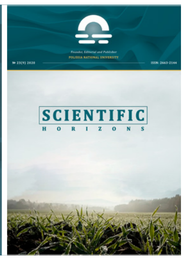
SCIENTIFIC HORIZONS
Journal homepage: https://sciencehorizon.com.ua
Scientific Horizons, 28(7), 62-78
UDC 504.5:631.4
DOI: 10.48077/scihor7.2025.62



Biosecurity of agroecosystems under technogenic and environmental risks

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Article's History:
Received: 30.11.2024
Revised: 29.05.2025
Accepted: 25.06.2025

Abstract. The study aimed to establish the relationship between technogenic and environmental factors affecting the biosecurity of agroecosystems in Ukraine, with the development of adaptive monitoring and risk mitigation strategies through the integration of digital technologies. The research methodology was based on an interdisciplinary approach combining ecotoxicological analysis, biogeochemical modelling, and spatiotemporal assessment of anthropogenic impacts using geographic information systems, satellite observation, and algorithmic risk prediction based on Artificial Intelligence and big data analytics. The application of machine learning methods, spectral pollution analysis, and multi-level agroecosystem mapping revealed hidden patterns of agri-landscape degradation, assessed their ecological resilience, and formulated adaptive approaches to environmental management to reduce biological risks. The findings indicated an elevated chemical load on Ukrainian agroecosystems, manifested in exceedances of maximum permissible concentrations for ammonia (20-28 μg/m^3 in air), nitrogen oxides (over 35 μg/m^3), nitrates (over 50 mg/L in water), and pesticides (up to 0.05 mg/L). Humus content in chernozems decreased to 1.2-1.5%, accompanied by soil degradation. A correlational link was established between

Suggested Citation:
Zhumadilova, A., Zhigitova, S., Turalina, M., & Kudriavytska, A. (2025). Biosecurity of agroecosystems under technogenic and environmental risks. *Scientific Horizons*, 28(7), 62-78. doi: 10.48077/scihor7.2025.62.

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increased technogenic pressure and higher prevalence of oncological diseases, cardiovascular and respiratory pathologies, as well as reduced life expectancy (by 7-10 years) in highly polluted regions. Negative demographic trends were recorded, including rising child mortality, declining fertility, and increased environmentally driven migration. The results confirm the efficacy of digital technologies in enhancing the quality of monitoring, diagnostics, and risk management in agroecosystems undergoing transformational anthropogenic pressures

Keywords: artificial intelligence; machine learning; risk management; agri-landscape degradation; biosphere

INTRODUCTION

The escalation of technogenic and environmental threats has significantly impacted the biosecurity of agroecosystems, leading to adverse consequences for public health and quality of life. Emissions of hazardous substances, climate change, water and air pollution, and the aftermath of industrial disasters are considered potential factors contributing to increased morbidity, mortality, and deteriorating socio-economic conditions. As an integral indicator of physical, social, and environmental well-being, quality of life has been used to assess the biosecurity of agroecosystems and health risks for populations in agricultural regions.

Large-scale urbanisation, soil degradation, agro-landscape pollution, and industrial accidents have contributed to rising chronic diseases, immune system suppression, and oncological pathologies among residents of agrarian territories (Rahman *et al.,* 2021). Chemical and radioactive contamination has created threats at both regional and global scales, necessitating the development of effective biosecurity strategies in agriculture (Khomutinin *et al.*, 2024). The lack of comprehensive measures, low environmental awareness among agricultural producers, and inadequate monitoring of ecological hazards exacerbate risks to agricultural products and public health. A review of scientific literature confirms the importance of an interdisciplinary approach to assessing technogenic and environmental risks in agriculture. C. Piskunova and V. Bondar (2022) emphasise the need for integrated methodologies to analyse biological threats and physiological responses of organisms under critical conditions. The significance of the discipline "Life Safety" in training crisis management and risk analysis specialists is highlighted, along with the necessity for further empirical research in agroecosystem biosecurity.

A crucial aspect of studying technogenic and environmental threats is the development of effective mitigation and management strategies for agricultural impacts. In this context, the work of M.V. Kustov *et al.* (2021) is noteworthy, focusing on a comprehensive monitoring and control system for atmospheric pollution in agrarian regions by chemical and radioactive substances. The proposed approach is based on predictive mathematical modelling, artificial precipitation methods for hazardous substances, and decision-making systems, enhancing the ecological safety of the agricultural sector. S. Bondarenko *et al.* (2022) analysed threat forecasting mechanisms and optimisation of managerial decisions in Ukraine's agrarian security. Emphasis is placed on a holistic risk assessment framework, improving hazardous substance monitoring efficiency, and developing informational-analytical platforms for rapid response to ecological challenges in the agro-sector. The rise of legal and ethical challenges associated with biotechnology, agrochemicals, and digital systems in agriculture has necessitated a revision of regulatory frameworks for agrarian biosecurity (Polukarov *et al.*, 2024).

O.V. Mudrak *et al.* (2023) analysed the impact of environmental determinants on demographic processes in rural Ukraine. The authors note that industrial pollution and socio-economic factors contribute to the depopulation of agrarian regions, rising youth mortality, and demographic aging, directly affecting agroecosystem stability The study by D. Hryhorczuk *et al.* (2024) examines the ecological consequences of Russia's war against Ukraine, revealing large-scale degradation of agricultural lands, soil contamination, and pollution of water resources, which pose long-term threats to public health and food security. Similar factors were analysed by D. Rawtani *et al.* (2022), who investigated the environmental impacts of the war in Ukraine: water pollution, soil degradation, and biodiversity loss. The authors emphasise the associated health risks and the need to criminalise environmental crimes; however, ecosystem restoration mechanisms require further research.

Y.M. Kopytsia and E.Y. Tulina (2021) explored the legal regulation of invasive alien species in Ukraine within the context of climate change. The authors note that climate change facilitates the spread of undesirable species, threatening biodiversity and the agricultural sector, while effective legislative control mechanisms remain absent. However, the study does not examine the implementation mechanisms of these regulations within Ukraine's legal framework. Similar conclusions were drawn by R. Gentili *et al.* (2021), who investigated the legal regulation of invasive alien species (IAS) in the context of climate change. The authors highlight that these factors act synergistically, posing risks to biodiversity; however, Ukrainian legislation addresses them separately, complicating effective environmental risk management. Beyond the legal regulation of IAS, a critical issue of environmental security is the impact of war on the environment.

O. Grybko *et al.* (2022) identified biosecurity as a critical national interest for Ukraine, necessitating international cooperation. An algorithm for responding to biological threats was developed in accordance with the strategic directions of the National Security and Defence Council. However, the mechanisms for its integration into state governance remain undetailed, requiring further research. The integration of assessment methodologies, biomonitoring, and digital platforms into the environmental risk management system of the agricultural sector has become systemic, as evidenced by the increasing number of scientific and applied developments in the digital monitoring of agroecosystems. The refinement of relevant tools has contributed to the development of comprehensive biosecurity management models. Nevertheless, the long-term effects of anthropogenic pollution and the efficacy of mitigation measures remain understudied, necessitating further standardisation of methodological approaches.

The aim of this study was to assess quality of life as an indicator of agroecosystem biosecurity under technogenic and environmental risks. A series of interrelated tasks were addressed to achieve this objective. Specifically, the primary environmental and technogenic factors influencing agroecosystem biosecurity and the quality of life in agrarian regions were identified. The long-term consequences of anthropogenic pollution on agro-landscape transformation, public health dynamics, and socio-demographic processes were evaluated. Additionally, the efficacy of modern digital technologies in environmental threat monitoring, biosecurity management, and the development of adaptive protection mechanisms for agro-systems was analysed.

MATERIALS AND METHODS

The study employed an applied approach incorporating elements of analytical, evaluative, and digital monitoring methodologies. The geographical scope included six regions of Ukraine – Donetsk, Dnipropetrovsk, Zaporizhzhia, Kharkiv, Kyiv, and Mykolaiv oblasts – which exhibited the highest levels of technogenic pressure according to environmental reports and satellite-based indices of agro-landscape degradation. Primary data for analysis were obtained from open government and international sources. Ukrainian datasets included statistical information from the State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), data from the Center for Public Health of the Ministry of Health of Ukraine (n.d.), analytical materials from the National Scientific Center "O.N. Sokolovsky Institute of Soil Science and Agrochemistry" (n.d.), the Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), and records from the Ministry of Agrarian Policy and Food of Ukraine (n.d.).

International sources comprised digital platforms for satellite monitoring and agroanalytics: EOS Data Analytics (Sushchuk, 2025), FarmFacts (n.d.), John Deere (n.d.), Reports Netafim (n.d.), AgriTechHub (n.d.); as well as data from the World Health Organization (WHO) (n.d.), the European Environment Agency (EEA) (n.d.), the International Agency for Research on Cancer (IARC) (n.d.), the United Nations Environment Programme (UNEP) (n.d.), the Chornobyl Research Institute (n.d.), the European Society of Human Reproduction and Embryology (ESHRE) (n.d.), the United Nations High Commissioner for Refugees (n.d.), Ukrainian Hydrometeorological Center the State Emergency Service of Ukraine (n.d.), and the World Bank (n.d.). Additionally, materials from the European Educational Research Association (n.d.) and the State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.) were utilised.

Assessment of agroecosystem status was conducted using satellite-derived indices Normalized Difference Vegetation Index (NDVI) (Li *et al.,* 2021), Serial Peripheral Interface (SPI) (Laimighofer & Laaha, 2022), and CIred-edge (Yadav *et al.,* 2024). Spatial analysis was implemented through k-means clustering followed by risk zone mapping in QGIS 3.22, with geodata processing in Python using the geopandas, rasterio, and scikit-learn libraries. For soil degradation assessment, data on organic matter (humus) content, acidity indices, residual agrochemical concentrations, and satellite observations of land-use structure were employed. Chemical load was evaluated based on concentrations of ammonia, nitrogen oxides, nitrates, and pesticides in air, water, and soils, in accordance with hygienic safety standards (Order of the Ministry of Health of Ukraine No. 721, 2022).

Biosurveillance was implemented using the conceptual model proposed by model proposed by Wagner, integrating satellite, ecological, and demographic data to identify environmentally hazardous clusters (Tan *et al.,* 2023). Additionally, the model by A.J. Kim and S. Tak (2019) was adapted, incorporating digital degradation indicators to spatially delineate high-risk zones with elevated anthropogenic impact. Data interpretation followed a systems-based analytical approach: risk zone delineation was cross-referenced with soil degradation metrics and population demographic structure. The study incorporated insights from countries with advanced digital agroecological monitoring systems (e.g., Germany, the USA, and Israel), as well as Kazakhstan as an example of a nation transitioning to such frameworks. This facilitated the identification of potential strategies to enhance biosecurity governance in Ukraine's agricultural sector. The analysis enabled systematic data organisation for developing a digital biosecurity assessment model for agroecosystems, grounded in digital monitoring, satellite analytics, and spatial modelling.

RESULTS

Ecological and technogenic factors as threats to quality of life and agroecosystem biosecurity. The analysis of ecological and technogenic factors is fundamental for assessing agroecosystem biosecurity and the overall quality of life in agrarian regions. Anthropogenically induced environmental changes are multidimensional, encompassing chemical, biological, and physical factors that affect public health, demographic dynamics, and socio-economic stability. Amid global ecological transformation, particular attention must be paid to the interplay between technogenic pressures and the adaptive capacity of agroecosystems to sustain the viability of human communities.

Ecological and technogenic threats to agroecosystems vary in origin, scale, and destructiveness. Key ecological risks include anthropogenic soil pollution, agri-landscape degradation, reduced agro-biodiversity, and microclimatic shifts. Technogenic factors comprise agricultural facility accidents, agrochemical use, and pesticide/fertiliser contamination of groundwater and surface water, posing direct threats to agroecosystem equilibrium and public health. Ukraine's agroecosystems face significant anthropogenic pressure due to intensive farming, industrial agricultural production, irrational pesticide use, and monoculture dominance. These factors drive the accumulation of hazardous substances (e.g., ammonia, nitrogen oxides, pesticides, and nitrates) in air, soils, and water bodies. Consequences include air pollution, acid rain, soil degradation, water eutrophication, and declining land productivity. Empirical statistical data detail the extent and nature of key pollution sources' impact on agroecosystems (Table 1).

Table 1*. Impact of harmful emissions on agroecosystems of Ukraine*

Pollution source	Harmful substances	Statistical indicators	Environmental consequences
Intensive agriculture	Ammonia (NH_3)	Average NH_3 levels: 20-28 μg/m^3 in air	Acid rain, eutrophication, soil degradation
Industrial agroproduction	Nitrogen oxides (NO_x)	NO_2 concentration: exceeding 35 μg/m^3	Soil acidification, reduced crop yields
Agrochemical use	Pesticides, nitrates	Nitrates in water: >50 mg/L; pesticides: up to 0.05 mg/L	Water pollution, toxicity, reduced biodiversity
Monoculture farming	Reduced humus content	Humus decline to 1.2-1.5% in chernozems	Erosion, reduced fertility, degradation of agrolandscapes

Source: *compiled by the authors based on Center for Public Health of the Ministry of Health of Ukraine (n.d.), M. Sushchuk (2025)*

The presented statistical data indicate a significant level of chemical load in Ukraine's agricultural regions, manifested through elevated concentrations of ammonia, nitrogen oxides, nitrates, and pesticides. These metrics substantially exceed recommended hygienic norms, particularly in cases of air and water pollution (Order of the Ministry of Health of Ukraine No. 721..., 2022). Specifically, atmospheric ammonia concentrations and nitrate levels in groundwater pose direct threats to both the environment and public health. Simultaneously, structural issues in agroproduction, such as monoculture farming and excessive agrochemical use, contribute to rapid soil degradation, erosional processes, and the decline of ecosystem functions in agrolandscapes. This situation necessitates urgent improvements in environmental monitoring systems, particularly through the integration of digital technologies for precise identification of risk zones and the development of adaptive ecological strategies.

Accidents at agro-industrial enterprises, including releases of agrochemical pollutants, heavy metals, and radionuclides, lead to prolonged ecological destabilisation of agroecosystems, causing the accumulation of toxic compounds in soils and water (Makhazhanova *et al.*, 2024). Radiation and chemical pollution, particularly the use of persistent organic pollutants (POPs) in agriculture, impose significant genetic and epigenetic stress on populations, evidenced by high rates of endocrine and oncological pathologies among rural communities. For instance, following the accident at RivneAzot in July 2021, a substantial volume of nitrogen oxides (NO_x)was released into the atmosphere, forming an orange toxic cloud over populated areas (Romanenko, 2021). Emissions of this type are classified as Class I hazards, and their concentrations exceeding 0.085 mg/m^3 in air cause acute respiratory irritation, methaemoglobinaemia, increased cardiopulmonary disorder risks, and possess mutagenic properties. Releases of toxic chemical agents create persistent anthropogenic pressure on agroecosystems, disrupting metabolic processes in living organisms and elevating the risk of ecological catastrophe.

Agroecosystem degradation is a factor of socio-economic destabilisation, driving increased morbidity and premature mortality among rural populations, which in turn exacerbates strain on national healthcare systems (Ongayev *et al.*, 2024). Negative demographic trends linked to environmental factors include reduced life expectancy in agricultural regions, declining birth rates, and rising forced migration levels. The depletion of natural resources, particularly soil degradation, compromises food security, necessitating the development of adaptive agroecosystem management strategies and environmental governance. Table 2 presents a structured analysis of ecological and technogenic threats, integrating anthropogenic impact sources, environmental consequences, public health risks, and strategic mitigation measures in the context of agroecosystem biosecurity. The outlined data reflect a multifactorial approach to assessing environmental degradation processes, including mechanisms of natural ecosystem disruption, toxic load dynamics, and socio-economic consequences for agricultural territories. The proposed systemic analysis enables the evaluation of technogenic-ecological threat scales, underscores the need for enhanced environmental policies, improved technological efficiency in risk monitoring, and the adaptation of ecological strategies to align with global biosecurity challenges.

Table 2*. Analysis of ecological and technogenic threats to agroecosystems: Threat assessment and strategic mitigation measures*

Factor	Primary anthropogenic sources	Primary ecological consequences	Impact on agroecosystem biosecurity	Prevention and adaptation methods
Atmospheric pollution	Emissions from agricultural/industrial enterprises, transport, biomass combustion	Smog formation, increased precipitation acidity, ozone layer depletion, degradation of plant cover	Soil quality deterioration, reduced crop productivity, weakened plant immunity	Transition to eco-friendly technologies, emission control, phytoremediation
Soil degradation	Intensive farming, agrochemicals, deforestation	Reduced fertility, humus depletion, erosion	Declining yields, spread of phytopathogens, disruption of soil microbiota	Implementation of soil conservation technologies, organic farming
Water resource pollution	Discharge of agricultural/industrial wastewater, pesticide/fertiliser use	Eutrophication, groundwater contamination, aquatic ecosystem collapse	Accumulation of toxins in soils, plants, and food products, increased zoonotic disease risks	Biological water treatment methods, reduced chemical use
Radiation pollution	Nuclear power plant accidents, radionuclide leaks, nuclear waste disposal	Biosphere contamination by radioactive isotopes, radionuclide bioaccumulation, genetic mutations	Radioactive contamination of soils/water, mutations in agrocenoses	Development of safe disposal technologies, radiation monitoring, bioremediation
Technogenic disasters	Chemical/oil spills, transport accidents, industrial explosions	Mass contamination of air/water/soil, ecosystem disruption	Agroecosystem poisoning, toxic accumulation in food products	Environmental monitoring, eco-safe technology development
Global climate change	Greenhouse gases, deforestation	Increased extreme weather events (droughts, floods, temperature extremes), rising sea levels	Disrupted agricultural cycles, yield reduction, emergence of new pests/diseases	Sustainable agricultural development, crop adaptation
Socio-economic impacts	Rising disease prevalence, food crises, economic losses	Deterioration of public health, migration, heightened social tensions	Food shortages, increased zoonotic epidemic risks	Investments in biosecurity, agroecological programme development

Source: *compiled by the authors based on M.V. Kustov et al. (2021), S. Bondarenko et al. (2022), D. Garcia-Caro (2023), O.V. Mudrak et al. (2023), D. Hryhorczuk et al. (2024), D. Rawtani et al. (2022), L. Moldavan et al. (2024), S. Sharafi and F. Salehi (2025)*

Effective management of ecological and technogenic threats to agroecosystems requires an integrated approach encompassing legislative regulation, technological innovation, and international cooperation. Key policy directions include implementing environmental monitoring tools for agricultural territories, modernising agro-industrial technologies to reduce pollution, and enhancing ecological awareness among farmers and local communities. The integration of digital technologies – particularly artificial intelligence (AI) and Big Data – enables precise forecasting of ecological risks and optimises agroecosystem management mechanisms (Li *et al.,* 2022). Ecological and technogenic factors are decisive determinants of biosecurity levels in agroecosystems and population well-being, influencing ecological resilience, public health, and socio-economic development. Large-scale air, water, and soil pollution exacerbate disease incidence, while technogenic disasters increase risks of genotoxic and mutagenic effects. Effective ecological risk management demands comprehensive adaptive strategies to strengthen agro-industrial biosecurity, environmental governance, and international cooperation within the sustainable development framework.

Long-term consequences of technogenic pollution for health and demographic processes: Transformation of agro-landscapes in the context of agroecosystem biosecurity. Technogenic environmental pollution is a primary driver of ecological destabilisation, causing systemic adverse effects on public health and demographic processes. In agroecosystem biosecurity, anthropogenic pollution triggers transformative changes in agro-landscapes, affecting soil quality, hydrosphere conditions, and biotic communities. The bioaccumulation of xenobiotics correlates with reduced quality of life, eco-pathological syndromes, and increased general and disease-specific morbidity. These processes directly impact sustainable agricultural development and food security. A comprehensive assessment of technogenic pollution's effects on population health and demographics in Ukraine's agrarian regions identifies key risks arising from environmental components. Table 3 systematises major toxicants, their sources, clinical manifestations, and potential demographic consequences, elucidating the interplay between technogenic pressure and agroecosystem biosecurity.

***Table 3**. Long-term consequences of anthropogenic pollution on health and demography*

Impact factor	Key toxicants	Health consequences	Demographic consequences
Atmospheric pollution	PM2.5, NO_x, SO_2, polycyclic hydrocarbons	Chronic obstructive pulmonary disease (COPD), lung cancer, ischaemia, hypertension	Reduced life expectancy by 7-10 years
Hydrosphere pollution	Nitrates, heavy metals, pesticides	Nephrotoxicity, reproductive disorders, mutagenesis	Increased child mortality, reduced fertility
Pedosphere pollution	Cadmium, lead, arsenic, mercury	Oncological diseases, developmental disorders in children	Rising infertility, congenital anomalies
Complex anthropogenic impact	Multicomponent mixtures	Multi-organ failure, chronic diseases	Declining birth rates, depopulation

***Source:** compiled by the authors based on World Health Organization (n.d.), European Environment Agency (n.d.), International Agency for Research on Cancer (n.d.), United Nations Environment Programme (n.d.), State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.)*

The statistically aggregated data presented demonstrate a broad spectrum of adverse health effects caused by chemical and physical environmental pollution. Exposure to atmospheric toxicants, such as fine particulate matter ($PM_{2.5}$), nitrogen and sulphur oxides, is directly linked to the increased prevalence of COPD, cardiovascular pathology, and reduced life expectancy. Similarly, hydrosphere contamination with pesticides and nitrates threatens the development of nephrotoxic and mutagenic processes, particularly among children and pregnant women. Furthermore, significant anthropogenic pressure on the pedosphere due to heavy metal accumulation induces oncogenic processes and reproductive dysfunction, adversely affecting the demographic structure of rural populations. The most critical factor is the combination of multiple pollution sources, which leads to multi-organ pathologies, declining fertility rates, and increased risks of depopulation trends. Thus, the table underscores the necessity of implementing comprehensive measures for monitoring, prevention, and mitigation of environmental threats within national biosecurity strategies.

The study examines region-specific manifestations of anthropogenic hazards in Ukraine, particularly the consequences of the Chornobyl Nuclear Power Plant accident. The 1986 disaster caused radioactive contamination, creating a zone of persistently high background radiation with long-term ecological and biological impacts. Excess levels of caesium-137 in soils (exceeding 370 Bq/kg) are associated with increased frequencies of chromosomal aberrations, thyroid neoplasms, haematological malignancies, and reduced reproductive function (Chornobyl Research Institute, n.d.). Bioindicators in these territories demonstrate reduced species diversity, genetic mutations in biocenoses, and slowed ecosystem recovery, indicating persistent agro-landscape transformation. The presence of radionuclides in food products, soil, and aquatic ecosystems poses long-term biosecurity risks for the population.

A separate category comprises airborne anthropogenic hazards in industrially burdened regions of Ukraine, particularly Donetsk, Dnipropetrovsk, and Zaporizhzhia oblasts. Concentrations of fine particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and polycyclic aromatic hydrocarbons (PAHs) exceed permissible limits by 2-5 times, as confirmed by European Environment Agency monitoring data. These conditions correlate with increased incidence of COPD, broncho-obstructive syndrome, ischaemic heart disease, cancers, and other pathologies linked to toxicological exposure. Combined with soil degradation, chemical water pollution, and microclimatic changes, this creates a persistent risk framework for demographic trends, including declining birth rates, rising mortality, and outmigration from ecologically disadvantaged areas. The pathophysiological mechanism involves oxidative stress, proinflammatory cytokine activation (*IL-6*, *TNF-α*), and apoptotic cascades in alveolocytes, progressively impairing lung parenchyma functionality (Li *et al.,* 2022; Hashemi *et al.,* 2023). These effects are particularly pronounced among agricultural workers, elevating occupational disease risks.

Atmospheric pollutants, including polycyclic aromatic hydrocarbons and heavy metals, contribute to atherosclerotic pathogenesis via endothelial dysfunction and oxidative modification of vascular structures. High airborne toxicant concentrations trigger sympathetic nervous system activation, inducing hypertension, ischaemic heart disease, and cerebrovascular complications. Epidemiological studies confirm that prolonged exposure may reduce average life expectancy by 5-10 years (Tsai *et al.,* 2023). Accumulation of carcinogens (e.g., benzo[a]pyrene, formaldehyde, cadmium, arsenic) induces mutagenesis through DNA damage, activating oncogenic signalling pathways and disrupting apoptosis (Goodman *et al.,* 2022). Radioactive contamination causes genomic instability, increased chromosomal aberrations, and elevated risks of lung carcinoma, haematological malignancies, and thyroid neoplasms. In agroecosystems, this leads to toxicant bioaccumulation in food chains, threatening food security. Xenobiotics in water resources and food (phthalates, dioxins, pesticides) act as endocrine disruptors, impairing neurohormonal regulation of reproductive systems. Effects include reduced fertility, ovulatory cycle disruption in women, spermatogenic dysfunction in men, higher miscarriage rates, and congenital anomaly risks (Ghosh *et al.,* 2022). In agroecosystems, these compounds alter biogeochemical processes, affecting soil microbiomes and agri-biocenoses.

Chronic heavy metal exposure (lead, mercury, manganese) induces neurotoxicity via glutamatergic excitotoxicity and blood-brain barrier disruption. Central nervous system damage correlates with cognitive impairment, neuropsychiatric disorders, and elevated risks of neurodegenerative diseases (e.g., Alzheimer's, Parkinson's) (Shabani, 2021). Trophic chain bioaccumulation exacerbates ecological impacts. Anthropogenic pollution has caused significant long-term public health effects, increasing morbidity, demographic crises, and socioeconomic instability. Risk mitigation requires innovative environmental strategies, expanded monitoring, and integrated biosecurity/sustainable development policies. Ecological degradation stimulates migration, reducing labour resources and exacerbating socioeconomic disparities. Similar threats have been documented in the agroecosystems of Kazakhstan, where anthropogenic pressure on water bodies was chronic, and the primary sources of pollution were the mining industry and the agricultural sector. As noted in the study by G. Abenova *et al.* (2024), industrial effluents, particularly from mining enterprises, contained high concentrations of heavy metal compounds, leading to their accumulation in aquatic environments. Additionally, inefficient irrigation systems and excessive use of agrochemicals in agriculture contributed to the eutrophication of water bodies and secondary soil contamination, disrupting the biochemical balance of agro-landscapes.

A separate concern was thermal pollution caused by the discharge of heated water after its use in cooling systems of thermal power plants. This resulted in localised increases in water temperatures and disrupted biotic interactions in aquatic ecosystems. Such changes significantly affected microbial activity, led to the displacement of autochthonous flora and fauna, and promoted the proliferation of toxic algae. The overall ecological state of water bodies in Kazakhstan was characterised as critical, necessitating urgent measures to restore biodiversity and implement integrated water resource protection strategies (Abenova *et al.*, 2024). The accumulation of toxicants in Kazakhstan's aquatic environment had a multiplicative effect on agricultural ecosystems, as contaminated water was used for irrigation, leading to secondary chemical loading on soils and crop production. Consequently, elevated levels of heavy metals were observed in the food chain, exacerbating public health risks and posing a potential threat to food security. These trends highlighted the need for enhanced regional monitoring and the implementation of transboundary biosecurity programmes for Central Asian agroecosystems.

A synthesis of key parameters was conducted to assess the long-term impact of anthropogenic pollution on public health, demographic processes, and agrolandscape transformations within the context of agroecosystem biosecurity. The data presented in Table 4 illustrate the correlations between pollutant concentrations in the environment and the incidence of oncological, cardiovascular, and neurological pathologies, as well as their influence on birth rates, mortality, and migration trends in regions with high anthropogenic pressure. Particular attention was given to agro-landscape degradation, contamination of groundwater and water resources by heavy metals, pesticides, and radionuclides, which disrupt ecosystem processes, reduce agroecosystem productivity, and lead to the accumulation of toxic substances in food chains. The analysis of the effects of chemical pollution, radiation levels, and agro-landscape degradation on reproductive health, infant mortality, and depopulation processes underscores the need for further development of comprehensive biosecurity measures, ecological balance restoration, and demographic stabilisation.

Table 4. *Comprehensive analysis of the long-term impact of anthropogenic pollution on health, demographic processes, and agroecosystems*

Parameter	Health impact	Demographic consequences	Additional data
PM2.5 concentration in industrial zones (μg/m^3)	Increased risk of COPD, asthma, lung cancer	Reduction in average life expectancy by 7-10 years	Exceeds safe limits by 2-5 times
Heavy metal content in soils (mg/kg)	Neurotoxicity, developmental disorders in children	Elevated infant mortality, congenital anomalies	Cadmium, lead, and mercury exhibit the highest toxicity

Table 4. Continued

Parameter	Health impact	Demographic consequences	Additional data
Radiation contamination (Bq/kg)	Oncogenic mutations, leukaemia	Increased infertility cases, genetic abnormalities in new-borns	Recorded in areas of nuclear power plant accidents
Consumption of contaminated water (mg nitrates/L)	Methaemoglobinaemia, liver damage	Higher infant mortality, reduced birth rates	Exceeds permissible concentrations in river water
Sulphur dioxide emissions (tons/year)	Cardiovascular diseases, respiratory disorders	Increased overall mortality	Particularly prevalent in coal energy zones
Infertility rate in polluted areas (%)	Reproductive disorders, hormonal imbalance	Population ageing, declining birth rates	Infertility rates rise by 20-30% in industrial regions
Frequency of environmentally induced migration (%)	Stress disorders, mental exhaustion	Depopulation, demographic imbalance	High internal migration driven by environmental factors
Cancer incidence (per 100,000)	Malignant tumours, mutagenic effects	Increased mortality, reduced life expectancy	Clear correlation with pollution levels
Outmigration from industrial-agrarian regions (%)	Social instability, adaptation disorders	Economic decline, labour shortages	Urbanisation hindered by environmental threats

***Source:** compiled by the authors based on State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), Center for Public Health of the Ministry of Health of Ukraine (n.d.), National Scientific Center "O.N. Sokolovsky Institute of Soil Science and Agrochemistry" (n.d.), Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), Ministry of Agrarian Policy and Food of Ukraine (n.d.), M. Sushchuk (2025), FarmFacts (n.d.), John Deere (n.d.), Netafim (n.d.), AgriTechHub (n.d.), World Health Organization (n.d.), European Environment Agency (n.d.), International Agency for Research on Cancer (n.d.), United Nations Environment Programme (n.d.), State Institutuin "Marzieiev Institute for Public Health of the National Academy of Medical Sciences of Ukraine" (n.d.)*

The data presented in Table 4 demonstrate a clear correlation between the level of anthropogenic environmental pollution and the increase in medical-demographic risks in industrial-agrarian regions. The most critical parameter is the concentration of fine particulate matter ($PM_{2.5}$), which exceeds safe levels by 2-5 times and is directly associated with the development of chronic respiratory diseases, oncological pathology, and a reduction in life expectancy by 7-10 years. Equally significant are the levels of heavy metals in soils and background radiation, which affect reproductive health, induce mutagenic processes, increase infant mortality, and contribute to rising infertility rates. From a demographic perspective, the most pronounced consequences include depopulation, declining birth rates, and intensified migration trends driven by deteriorating environmental quality. The proportion of environmentally motivated relocations is increasing, indicating a tangible threat to the social structure and economic potential of these regions. The incidence rates of oncological and cardiovascular diseases in polluted areas further confirm the adverse impact of environmental determinants on public health. Thus, the table clearly illustrates the complex effect of anthropogenic pressures on the biosecurity of agroecosystems, necessitating the implementation of preventive environmental strategies.

Digital technologies in environmental threat monitoring, biosecurity management, and agroecosystem protection. Digital technologies play a pivotal role in monitoring environmental threats, managing biosecurity, and protecting agroecosystems. Amid intensifying anthropogenic impacts, climate change, and the globalisation of pathogenic threats, the integration of modern information technologies enhances the efficiency of agro-landscape condition analysis, optimises environmental monitoring systems, and enables adaptive risk management. The use of Big Data, AI, IoT, and satellite monitoring contributes to improving environmental safety in the agricultural sector and the early detection of threats related to soil degradation, phytopathogen spread, and toxic compound exposure (van Wynsberghe, 2021; Li *et al.,* 2022). The application of AI and machine learning in agroecosystem environmental management is becoming increasingly relevant for optimising biosecurity monitoring and governance. These technologies facilitate the effective interpretation of complex agroecological data, identification of hidden patterns, and improved risk prediction accuracy. Below is a table illustrating the key applications of AI in an agroecological context.

***Table 5**. Applications of artificial intelligence in agroecological monitoring*

Application area	Specific technology/Method	Expected outcome
Agroecological data analysis	Neural networks, clustering	Identification of pollution distribution patterns
Soil condition monitoring	Spectral image analysis	Classification of degradation types
Crop risk prediction	Machine learning (regression models)	Yield forecasting, pest infestation probability
Phytopathogen detection	Deep learning	Automated recognition of disease symptoms

Table 5. Continued

Application area	Specific technology/Method	Expected outcome
Eco-protection efficacy assessment	Algorithmic modelling	Comparative analysis of impact mitigation measures

Source: *compiled by the authors based on Ministry of Agrarian Policy and Food of Ukraine (n.d.), M. Sushchuk (2025)*

The table analysis highlights the broad potential of AI in agroecosystem biosecurity. Deep learning holds the greatest promise, enabling precise phytopathogen detection, as well as spectral analysis of satellite imagery for diagnosing soil degradation. Machine learning allows adaptive responses to dynamic environmental changes, which is critical in the context of climatic challenges and anthropogenic threats. The structural model of the biosurveillance system, presented in Figure 1, outlines the operational principles of digital environmental monitoring platforms (Tan *et al.*, 2023). This system encompasses multi-source data collection, including information from agricultural enterprises, monitoring stations, environmental laboratories, satellite observation systems, and sensor networks. The acquired data undergo analytical processing to identify ecological risks, map agroecosystems, model spatial pollution dynamics, and comprehensively assess agro-biodiversity status.

The integration of digital agroecosystem monitoring systems enables the combination of data analysis across different levels – from local sensor platforms to global satellite observations. The use of deep learning and satellite image processing facilitates the automatic identification of degradation processes in agricultural landscapes, such as soil erosion, salinisation, or declining organic matter content. Additionally, spatial change analysis algorithms allow for the assessment of pesticide, heavy metal, and microplastic contamination, which is crucial for ensuring sustainable agricultural development. In turn, Figure 2 presents an integrated data collection and analysis system in agri-biosecurity, combining continuous monitoring of soil, water, atmospheric parameters, and plant community status. The detection of environmental threats, particularly abnormal changes in agro-biocenosis composition, enables timely decision-making for optimising land use and ensuring ecological safety in agricultural production.

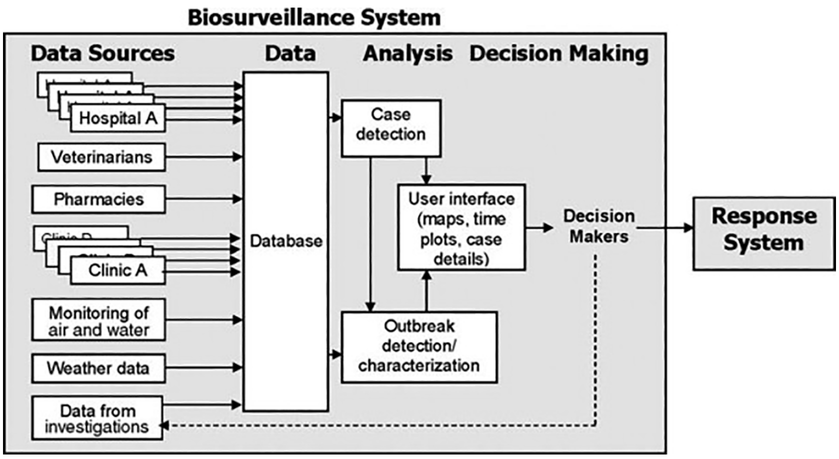

Figure 1*. Wagner's systemic surveillance framework*

Source: *compiled by the authors based on A. Tan et al. (2023)*

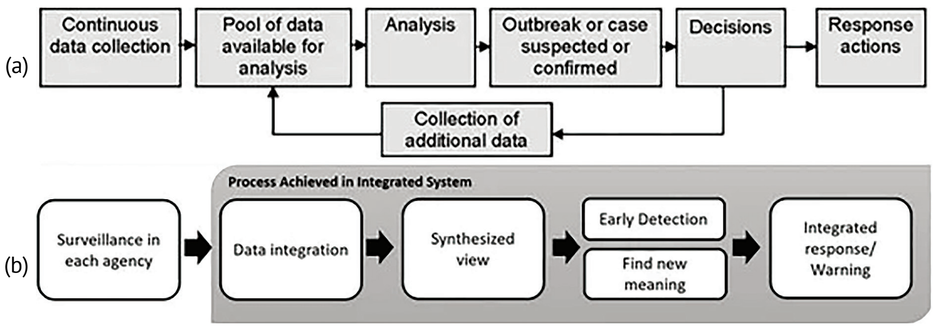

Figure 2*. Biosurveillance process according to (a) Wagner, (b) Kim and Taka*

Source: *compiled by the authors based on A.J. Kim and S. Tak (2019), A. Tan et al. (2023)*

Particular attention should be given to the use of convolutional neural networks (CNNs) for satellite image analysis, which enables the automatic identification of anomalous changes in natural ecosystems, such as deforestation, toxic algal blooms, or illegal industrial emissions. Furthermore, pattern recognition algorithms facilitate the tracking of atmospheric and aquatic geochemical changes, which is critical for early ecological risk detection. The integration of such technologies into environmental monitoring systems enhances governmental biosecurity efficiency, enabling prompt threat response policies and laying the groundwork for adaptive ecological management mechanisms. The advancement of the Internet of Things (IoT) in agroecological monitoring supports the development of sensor networks that continuously track soil moisture, acidity, toxic substance levels, and pathogenic microorganism concentrations (van Wynsberghe, 2021). The deployment of autonomous sensor platforms combined with drones and underwater unmanned vehicles improves the monitoring of water resources, particularly in assessing eutrophication levels, agrochemical pollution, and soil degradation processes.

Geographic Information Systems (GIS) serve as a tool for spatial analysis of ecological risks, enabling the integration of satellite data, remote sensing, and real-time sensor networks (Mouha, 2021). This technology facilitates the creation of multi-layered risk maps that display pollution levels, hotspots of ecological disasters, and demographic parameters, thereby supporting comprehensive biosecurity management. GIS technologies enhance environmental management by enabling rapid identification of critical zones, prediction of anthropogenic accident consequences, and optimisation of mitigation measures (Remeshevska *et al.*, 2021). Spatial analysis allows for the assessment of long-term environmental changes on public health, promotes adaptive urban planning, and improves infrastructure resilience. The integration of GIS into national biosecurity monitoring systems enables more effective risk forecasting and the development of preventive strategies at a global level (Llupa, 2025).

Bioinformatics and genomic data analysis hold significant potential in ensuring agro-biosecurity, particularly in detecting resistant pathogens, analysing soil microbiomes, and assessing the impact of anthropogenic pollution on biodiversity. Next-generation sequencing (NGS) technologies allow for the identification of mutational changes in pathogenic microorganisms, which is critical for early threat detection in agriculture (John *et al.,* 2021). Automated algorithms for analysing genetic reserves can predict evolutionary trends, enabling rapid adaptation of bioprotection strategies. Satellite monitoring technology for agroecosystems provides remote assessment of agricultural land conditions, crop yield dynamics, and changes in landscape moisture balance. Earth remote sensing (ERS) data are used to model climatic changes and their impact on agro-landscape productivity (Janga *et al.,* 2023). Spectral analysis enables the detection of plant stress factors, such as water deficiency, disease spread, or phytotoxic effects of pollution. In contrast, digital platforms and cloud technologies allow the integration of data from multiple sensor sources, automate real-time analysis, and generate predictive models of agroecosystem conditions (Kadyraliev *et al.*, 2024). The use of blockchain technology ensures transparency and protection of environmental data, which is crucial for sustainable agricultural development. The creation of global ecological databases enables researchers and government agencies to access high-precision analytical reports on environmental status.

The development of cyber-physical systems and ecological process modelling is facilitated by the creation of digital twins of natural ecosystems. These technologies enable real-time environmental monitoring, prediction of ecological threats, and testing of various climate change adaptation scenarios. Particularly promising are models simulating pollutant circulation in soil and the atmosphere, allowing for the development of pre-emptive measures to minimise pollution impacts. The integration of bio-digital technologies into biosecurity monitoring has enabled detailed analysis of microbial environments, identification of hazardous microorganisms, and assessment of their interactions with biosystems. Advances in nanotechnology for environmental monitoring have led to the development of highly sensitive biosensors capable of detecting pollutants at the molecular level, opening new prospects for early diagnosis of ecological threats. An evaluation of digital technology implementation in agroecological monitoring demonstrates significant progress in improving diagnostic accuracy, agroecosystem adaptability, and strategic environmental planning. The use of artificial intelligence, satellite platforms, GIS, and the IoT in countries with advanced agricultural sectors confirms the high efficiency of such solutions. Table 6 presents examples of practical innovations implemented in various countries, including Ukraine, with an analysis of key outcomes.

Table 6. *Examples of digital technology implementation in agroecosystem monitoring*

Country/Region	Technology	Implementation	Results/Effects
Ukraine	Artificial Intelligence, Satellite Monitoring	EOS Data Analytics, (agrolandscape monitoring)	Soil degradation mapping, satellite-based crop rotation and yield tracking
Ukraine	GIS	Landscape zoning models, agrobiocartography	Digital mapping of biodiversity and regional pollution patterns

Table 6. Continued

Country/Region	Technology	Implementation	Results/Effects
USA	IoT, Machine Learning	John Deere – Smart Farming Technologies	Reduced agrochemical costs, precision farming, increased productivity
Germany	Big Data+Soil Analysis	FarmFacts – Field Management System	Automated fertiliser application, minimised soil erosion
Israel	Sensor Platforms+AI	Netafim – Digital Irrigation Control	Optimised water regime, improved crop yields under resource scarcity
Kazakhstan	GIS, AI, Agri-Data Analytics	AgriTechHub, Kazhydromet	Indexing of agro-water resources, heavy metal monitoring in soil/water, climate risk forecasting

Source: *compiled by the authors based on State Service for Geodesy, Cartography and Cadastre of Ukraine (n.d.), Institute of Agroecology and Environmental Management of the National Academy of Agrarian Sciences of Ukraine (n.d.), M. Sushchuk (2025), FarmFacts (n.d.), John Deere (n.d.), Netafim (n.d.), AgriTechHub (n.d.)*

Based on an analysis of digital agroecosystem monitoring technologies implemented in Ukraine and abroad, it is advisable to formulate recommendations for enhancing the national environmental management system. Primarily, state support must be ensured for the development and implementation of innovative digital platforms capable of conducting high-precision real-time monitoring of agro-landscape ecological conditions. Such support should include funding for IT infrastructure and fostering collaboration between research institutions, agribusinesses, and government agencies. A key objective is the establishment of an integrated satellite monitoring system for agroecosystems using GIS modules, enabling timely detection of ecological risks, assessment of natural resource degradation levels, and the development of predictive risk models. This requires institutional framework improvements, standardisation of data collection and processing methodologies, and interdepartmental data sharing. Equally important is human capital development – implementing training programmes and workshops for farmers, agronomists, ecologists, and local authorities to enhance digital literacy and skills in working with intelligent ecosystems. Special attention should be given to establishing digital laboratories at leading Ukrainian agricultural universities, specialising in ecological data analysis, risk modelling, and the development of biosecurity solutions using AI, Big Data, and bioinformatics.

Overall, the implementation of these measures will enhance strategic agroecosystem management, reduce anthropogenic environmental pressure, and ensure national-level biosecurity and food stability. Thus, digital technologies have become a key instrument in transforming agroecosystem biosecurity monitoring and ecological threat assessment. The integration of artificial intelligence, IoT, satellite data, and GIS not only enables real-time environmental analysis but also creates opportunities for precise forecasting of agro-landscape changes and their impact on ecosystem processes. Through digital platforms and bioinformatic approaches, adaptive response strategies can be developed to minimise anthropogenic impacts and optimise natural resource management.

DISCUSSION

Within the framework of this study, the chronic accumulation of technogenic pollutants was identified as a key factor driving destructive changes in Ukraine's agroecosystems. The most pronounced adverse effects were associated with elevated levels of persistent organic compounds, heavy metals, and radionuclides. It was established that these substances induced profound transformations in the microbiological composition of soils and water bodies, disrupted biogeochemical cycles, contributed to the degradation of agricultural landscapes, and intensified the ecological burden on land use. A decline in agro-biological characteristics of soil resources, deterioration of water quality, and reduced resistance of crops to abiotic and biotic stressors were documented. The identification of correlations between pollution types, microbial community transformation parameters, and ecosystem degradation indicators provided a basis for justifying the need to implement digital risk prediction models as part of adaptive environmental governance.

In the publication by G.N.T. Hasnat (2021), the impact of emerging pollutants – including pharmaceutical residues, nanomaterials, flame retardants, and persistent organic compounds – on agroecosystems was characterised. It was demonstrated that these substances disrupted biogeochemical equilibrium, triggered toxicant bioaccumulation, and altered the microbiological structure of ecosystems. The obtained results align with empirical observations recorded in the analysis of toxic load effects on soil and water microbiomes. The presence of such parallels underscores the necessity of continuous ecotoxicological monitoring using digital tools for adaptive biosecurity management. The study by M. Fenzi *et al.* (2024) analysed the consequences of uncontrolled dissemination of genetically modified organisms in Mexican agroecosystems. It was found that the lack of interaction between traditional farming practices and regulatory policy facilitated genetic diversity erosion and the destruction of local biocultural structures. Despite the study's focus on genetic risks, a typological similarity was observed with the changes induced by chemical and radiological contamination. Both approaches demonstrate a decline in agroecosystem resilience due to the disruption of equilibrium between natural and anthropogenic factors, as well as the loss of adaptive potential in agroecological environments.

The work of R.I.A. Briseño *et al.* (2023) presented an example of integrating molecular technologies and machine learning algorithms into biosanitary monitoring practices. Combining high-throughput sequencing (HTS) with mathematical models enhanced the accuracy of phytovirus detection and enabled the prediction of viral load in plant systems. The efficacy of using satellite indices, AI elements, and digital platforms for identifying ecological degradation hotspots was demonstrated. A comparative analysis with digital agroecological risk monitoring results confirmed the feasibility of employing digital technologies as the foundation for intelligent environmental governance in the context of agroecosystem biosecurity. The conceptual foundations of a multilevel biosecurity system, based on the interconnectedness of human, animal, plant, and environmental health, were further developed within the One Health framework proposed by L.L. Vázquez (2024). In this model, biosecurity is interpreted as a component of food security and sustainable development, requiring the integration of ecological and biomedical factors. Correlations were established between microbiome transformation, ecosystem process disruption, and increased demographic risks in areas with elevated technogenic pressure. The identified links between chronic pollution and structural disturbances in microbial communities align with findings from this study, which analysed agroecosystems under persistent toxicant accumulation.

The biological consequences of technogenic impact on agricultural environments manifest, in part, through adaptive mechanisms in biotic components (Shaforost *et al.*, 2024). The work of P. Neve and A.L. Caicedo (2022) described evolutionary processes such as hybridisation, mimicry, and herbicide resistance development, which emerge under selective pressure induced by agronomic practices. The presence of microbiological disturbances in soils, identified through pollution impact analysis, may be considered a factor amplifying this pressure and facilitating phytocenosis transformation. The obtained data confirm the increasing complexity of ecological control due to the growing adaptive variability of undesirable plant species. In contemporary contexts, the issue of cyberbiosecurity has gained particular significance, as explored in the study by S. Stephen *et al.* (2023). Vulnerabilities were identified in digital platforms used in precision agriculture, automated farm management, and supply chain logistics. The absence of unified biosecurity information standards was noted. Although the study did not directly focus on bioecological monitoring, it substantiated the importance of digital integration for risk prediction and rapid response to technogenic threats. The conclusions align with intelligent environmental monitoring approaches based on automated spatial and biological data analysis.

The implementation of nature-oriented stabilisation technologies in agroecosystems has been analysed in the publication by M. Mustafa *et al.* (2022). It has been demonstrated that agroforestry measures contribute to improved microclimatic conditions, reduced erosional processes, stabilised moisture levels, and decreased crop susceptibility to external stressors. The study established that increasing abiotic pressures caused by chemical and radioactive pollution negatively affect soil productivity. The identified need for integrating ecological and managerial solutions into strategies for maintaining ecosystem resilience confirms the efficacy of a multicomponent approach to agroecosystem adaptation. In the study by A. Tyczewska *et al.* (2023), the potential applications of agricultural biotechnology under global challenges induced by the COVID-19 pandemic and geopolitical risks in Eastern European countries were examined. Conclusions were drawn regarding the effectiveness of genetic modification technologies, as well as artificial intelligence (AI) tools, for enhancing crop yields, adapting agricultural crops to adverse conditions, and minimising environmental burdens. Furthermore, the study demonstrated the efficacy of AI algorithms and Big Data systems in detecting ecotoxicological threats and diagnosing degradation processes in agricultural landscapes. The obtained results confirmed the significant potential of digital and biotechnological innovations as tools for adapting the agricultural sector to conditions of environmental and socio-economic instability.

An expert assessment of pollinator population status and risk factors in European agricultural ecosystems was conducted in the study by B.K. Willcox *et al.* (2023). It was established that the primary threats to bee population stability remain high agrochemical loads, declining environmental biodiversity, parasitic infestations, and climatic anomalies. The study proposed integrating digital monitoring tools, particularly AI, the IoT, and Big Data, into adaptive ecological management systems to enhance biosecurity control efficiency. It was identified that toxic pollution and changes in microbial community composition weakened the functional resilience of agroecosystems, particularly through disruptions in mediated ecosystem services. Comparative analysis with degradation processes in agrosystems confirmed a general trend of declining adaptive capacity in ecosystems under anthropogenic pressures.

The study revealed a strong correlation between technogenic pollution of agricultural environments and a complex of changes, including transformations in soil and water microbiological composition, disruptions in biogeochemical equilibrium, and reduced ecosystem stability. Prolonged exposure to persistent organic pollutants, heavy metals, and radionuclides was found to contribute to chronic toxicological burdens, impairing regulatory mechanisms in agrobiocenoses. The accumulation of toxic components not only reduces agroecosystem productivity but also has indirect effects on rural demographic trends due to increased biological risks and deteriorating living conditions. The empirical data underscore the urgency of developing a systemic approach to agroecological safety monitoring using digital tools. Given the complexity of identified ecotoxicological interactions, it was proposed that monitoring systems should integrate spatial data, satellite observation indices, microbiological analyses, and AI-based predictive modelling. This approach enables early risk detection, long-term pollution impact assessment, and adaptive management responses at local and regional levels. Enhanced diagnostic accuracy for agroecosystem instability under variable technogenic pressures is critical for mitigating degradation processes (Fedoniuk *et al.*, 2024). A trend towards convergence in scientific methodologies was observed, particularly in interdisciplinary ecological risk assessment, digital ecosystem monitoring, and adaptive biosecurity management. The formulated concepts address escalating challenges posed by combined technogenic, biotic, and climatic threats, providing a theoretical foundation for sustainable agroecosystem tools under ecological instability.

CONCLUSIONS

Analysis of the obtained results confirmed the efficacy of a holistic approach to assessing the impact of technogenic and natural-ecological factors on agroecosystem biosecurity. Integration of ecotoxicological, biogeochemical, and agroecological parameters enabled a multi-level evaluation of agroecosystem conditions and identification of spatiotemporal degradation patterns. Specifically, ambient ammonia concentrations averaged 20-28 μg/m^3, nitrogen oxides exceeded 35 μg/m^3, while nitrate levels in water surpassed 50 mg/L, and pesticides reached 0.05 mg/L. Chernozem soils exhibited humus content reductions to 1.2-1.5%, indicative of degradation. Exposure to chemical, radioactive, and biological stressors correlated with increased malignancy incidence (showing clear pollution-dose dependency), reduced average lifespan by 7-10 years in industrial-agrarian regions, and higher frequencies of congenital anomalies and infertility. Areas with elevated PM2.5 particulate concentrations (2-5 times above permissible limits) showed prevalent cases of COPD, ischemic heart disease, and neurodegenerative pathologies. Soil radionuclide levels (exceeding 370 Bq/kg for Cs-137) were associated with elevated genetic mutations, endocrine disorders, and oncological haematological risks.

Concurrently, intensive technogenic pressures exacerbated environmentally driven migration, social tensions, and economic decline in agrarian regions. Infertility rates in polluted zones rose by 20-30%, while child mortality and declining birth rates confirmed critical demographic impacts. These findings underscore the necessity for systemic modernisation of ecological monitoring and adaptive biosecurity management in agroecosystems. The obtained results substantiated the feasibility of large-scale implementation of intelligent monitoring platforms based on satellite analytics, GIS, and machine learning methods. This approach facilitated the development of dynamic ecological threat maps, prompt identification of critical zones, and informed decision-making to minimise environmental risks. The necessity of developing adaptive management strategies was established, incorporating local pollution indices, soil-water resource conditions, and demographic characteristics. Strengthening interdisciplinary collaboration among agroecologists, toxicologists, digital technology specialists, and environmental medicine experts is a prerequisite for establishing robust biomonitoring systems capable of predicting agroecosystem transformations.

The study was accompanied by several limitations that must be considered when interpreting the results. The spatial coverage was restricted to six regions of Ukraine, complicating the extrapolation of findings to the national level. The assessment of agroecosystem conditions relied primarily on composite ecological indices without accounting for seasonal dynamics, which may have affected the accuracy of the established correlations. Further limitations pertained to the quality of satellite data, particularly in terms of resolution, as well as the availability of comprehensive geoecological databases. Demographic information was obtained from open sources, constraining the depth of causal relationship analysis. Promising directions for future research include the development of neuromathematical models for predicting long-term ecological consequences, evaluating the effectiveness of agroecosystem rehabilitation measures, and implementing automated data collection and analysis systems. The application of blockchain technologies for recording environmental data is advisable to ensure monitoring process transparency and enhance trust in biosecurity management systems. The establishment of adaptive regulatory mechanisms that account for spatial risk heterogeneity will contribute to the formulation of effective policies for sustainable agrosector development amid global ecological transformations.

ACKNOWLEDGEMENTS

None.

FUNDING

None.

CONFLICT OF INTEREST

None.

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Біозахист агроекосистем в умовах техногенних та екологічних ризиків

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Анотація. Метою дослідження було встановлення зв'язку між техногенними та екологічними факторами, що впливають на біобезпеку агроекосистем в Україні, з розробкою адаптивного моніторингу та стратегій зменшення ризиків шляхом інтеграції цифрових технологій. Методологія дослідження базувалася на міждисциплінарному підході, що поєднує екотоксикологічний аналіз, біогеохімічне моделювання та просторово-часову оцінку антропогенного впливу з використанням геоінформаційних систем, супутникового спостереження та алгоритмічного прогнозування ризиків на основі штучного інтелекту та аналітики великих даних. Застосування методів машинного навчання, спектрального аналізу забруднення та багаторівневого картографування агроекосистем виявило приховані закономірності деградації агроландшафтів, оцінило їхню екологічну стійкість та сформулювало адаптивні підходи до управління навколишнім середовищем для зниження біологічних ризиків. Результати дослідження вказали на підвищене хімічне навантаження на українські агроекосистеми, що проявляється у перевищенні гранично допустимих концентрацій аміаку (20-28 мкг/м^3 у повітрі), оксидів азоту (понад 35 мкг/м^3), нітратів (понад 50 мг/л у воді) та пестицидів (до 0,05 мг/л). Вміст гумусу в чорноземах знизився до 1,2-1,5 %, що супроводжувалося деградацією ґрунту. Встановлено кореляційний зв'язок між підвищеним техногенним тиском та вищою поширеністю онкологічних захворювань, серцево-судинних та респіраторних патологій, а також скороченням тривалості життя (на 7-10 років) у регіонах із високим рівнем забруднення. Зафіксовано негативні демографічні тенденції, включаючи зростання дитячої смертності, зниження народжуваності та збільшення екологічно зумовленої міграції. Результати підтверджують ефективність цифрових технологій у підвищенні якості моніторингу, діагностики та управління ризиками в агроекосистемах, що зазнають трансформаційного антропогенного тиску

Ключові слова: штучний інтелект; машинне навчання; управління ризиками; деградація агроландшафтів; біосфера