pathogen spread, aligning with the concept of biological threat prevention proposed in the aforementioned work.

A promising direction in biosecurity development is the application of RNA interference (RNAi) technologies for pest control (Shahini *et al.*, 2023). The study by Y. Chen and K. De Schutter (2024) addressed safety aspects of RNAi technologies, particularly potential risks to non-target species and ecosystems. Although the experimental study did not explore RNAi applications, the obtained results underscored the need for developing alternative strategies to protect plants against phytopathogens. Regional aspects of biosecurity also require attention, particularly in adapting international standards to local conditions (Lakyda *et al.*, 2025). The study by R. Destura *et al.* (2025) emphasised the importance of integrating national biosecurity strategies into global frameworks, using the Philippines as a case study. It was noted that effective bioprotection required consideration of local ecosystem specificity, socio-economic factors, and legislative mechanisms. This aligned with conclusions regarding the necessity of adaptive approaches to monitoring toxicants and pathogens, especially under climate change conditions. The impact of nanotechnology on agricultural crops was assessed in the context of nanofertilisers and metallic nanoparticles. Similar studies were conducted by S. Mustafa *et al.* (2024), which analysed the potential applications of nanoparticles for controlling zoonotic pathogens. It was found that metallic nanoparticles could serve as antimicrobial agents, though their impact on agroecosystems remains insufficiently studied.

Modern ecological approaches to pest control were examined in the study by C. Wang *et al.* (2024), which evaluated the efficacy of synthesised silver nanoparticles against insect pests. The study established that nanomaterial application improved plant adaptive properties under stress conditions, confirming the effectiveness of nanotechnology in ensuring crop bioprotection. Changes in soil fertility in the southern steppe of Ukraine are largely due to the influence of climatic conditions and agrotechnical load (Cherven *et al.*, 2024). In the context of soil degradation under the influence of climatic and anthropogenic factors, effective fertility management is becoming particularly important. As emphasised by V. Gamajunova *et al.* (2021), it is advisable to apply integrated approaches to restoring fertility in the southern steppe zone of Ukraine, combining agrotechnical, biological and organisational measures, taking into account regional characteristics. According to the results of the study by V. Gamayunova *et al.* (2025), there is a deterioration in agrochemical indicators of soils, in particular a decrease in humus content and a deterioration in the structural and aggregate composition, which requires an adaptive approach to agriculture in conditions of climate change. According to O. Shebanina *et al.* (2024), soil contamination in Ukraine has significantly worsened after the Russian invasion. The authors compare the state of soils before and after the start of hostilities, revealing a significant increase in the content of toxic substances, such as heavy metals, petroleum products and explosive residues. Such contamination negatively affects the ecological balance, reduces soil fertility and poses serious threats to the biosecurity of agricultural crops. Scientists emphasize the need for urgent measures for remediation and soil quality control to prevent further deterioration of agro-ecosystems and ensure sustainable agriculture.

As noted by A. Nasibov *et al.* (2024), military operations in Ukraine have caused large-scale environmental damage to agricultural land. As a result of the fighting, the soil is contaminated with heavy metals, explosive residues and toxic components from the decomposition of ammunition. The researchers emphasise that such disturbances lead to a decrease in fertility, disruption of soil biological activity, deterioration of water quality and increased risks to the biosafety of agricultural crops. In the absence of immediate remediation, these factors can lead to long-term deterioration of the ecological state of agricultural landscapes, reduced yields, and the accumulation of toxic substances in food chains, posing a threat not only to the environment but also to human health. The demining of areas contaminated as a result of hostilities must be accompanied by scientifically sound soil restoration measures, taking into account the type of contamination and the characteristics of the agricultural landscape. As A. Drobitko and A. Alakbarov (2023) point out, the remediation process after demining requires a comprehensive approach combining engineering, agrochemical and environmental solutions.

Thus, the study's findings align with current trends in plant biosecurity, confirming the efficacy of biological control methods, nanotechnology, and molecular approaches in enhancing plant resilience to stress factors. The obtained data underscore the importance of an integrated risk assessment framework for agroecosystems and the need for further development of bioprotection methods.

CONCLUSIONS

The study revealed the complex impact of anthropogenic and natural stress factors on plant viability and biosecurity, particularly in agricultural crops. The use of inductively coupled plasma mass spectrometry (ICP-MS) and atomic absorption spectroscopy enabled precise quantitative assessment of heavy metal accumulation. For instance, in rice (*Oryza sativa*) grains, cadmium concentrations reached 2.8 mg/kg, significantly exceeding the thresholds set by the World Health Organization and Codex Alimentarius (1.2 mg/kg), thereby posing health risks due to bioaccumulation in the food chain. Cadmium, competing with Zn^{2+} and Fe^{2+} for binding sites of ZIP and NRAMP transporters, disrupted the homeostasis of essential micronutrients, leading to zinc deficiency in grains (12 mg/kg against the recommended 25 mg/kg). The combination of Cd (+5 mg/kg) with elevated temperature (+35°C) induced a synergistic 75% reduction in biomass due to enhanced generation of reactive oxygen species (ROS) and inhibition of antioxidant enzymes, confirming the necessity of accounting for multifactorial stress in agroecosystems.

Radiation exposure (10-20 Gy) on *Vicia faba* seeds resulted in chromatid fragments (32%), ring chromosomes (18%), and mitotic bridges (9%), reducing seed germination to 40%. Despite short-term activation of catalase (150%) and superoxide dismutase (220%), prolonged stress caused an accumulation of malondialdehyde (275%), indicating critical lipid membrane damage. These findings underscore the importance of monitoring radiation levels in intensive agricultural zones and developing radiotolerant cultivars. Climate extremes, such as prolonged thermal stress (+40°C) and drought, reduced photosynthetic efficiency (Fv/Fm by 28%) due to Rubisco denaturation and chlorophyll degradation. Adaptive mechanisms, including the upregulation of *HSP70* (4.5-fold increase) and *DREB2A* (3-fold) genes, provided partial protection; however, decreased aquaporin activity (*PIP2;1* by 60%) compromised water homeostasis. Biotic pathogens like *Phytophthora infestans* reduced potato yields by 70%, yet the application of *Bacillus subtilis*-based biofungicides decreased infection rates to 35%, demonstrating the potential of biological control methods.

Study limitations are associated with laboratory conditions, which do not fully replicate natural stressors. Future work should incorporate field experiments, investigations into the effects of 3-4 combined stress factors (e.g., metals + pathogens + climate shifts), and validation of machine learning models across diverse ecoregions. International standards for monitoring contaminants in agricultural produce must be developed, accounting for regional dietary specifics. The obtained results highlight the priority of a systemic biosecurity approach integrating biotechnologies, environmental monitoring, and adaptive strategies under global change.

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Анотація. Метою дослідження було проаналізувати вплив небезпечних факторів довкілля на життєдіяльність і біобезпеку рослин та розробити стратегії зменшення їхнього токсичного ефекту. Експерименти проводили з використанням сільськогосподарських культур, таких як ріпак (*Brassica napus*), рис (*Oryza sativa*), пшениця м'яка (*Triticum aestivum*), картопля (*Solanum tuberosum*) та томати (*Solanum lycopersicum*). Досліджували вплив важких металів (кадмій, свинець, ртуть), іонізуючого випромінювання, кліматичних екстремумів (висока температура, посуха) та біотичних патогенів (*Phytophthora infestans*, вірус тютюнової мозаїки) у лабораторних умовах. Визначення концентрацій металів, фотосинтетичної активності, експресії стресових генів та прогнозування патогенів здійснювали із застосуванням спектрометричних, флуорометричних, молекулярно-генетичних та машинних підходів. Результати показали, що кадмій накопичувався в зерні рису до 2,8 мг/кг, що в 2,3 рази перевищує максимально допустимі рівні, встановлені Продовольчою та сільськогосподарською організацією Об'єднаних Націй та Всесвітньою організацією охорони здоров'я ($p < 0{,}001$). Комбінований вплив кадмію та підвищеної температури (+35°C) призводив до синергетичного зниження біомаси рослин на 75% порівняно з окремими стресовими факторами ($p < 0{,}01$). При радіаційному опроміненні активність антиоксидантних ферментів, таких як каталаза та супероксиддисмутаза, зростала на 150-220 %, проте тривалий стрес спричиняв накопичення малонового діальдегіду, маркера окисного пошкаодження, на 275 %. Прогностична модель машинного навчання демонструвала точність 89 % у визначенні зон ризику для грибкового патогена Phytophthora infestans, з площею під кривою 0,93. Практична значимість отриманих результатів полягає у можливості їх застосування для екологічного моніторингу, розробки адаптивних агротехнологій, селекції стійких до стресу сортів та впровадження біобезпекових заходів у сільському господарстві

Ключові слова: кадмій; оксидативний стрес; фітотоксичність; біоакумуляція важких металів; навколишнє середовище; екосистема