UDC 631.15:011.44:635.132
DOI https://doi.org/10.32848/0135-2369.2026.85.10

BIBLIOGRAPHIC ANALYSIS OF RISK IDENTIFICATION AND MANAGEMENT IN TREATED WASTEWATER REUSE FOR AGRICULTURAL IRRIGATION AS A METHOD FOR IMPLEMENTING BEST PRACTICES IN UKRAINE

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Introduction. The increasing scarcity of freshwater resources has become a pressing global concern, particularly under the combined pressures of climate change, population growth, and rising agricultural demand. Conventional water sources are no longer sufficient in many arid and semi-arid regions, compelling policymakers and researchers to seek alternative solutions. Among these, the reuse of treated wastewater for irrigation has gained recognition as a promising, cost-effective, and environmentally sustainable practice [11, 14].

A substantial body of research has highlighted the agronomic and environmental benefits of reclaimed wastewater use. When adequately treated, effluents can supply both irrigation water and essential nutrients, thereby reducing the need for synthetic fertilizers [32, 20]. However, wastewater reuse is not without challenges. Numerous studies have demonstrated the persistence of microbiological hazards such as pathogenic bacteria, viruses, and helminths [10, 26], as well as chemical contaminants including heavy metals, pharmaceuticals, and pesticides [19, 17]. These risks may affect food safety, soil fertility, and human health, and are exacerbated in regions where monitoring and treatment infrastructure remain underdeveloped.

Beyond health and environmental considerations, wastewater reuse also entails socio-economic complexities. Farmers may benefit from lower irrigation costs, but consumer perception of “wastewater-grown” products can negatively influence market acceptance [18]. Infrastructure costs for advanced treatment, such as nanofiltration or ozonation, can further limit implementation in low- and middle-income countries [21]. At the same time, cost–benefit analyses in southern Europe suggest that reuse projects can achieve both environmental and financial sustainability when designed with strong regulatory backing [15].

The regulatory landscape is evolving rapidly. In Europe, the adoption of **Regulation (EU) 2020/741** introduced harmonized minimum requirements for agricultural wastewater reuse, emphasizing a risk-based approach [16]. Other key frameworks, such as the **Urban Wastewater Treatment Directive 91/271/EEC** and the **Water Framework Directive 2000/60/EC**, provide the broader context for water quality and resource management. These policies stand in contrast to the fragmented regulatory systems in many non-EU countries, where guidelines remain incomplete or inconsistent [6].

Recent reviews highlight a notable diversification of research directions. Some scholars have developed quantitative microbial risk assessment (QMRA) models to estimate infection probabilities under different irrigation scenarios [14, 28]. Others emphasize soil and plant responses to long-term irrigation with treated wastewater, including effects on salinity, nutrient cycling, and microbial community dynamics [13, 22, 30]. Still others underscore socio-environmental dimensions, exploring consumer attitudes, governance models, and One Health perspectives [18, 28]. Collectively, these works reveal that while the potential of wastewater reuse is widely acknowledged, significant research gaps persist regarding integrated risk assessment and context-specific regulatory adaptation.

In Ukraine, studies are emerging on wastewater reuse as part of national climate adaptation and irrigation strategies [27, 29, 34]. These efforts are still at an early stage, but they highlight the importance of aligning Ukrainian practice with EU regulatory standards, particularly in the framework of the national Irrigation and Drainage Strategy through 2030.

Building on this body of literature, we hypothesize that wastewater reuse in agriculture, when governed by integrated risk-based frameworks and adapted to regional contexts, can provide a sustainable and resilient solution to water scarcity while minimizing public health and environmental risks.

The purpose of this article is to conduct a comprehensive bibliographic analysis of scholarly publications addressing the risks associated with reclaimed wastewater use in agriculture. By mapping thematic trends, identifying methodological approaches, and highlighting research gaps, this study seeks to contribute evidence for developing regulatory frameworks and best practices tailored to both European and Ukrainian contexts.

Materials and Methods. This study adopted a structured bibliographic and qualitative analysis to examine the current scientific discourse on risk identification and management in the reuse of treated wastewater for agricultural irrigation. The methodology was designed to balance global perspectives with regional specificity, ensuring that the findings are both internationally relevant and directly applicable to the Ukrainian context.

The analytical process began with the careful selection of data sources. Three bibliographic databases were identified as most appropriate for the task: Scopus, the Web of Science Core Collection, and the Open Ukrainian Citation Index (OUCI). Scopus and Web of Science were chosen due to their broad international coverage, stringent indexing criteria, and advanced functionalities that allow for the detection of research trends and highly cited contributions across disciplines. OUCI, developed and maintained by the State Scientific and Technical Library of Ukraine, was included to ensure that Ukrainian-language publications and other regionally significant works, which are often underrepresented in international indices, were not overlooked. The combination of these resources made it possible to capture both the global state of the art and the local scientific response to wastewater reuse challenges.

The search process was conducted between March and May 2025. To maintain consistency, a predefined set of keywords was applied across all databases. These included terms such as *treated wastewater, wastewater reuse, agricultural irrigation, risk assessment, microbiological risk, chemical contamination, antibiotic resistance genes, environmental risk, constructed wetlands,* and *socio-economic barriers.* Boolean operators (AND, OR) were employed to combine related concepts and refine results. The search was limited to peer-reviewed journal articles, review papers, and conference proceedings published between 2004 and 2024. No language restrictions were introduced, although the majority of the final dataset consisted of English-language works.

After the initial collection, the records were carefully processed through a multi-step procedure. Duplicate entries retrieved from multiple databases were first removed. The remaining titles and abstracts were then screened to assess their alignment with the study's objective–namely, the identification and management of risks associated with treated wastewater reuse in agriculture. Studies focusing exclusively on industrial reuse, desalination, or drinking water supply were excluded at this stage. Those publications that passed the screening were subsequently examined in full text to confirm thematic relevance and methodological soundness. Particular emphasis was placed on works that implemented quantitative microbial risk assessment (QMRA), chemical contaminant profiling, or socio-technical analyses of stakeholder engagement and regulatory frameworks.

The final dataset, which comprised 115 publications, was imported into the qualitative data analysis software NVivo 14 (QSR International, https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home). Using NVivo allowed for systematic coding and in-depth thematic exploration. The coding strategy combined deductive and inductive approaches: pre-established categories such as microbial risk, heavy metal contamination, regulatory frameworks, and technological innovations were complemented by emergent codes that arose from the data itself. This dual approach ensured that established risk domains were represented while also leaving space for the identification of novel or cross-cutting issues.

To strengthen the interpretative dimension of the study, co-occurrence analysis was applied to detect thematic clusters and map interdisciplinary linkages across the literature. In addition, citation data drawn from OUCI were analyzed manually to assess the integration of Ukrainian research into the international academic landscape. This included tracking citation flows, identifying institutional affiliations, and comparing thematic overlaps between national and international publications. By combining automated tools with manual verification, the analysis ensured both comprehensiveness and contextual sensitivity.

Overall, the methodological workflow can be summarized as follows: the study began with database selection and keyword-driven searches, followed by deduplication, abstract and title screening, full-text review, qualitative coding in NVivo, and finally, comparative analysis between international and Ukrainian data sources. Each stage built logically upon the previous one, forming a coherent sequence that transformed raw bibliographic records into a structured body of evidence.

This approach not only enabled the identification of global trends in wastewater reuse research but also highlighted the specific contributions and challenges faced by Ukrainian scholars. In this way, the methods ensured that the resulting findings are grounded in a solid empirical base, bridging international experience with regional realities and offering practical recommendations for advancing sustainable agricultural practices in Ukraine.

Results. Analysis of the literature over the past two decades reveals a clear upward trajectory in research addressing the risks associated with agricultural wastewater reuse. Initially, studies were predominantly descriptive, focusing on the fundamental microbiological and chemical characteristics of treated effluents [11]. However, from approximately 2015 onward, research shifted toward more complex and integrated approaches, including risk assessment, predictive modeling, and socio-economic evaluations [2, 28]. This growth reflects the increasing global awareness of water scarcity and the impact of climate change, as well as the implementation of regulatory frameworks such as the European Union's Regulation 2020/741, which established minimum quality standards for water reuse [41]. The increasing number of publications indicates both the scientific and policy-driven impetus to evaluate wastewater reuse comprehensively. Early work was limited by methodological constraints, often relying on single-parameter analyses, while recent studies incorporate multi-factorial assessments encompassing microbiological, chemical, and socio-economic dimensions (Fig. 1).

Geographically, research has been concentrated in regions with acute water scarcity, including Southern Europe and the Middle East. Mediterranean countries such as Spain and Italy have generated extensive studies examining compliance with EU directives and the implications of treated wastewater irrigation on soil and crop health [5, 15]. The Middle East, including Jordan, Israel, and Saudi Arabia, reflects long-term dependence on wastewater as an agricultural resource, often incorporating modeling approaches to predict supply-demand scenarios and risk outcomes [7, 3. Asian countries, particularly India and China, contribute research focusing on chemical contaminants, heavy metal accumulation, and socio-economic impacts of irrigation practices [19, 20]. Notably, Eastern Europe, including Ukraine, remains significantly underrepresented, which underscores both a gap in localized knowledge and an opportunity for region-specific investigations [29, 34]. The uneven distribution indicates that the urgency of water reuse research correlates closely with water stress intensity, policy frameworks, and available scientific infrastructure, rather than purely agricultural necessity (Fig. 2).

The literature demonstrates a gradual evolution in thematic focus. Microbiological risks remain central, with a particular emphasis on pathogens such as *Escherichia coli*, *Salmonella*, and protozoans like *Giardia* and *Cryptosporidium*. Quantitative Microbial Risk Assessment models are increasingly used to translate contamination levels into actionable risk estimates, reflecting a methodological maturation from simple presence-absence studies to probabilistic and exposure-based frameworks [18, 24]. Chemical contamination, particularly by heavy metals, pharmaceuticals, and persistent organic pollutants, represents another focal area, where studies assess soil accumulation, plant uptake, and potential human health implications [25, 19]. These studies reveal that conventional tertiary treatments often fail to completely remove contaminants, raising concerns for long-term soil fertility and crop safety. Emerging contaminants, including antibiotic resistance genes, represent a growing scientific frontier, highlighting risks that extend beyond immediate human consumption to broader ecological and evolutionary consequences [17, 4].

Socio-economic and governance considerations are increasingly integrated into risk analyses. Research shows that public perception, cultural attitudes, and regulatory enforcement significantly influence both the adoption and safety of wastewater reuse practices [2, 18]. Cost considerations remain a major barrier; advanced treatment technologies, while effective, are often inaccessible to low-resource regions, limiting the practical implementation of recommended safety standards [14, 23]. Thus, the literature increasingly recognizes that technical solutions alone are insufficient without concurrent governance and social engagement strategies.

Technological approaches to mitigating risk have diversified. Multistage treatment trains combining biological, chemical, and physicochemical processes are standard in high-resource settings, while constructed wetlands and other nature-based solutions offer cost-effective alternatives in resource-limited contexts [7].

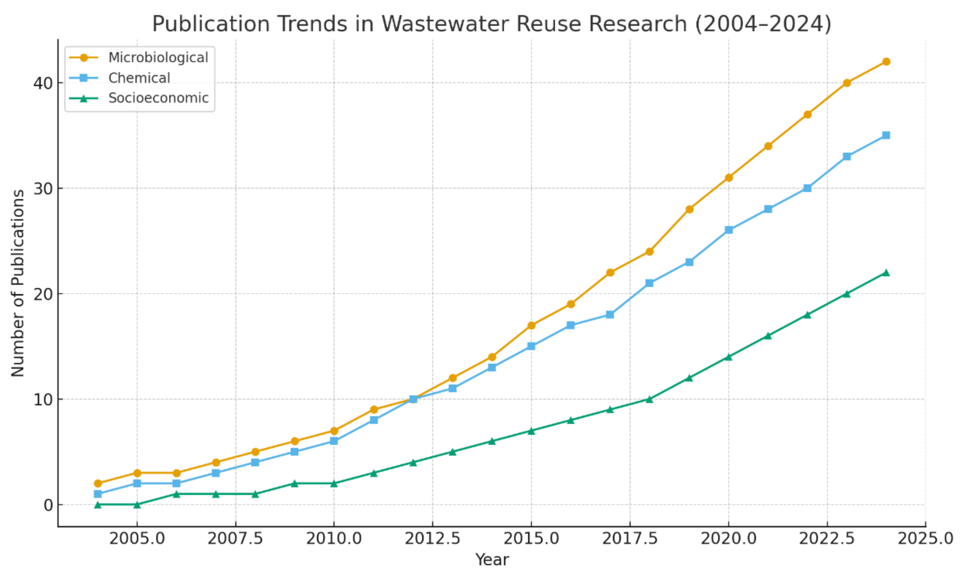

Fig. 1. Publication Trends Graph shows the annual number of publications from 2004 to 2024 across microbiological, chemical, and socio-economic focus areas

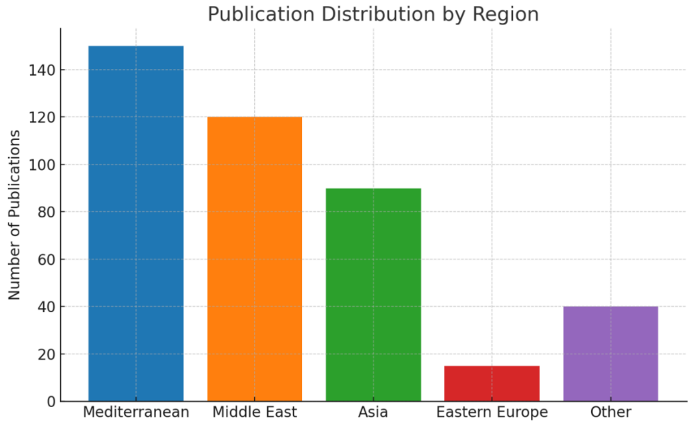

Fig. 2. Publication Distribution by Region illustrates geographic concentration of research publications

Studies indicate that short-term variations in treated wastewater quality can significantly affect soil microbial communities, which in turn influence nutrient cycling and crop metabolism [22, 8]. These interactions are complex: some effluent characteristics enhance soil fertility by providing additional organic matter and nutrients, while others, particularly residual chemical contaminants, pose long-term risks to soil health and crop quality. Such findings demonstrate that wastewater reuse cannot be evaluated solely from a contaminant removal perspective; ecological and agronomic outcomes must be considered simultaneously (Fig. 3).

The analysis highlights a striking gap in localized research in Ukraine. While international methodologies are adapted in preliminary Ukrainian studies [29, 27], comprehensive risk assessments that consider local agricultural practices, soil types, and post-conflict infrastructure vulnerabilities are largely absent. Addressing these gaps is critical for developing evidence-based national strategies that safely integrate wastewater reuse into agricultural water management. Furthermore, the limited body of research constrains policymakers' ability to evaluate potential ecological, health, and socio-economic risks, emphasizing the need for interdisciplinary studies that combine environmental sciences, agronomy, and socio-economic analyses.

The literature illustrates a maturing research landscape, with increasing methodological sophistication and integrated approaches. Despite this progress, significant challenges remain, including the management of emerging contaminants, the translation of scientific evidence into regulatory frameworks, and the incorporation of socio-economic and cultural factors into risk mitigation strategies. Moreover, the geographic and contextual gaps particularly in Eastern Europe highlight the importance of localized, multidisciplinary research to inform safe and sustainable wastewater reuse practices.

Discussion. Within the European Union, the reuse of treated wastewater for agricultural irrigation is governed by a well-defined and comprehensive legal framework. The central piece of legislation in this domain is Regulation (EU) 2020/741 of the European Parliament and of the Council of 25 May 2020 on mini-

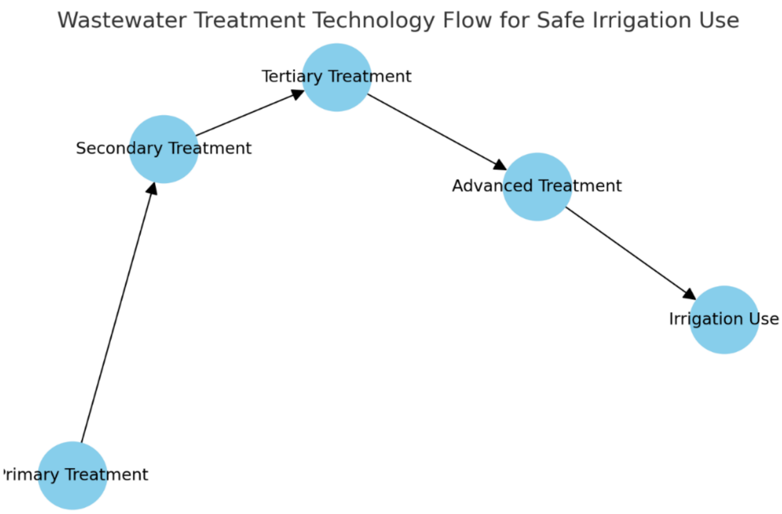

Fig. 3. Wastewater Treatment Technology Diagram flow of treatment processes leading to safe irrigation use

mum requirements for water reuse, which came into effect on June 26, 2023 [41]. From that date, its provisions became legally binding in all EU Member States. The regulation seeks not only to facilitate the safe and sustainable use of treated wastewater but also to harmonize water reuse standards across the EU, ensuring a high level of public health protection, environmental safety, and support for the circular economy, particularly in the face of growing freshwater scarcity.

Unlike permissive or advisory guidelines, this regulation sets mandatory requirements for water quality, usage conditions, monitoring protocols, and risk management measures. Its primary focus is on a specific use case: the reuse of treated urban wastewater for the irrigation of agricultural crops. Other forms of water reuse, such as for industrial purposes or landscape irrigation (e.g., parks or golf courses), fall outside the scope of this regulation and are instead addressed by national or regional legislation.

A central objective of the regulation is to reduce dependency on freshwater sources by encouraging the reuse of appropriately treated wastewater in agriculture. To that end, it introduces stringent quality classes A, B, C, and D based on the type of crop being irrigated and the degree of potential contact between the water and edible parts of the plant. For example, Class A, which applies to crops consumed raw with high water contact, imposes strict microbiological standards, including a limit of fewer than 10 colony-forming units (CFU) of *E. coli* per 100 ml. Moreover, for this category, daily monitoring is required. Alongside microbiological criteria, each class also specifies physico-chemical indicators, such as biochemical oxygen demand (BOD□), total suspended solids (TSS), and turbidity, and includes additional requirements for situations involving aerosolized water exposure, such as testing for *Legionella* spp.

One of the most crucial elements introduced by the regulation is the requirement for a Risk Management Plan (RMP). Every operator responsible for supplying treated wastewater must develop and submit such a plan to the competent regulatory authority. The plan must include:

− A detailed identification and assessment of potential risks to human health, the environment, soil integrity, and crop safety;

− Clearly defined monitoring procedures and emergency response protocols for cases in which parameters exceed safety thresholds;

− Specification of responsible actors at each stage of the treatment, distribution, and application chain;

− Scenario-based planning for system failures or incidents of substandard water quality;

− Public communication strategies, particularly for populations located in or near areas where reclaimed water is applied.

The risk management plan must be regularly updated, based on the latest hazard assessments and include geospatial mapping of potential threats. In this way, the regulation promotes not only technical robustness but also transparency and stakeholder engagement.

Moreover, the regulation mandates the establishment of a rigorous monitoring system. This includes:

− Regular sampling of treated water at the outlet of wastewater treatment plants;

− Monitoring along distribution routes to irrigation sites;

− Verification of compliance with established microbiological and chemical standards;

− Proper record-keeping and public access to monitoring results.

The frequency of monitoring is also standardized and varies depending on the quality class of the water ranging from daily to weekly or monthly, depending on the associated risk levels.

Importantly, Member States are required to submit annual reports to the European Commission detailing the quantities of reused water, compliance statistics, and any violations. Additionally, the public must have access to relevant data, including summaries of risk management plans, monitoring results, and corrective actions taken. This approach fosters accountability and public trust, which are essential for the broader societal acceptance of wastewater reuse practices.

Regulation 2020/741 is not an isolated policy but rather an integral component of a broader EU water governance framework, which includes: the Water Framework Directive (2000/60/EC) [36]; the Urban Wastewater Treatment Directive (91/271/EEC) [35]; the REACH Regulation (1907/2006/EC) [40]; and the Food Hygiene Regulation (852/2004/EC) [39]. Together, these legal instruments form a coherent and enforceable policy architecture aimed at ensuring that the reuse of treated wastewater is not only technically feasible, but also safe, transparent, and socially acceptable.

A particularly influential document in shaping the European Union's regulatory approach to water reuse is the technical report issued by the Joint Research Centre (JRC) titled Minimum Quality Requirements for Water Reuse in Agricultural Irrigation and Aquifer Recharge [16].This report served as the foundational scientific and technical basis for the formulation of Regulation (EU) 2020/741, particularly in defining the water quality classes, parameter thresholds, monitoring protocols, and risk management procedures. Drawing on a wide range of international sources–including guidelines from the World Health Organization (WHO), International Organization for Standardization (ISO) standards, the Australian Guidelines for Water Recycling, and numerous peer-reviewed scientific studies–the report represents a synthesis of global best practices contextualized for implementation within the EU policy framework.

What distinguishes the EU model is its integration of scientific evidence into legally binding instruments, thereby ensuring that policy decisions are not only politically legitimate but also technically robust and empirically grounded. The JRC's recommendations, for instance, underscore the importance of differentiated water quality requirements based on crop type and exposure risk, which was directly translated into the four-category classification system (A to D) now embedded in the EU regulation. Moreover, the JRC advocated for a multi-barrier approach to risk mitigation emphasizing the use of complementary safety measures such as source control, advanced treatment technologies, buffer zones, and continuous monitoring which has been reflected in both regulatory text and accompanying implementation guidelines.

The resulting EU regulatory framework can be seen as a comprehensive and multi-dimensional governance system that combines: legal enforceability, ensuring compliance through standardized obligations across Member States; scientifically validated quality benchmarks, which align with international health and environmental safety standards; mandatory monitoring procedures, including high-frequency sampling and public access to results; detailed risk management planning, tailored to site-specific conditions and operational realities; strong emphasis on transparency and stakeholder accountability, recognizing the role of public trust in the successful adoption of reclaimed water in agriculture.

This model does more than merely permit water reuse it institutionalizes it through a framework of trust, built on technical precision and administrative openness. Importantly, Member States are not only required to monitor and report annually to the European Commission, but also to ensure that farmers, consumers, and local communities are informed of water quality, risk measures, and any deviations from safety thresholds. Such transparency mechanisms serve a dual purpose: they enable public oversight and they strengthen the legitimacy of the policy itself.

In this way, the EU demonstrates how water reuse often regarded with skepticism due to concerns about health, safety, or consumer acceptance can be transformed into a mainstream component of sustainable water management. The system's robustness stems not only from its legal and technical architecture, but also from the way it encourages alignment among stakeholders, from regulatory authorities and water utilities to farmers and the general public.

As the impacts of climate change intensify and water security becomes an increasingly urgent issue across Europe and beyond, the EU’s framework offers a replicable model for other jurisdictions seeking to balance resource efficiency, environmental protection, and public health considerations. Its emphasis on risk-based thinking, cross-sectoral coordination, and adaptive governance makes it particularly well-suited for responding to complex and evolving challenges in the water sector.

In their 2023 article “Wastewater Reuse in Agriculture: Prospects and Challenges”, published in the journal Environmental Research, a team of international researchers presents an in-depth, interdisciplinary review of the environmental, sanitary, and technological dimensions of using treated wastewater for agricultural irrigation [14]. Drawing on a wide range of scientific literature, the authors offer a critical analysis of current wastewater treatment practices and the associated risks posed to ecosystems, human health, soils, and crops.

A central theme of the article is the quality of treated wastewater intended for reuse in agriculture, and the potential hazards that arise when treatment processes are inadequate or outdated. The authors examine the spectrum of pollutants that can persist in wastewater particularly microbial pathogens such as viruses and bacteria, as well as chemical contaminants including toxic salts, heavy metals, persistent organic pollutants, pharmaceutical residues, and microplastics. These elements, even in trace concentrations, can accumulate over time in soils and crops, with implications that may not become evident until after prolonged exposure.

The authors argue that conventional treatment approaches mechanical, biological, and chemical must increasingly be complemented by advanced technologies. These include membrane filtration, nitrogen removal through anoxic processes, the use of nanomaterials, and the incorporation of microalgae-based systems. While such integrated methods can achieve a high degree of water purification and pathogen removal, they also demand substantial financial investment, technical capacity, and continuous monitoring infrastructure resources that may be scarce in many regions where water scarcity is most acute.

Importantly, the study does not limit itself to technical analysis. It also engages with the socio-economic realities that drive the use of wastewater in agriculture, particularly in low-income countries and arid regions. The authors note that over 20 million hectares of agricultural land globally are irrigated with treated or in many cases, untreated wastewater. These areas are often situated near major urban centers, providing farmers with relatively easy access to water but also exposing them to heightened contamination risks. In many such contexts, farmers have no viable alternative sources of water, making the reuse of wastewater a necessity rather than a choice. This, however, raises urgent concerns about public health, as inadequately treated water often contains dangerous pathogens and hazardous chemicals.

A critical insight from the article concerns the global regulatory landscape, which the authors describe as fragmented and insufficiently harmonized. There is a lack of universally accepted standards for wastewater reuse, especially with regard to long-term environmental and health risks. For instance, few regulations address the cumulative impact of low-level contaminants on soil quality or their transfer through food chains. The article emphasizes the need for evidence-based guidelines that take into account not only immediate safety thresholds but also the long-term sustainability of wastewater reuse practices.

Framing their analysis within the broader context of the United Nations Sustainable Development Goals particularly SDG 6 on clean water and sanitation the authors contend that the reuse of treated wastewater should not merely be seen as an environmental imperative. Rather, it should be recognized as a strategic solution to the global freshwater crisis. However, they caution that this potential can only be realized under stringent safety protocols, robust institutional frameworks, and sustained scientific oversight.

Looking to the future, the authors highlight emerging trends in water treatment technology. They advocate for the adoption of integrated purification systems that combine biological, physicochemical, and membrane-based techniques, sometimes enhanced with microalgae or nanofiltration processes. In parallel, they stress the importance of developing standardized analytical methodologies capable of detecting emerging contaminants such as microplastics and pharmaceutical residues substances that are not yet adequately monitored in many parts of the world.

In light of accelerating climate change, rapid urbanization, and increasing competition for freshwater resources, the reuse of treated wastewater in agriculture is poised to play a pivotal role in ensuring water security. Nevertheless, the article makes clear that this approach is not without risks. Its success depends on a careful balance between technological innovation, economic feasibility, social acceptance, and regulatory coherence backed by rigorous, ongoing scientific research.

The article “Treated Wastewater Reuse for Crop Irrigation: A Comprehensive Health Risk Assessment”, published in Environmental Science: Advances (2024), represents one of the most thorough and up-to-date investigations into the health implications of using treated wastewater (TWW) for agricultural irrigation (Ofori et al., 2024). Authored by an international team of scientists, including experts from the Czech Republic and Italy, the study focuses on evaluating potential health risks for consumers of vegetables irrigated with TWW, considering three major categories of concern: heavy metals, pathogenic microorganisms, and emerging contaminants such as pharmaceutical residues and antibiotic resistance genes (ARGs).

The experimental component of the study was conducted in a controlled greenhouse environment, where researchers examined the impact of irrigating three common crops tomatoes, carrots, and cabbage with secondary-treated municipal wastewater sourced from a treatment facility in the Czech Republic. A control group of the same crops was irrigated using standard tap water. Throughout the experiment, detailed analyses were conducted on the composition of the water, soil, and plant biomass, focusing particularly on concentrations of copper, zinc, cadmium, lead, and arsenic.

The findings revealed that copper levels in tomatoes irrigated with TWW were 25 mg/kg, in carrots 30 mg/kg, and in cabbage 20 mg/kg. Notably, these concentrations did not exceed those found in the control group irrigated with tap water; in fact, copper levels in cabbage from the control group were as high as 65 mg/kg. Concentrations of highly toxic elements such as lead, cadmium, and arsenic in all samples were below detection limits. Based on these results, the authors concluded that there was no significant toxicological risk to adult consumers. Health risk assessments, calculated using the hazard quotient (HQ) and hazard index (HI), yielded values well below the safety threshold of one, indicating that the detected contaminant levels do not pose health concerns.

A critical element of the study was the assessment of microbiological safety. The researchers tested tomato fruits for the presence of pathogens such as Escherichia coli, Clostridium perfringens, and thermotolerant coliforms. None of these microorganisms were detected, suggesting that when secondary-treated wastewater is properly disinfected, the risk of microbial contamination in edible crops is minimal.

Particularly noteworthy is the study’s attention to pharmaceutical residues and ARGs. While common pharmaceuticals like carbamazepine and sulfamethoxazole were not detected in any crop samples, trace amounts of gabapentin (3 μg/kg) were found in tomatoes irrigated with TWW. However, this level is well below thresholds considered to pose a toxicological risk. Metagenomic DNA extracted from cabbage samples revealed the presence of several ARGs tetA, ermB, blaTEM, sul2, sul3, and qnrS. Importantly, these resistance genes were also detected in control samples irrigated with tap water. This suggests that the mere use of treated wastewater is not necessarily the primary driver of ARG dissemination in agricultural systems, and that other environmental and anthropogenic factors may be at play.

A key takeaway from the study is the recognition that risk assessment in the context of TWW irrigation must go beyond analyzing the water itself. The properties of the receiving soil such as pH, organic matter content, and microbial activity play a crucial role in determining the bioavailability and uptake of contaminants by plants. The researchers emphasize that a holistic approach is needed one that combines epidemiological, ecological, and chemical methodologies to accurately assess and mitigate health risks associated with wastewater reuse in agriculture.

Furthermore, the authors argue that safe and sustainable reuse of treated wastewater requires strict adherence to good agricultural and sanitary practices throughout the entire production chain. From irrigation to post-harvest handling, each stage must be guided by evidence-based protocols to ensure food safety. In light of growing water scarcity, climate pressures, and the need for resilient agricultural systems, the study provides a strong case for integrating TWW reuse into agricultural strategies provided it is supported by rigorous monitoring and cross-disciplinary risk evaluation.

The article “Co-contaminant Risks in Water Reuse and Biosolids Application for Agriculture” explores the multifaceted and often overlooked risks associated with using treated wastewater and sewage sludge (biosolids) in farming practices [17]. While returning water, nutrients, and organic matter to agricultural systems is seen as a cornerstone of circular economy strategies, the authors caution that these benefits come with serious trade-offs. Specifically, they highlight the presence of chemical pollutants (such as pharmaceuticals, pesticides, and PFAS), physical particles (including microplastics and engineered nanomaterials), and biological agents like antibiotic-resistant bacteria and resistance genes.

These contaminants make their way into the environment through reused water and biosolid applications, gradually building up in soils, entering plant tissues, and potentially passing into food chains. Such exposure pathways raise concerns not only for environmental integrity but also for public health.

One of the core arguments in the article is that current approaches to risk assessment are too narrow.

Most scientific studies focus on individual substances or types of contaminants, rarely accounting for how complex mixtures behave once released into ecosystems. However, in reality, pollutants are rarely present in isolation. Chemical interactions, as well as the influence of environmental factors such as temperature, soil type, and microbial activity, can amplify their impact in unpredictable ways. Failing to consider these interactions may significantly underestimate the true scale of the risks.

The issue of microplastics receives particular attention. Increasingly found in agricultural soils due to the land application of biosolids, these particles can interfere with soil aeration, water retention, and biological processes. Laboratory experiments especially those conducted in hydroponic systems have shown that small plastic particles can infiltrate plant roots and move into stems and leaves. Though these results suggest a possible exposure route, the authors advise caution when interpreting such data, as hydroponic conditions do not accurately mirror the complexity of real soils where interactions with organic matter and mineral particles can limit plastic mobility.

Antibiotic resistance is another urgent issue raised in the article. Despite treatment processes, both resistance genes and resistant bacteria persist in effluents and sludge. In some cases, the conditions during treatment may even enhance horizontal gene transfer, potentially facilitating the evolution of new, drug-resistant pathogens. This is particularly concerning given that wastewater treatment plants receive a constant influx of waste from households, livestock operations, food processing facilities, and hospitals making them potential breeding grounds for resistance.

The authors emphasize that the solid fraction of treated waste the sludge tends to hold the highest concentration of emerging contaminants. When applied to fields as fertilizer, this sludge becomes a vehicle for distributing pollutants across farmland. To manage these risks effectively, they argue for more robust monitoring frameworks, including tools to identify and prioritize contamination hotspots.

What emerges from the article is a call for coordinated global action. The authors stress the need to upgrade treatment technologies, modernize regulations, and harmonize safety standards worldwide. Without these measures, the risks associated with reuse could undermine its potential as a sustainable solution to water scarcity and declining soil fertility.

In conclusion, the paper sheds light on the intricacies and interdependencies of risks tied to water reuse and biosolid application. It makes a strong case for moving beyond single-contaminant assessments and adopting a multidisciplinary approach one that brings together expertise from environmental science, public health, agronomy, and policy. Only through such collaboration, they argue, can we ensure that the reuse of resources in agriculture supports both human wellbeing and environmental resilience in the long term.

The review article “Risks Associated with Wastewater Reuse in Agriculture: Investigating the Effects of Contaminants in Soil, Plants, and Insects”, developed under the PRIMA-SAFE project and published in Frontiers in Environmental Science, offers a comprehensive and nuanced examination of both the benefits and the risks linked to the use of treated wastewater in agricultural irrigation [30]. The authors focus on a dual reality while treated wastewater can be a valuable source of nutrients for crops, it may also carry a host of residual contaminants that pose threats to soil ecosystems, plant health, insects, and, ultimately, human wellbeing.

On the positive side, irrigation with treated effluent can improve soil fertility, enhance crop productivity especially for short-cycle crops like lettuce and tomatoes and reduce reliance on synthetic fertilizers. Treated wastewater often contains plant-available forms of nitrogen, phosphorus, and potassium, making it a potential input in circular agriculture. This resource recovery aspect aligns with broader sustainability goals and can contribute to closing nutrient loops in regions facing growing water stress.

However, the authors caution that alongside these agronomic advantages, there are critical risks stemming from contaminants that are not always fully removed during conventional treatment processes. These include persistent organic pollutants, pesticide residues, heavy metals, pathogenic microorganisms, pharmaceuticals, and a particularly concerning class of compounds: N-nitrosamines recognized for their carcinogenic properties. Once introduced into agroecosystems, these substances can accumulate in soils, be taken up by crops, affect insect biodiversity, and facilitate the spread of antimicrobial resistance.

The presence of pharmaceutical compounds and antibiotics in irrigation water is a source of particular concern. Their repeated introduction into the soil can disrupt microbial communities and exert selective pressure that promotes the survival and transmission of resistant strains. This, in turn, may have wide-reaching consequences not only for soil health and agricultural output but also for public health systems struggling to combat antibiotic resistance.

To mitigate these risks, the article underscores the importance of implementing advanced water treatment solutions, such as tertiary purification, biofiltration, and precision irrigation methods like drip systems. These approaches reduce the direct contact between edible plant parts and reclaimed water, thereby limiting contaminant transfer into the food chain. In addition, they contribute to more targeted and efficient water use, which is particularly valuable in arid and semi-arid regions.

A key takeaway from the review is the need for integrated, interdisciplinary strategies to manage water reuse safely. The authors call for collaboration across a wide range of fields–including ecology, agronomy, environmental engineering, microbiology, medicine, and legal studies. Closing regulatory gaps and directing investment into treatment technologies specifically designed to remove high-risk pollutants is viewed as essential. This becomes even more urgent in light of climate change and the increasing scarcity of freshwater in many parts of the world.

In summary, while treated wastewater has great potential to support more sustainable agricultural practices, its use must be accompanied by rigorous risk assessment and governance frameworks. The article provides a strong argument for aligning scientific knowledge, technological innovation, and policy development to ensure that water reuse practices not only conserve resources but also protect ecosystems and human health in the long term.

In Ukraine, comprehensive research on the reuse of treated wastewater and biosolids in agriculture remains relatively limited compared to the growing international body of literature. A few notable studies have addressed this topic, often focusing on adapting foreign technologies and evaluating environmental risks under local conditions.

For example, Oleksandr Shkvirko, I. Tymchuk, and M. Malovanyy from Lviv Polytechnic have explored the feasibility of applying international experience in wastewater sludge management to Ukrainian agricultural systems [29]. Their findings suggest that using sludge as fertilizer could be a promising solution, but they emphasize the need for further investigation to ensure environmental safety and optimize application practices under local agroecological conditions.

Researchers in Poltava, including V. Pysarenko, I. Samoylik, L. Dychenko, and O. Korchahin, have studied the phytotoxic effects of wastewater from waste disposal sites on common wheat [27]. Their experiments revealed significant adverse impacts: a reduction in germination rates and stunted development of both the aerial and root parts of the plants by 16%, 22%, and 44%, respectively compared to the control group. Plant biomass also decreased markedly, underscoring the risks of using insufficiently treated or contaminated wastewater in crop production.

At Kharkiv Polytechnic Institute, Zinchenko, Bukatenko, and Misyak investigated vermifiltration technology in 2024 [34]. Their research demonstrated that earthworm-based biofiltration systems can effectively treat both domestic and industrial wastewater. In addition to removing contaminants and pathogens, this method produces organic-mineral vermicompost suitable for use as a fertilizer in agriculture. While still in the early stages of development, the approach shows considerable promise as a low-cost, ecologically sound solution.

Among Ukrainian institutions, the Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences (NAAS) stands out as the leading organization systematically addressing the reuse of wastewater and biosolids in agriculture. The Institute conducts interdisciplinary research focused on sustainable water and nutrient management under conditions of climate change and increasing resource scarcity. Its scientists are developing practical guidelines for the use of treated wastewater in crop irrigation and exploring the agronomic potential of sewage sludge as a soil amendment.

In collaboration with national and international partners, the Institute carries out field trials to assess the impact of treated effluents on crop yields, soil properties, and food safety. It also monitors the accumulation of heavy metals and pharmaceutical residues in soils and plants to determine acceptable application thresholds. Furthermore, the Institute is actively involved in drafting policy recommendations for regulating wastewater use in agriculture, with a strong emphasis on aligning Ukrainian practices with European environmental standards.

By integrating agronomy, soil science, environmental engineering, and risk assessment, the Institute of Climate-Smart Agriculture plays a central role in shaping the scientific and policy discourse on safe and efficient water reuse in Ukraine's agricultural sector. Nonetheless, as the global interest in wastewater reuse continues to grow, there is a pressing need for broader national research efforts and more robust institutional coordination in Ukraine.

In Ukraine, the legislative basis for wastewater management is fragmented and remains insufficient to support large-scale reuse in agriculture. The Water Code of Ukraine (1995, with subsequent amendments) and the Law "On Drinking Water, Drinking Water Supply and Sewerage" (2002) establish general provisions on water use and wastewater treatment. However, they do not contain detailed standards governing the reuse of reclaimed wastewater for irrigation. Sanitary norms developed under the Ministry of Health provide certain restrictions on the use of untreated or partially treated effluents but do not set out a comprehensive risk-based approach comparable to the EU Regulation (EU) 2020/741.

The absence of clear quality classes, monitoring procedures, and operational guidelines creates regulatory uncertainty for utilities and farmers alike. For instance, wastewater treatment plants in southern Ukraine, particularly in Odesa and Kherson regions, have occasionally considered the reuse of treated effluents for irrigating industrial crops such as maize and sunflower. Yet, without binding sanitary standards and legal guarantees, such initiatives remain experimental rather than systemic.

Institutionally, responsibilities are dispersed. The Ministry of Environmental Protection and Natural Resources of Ukraine oversees water resource management, while the Ministry of Agrarian Policy and Food of Ukraine plays a role in agricultural water use. The Ministry of Health is responsible for sanitary and epidemiological oversight. However, coordination between these bodies is limited, and no single authority currently acts as the regulator for agricultural wastewater reuse. This stands in contrast to the EU model, where centralized regulation provides clarity and consistency across member states.

Despite the legislative gaps, Ukrainian research institutions are increasingly engaging with this issue. The Institute of Climate-Smart Agriculture of the National Academy of Agrarian Sciences (NAAS) has been at the forefront of studying sustainable irrigation practices, including the potential of reclaimed wastewater use under conditions of water scarcity and climate change. These efforts are part of the state-funded research program PND NAAS 5 "Formation of Balanced Farming Systems on Irrigated Lands under Climate Change" (Irrigated Agriculture). Within this framework, Task 05.00.02.08П specifically addresses the development of directions for additional treatment of domestic wastewater effluents to make them suitable for irrigation in line with European legislation.

Recent studies led by Ukrainian scholars have highlighted both the opportunities and the challenges of reclaimed wastewater use. For example, research by Piliarska, Shablia, and colleagues [42] has examined the application of treated wastewater for irrigating agricultural crops, providing preliminary assessments of agronomic potential, soil impact, and compliance gaps with EU regulatory requirements. These studies confirm that while reclaimed wastewater could significantly reduce pressure on freshwater resources, Ukraine still lacks robust standards for monitoring microbial and chemical contaminants.

Other research organizations, such as regional universities and specialized institutes under NAAS, are also contributing to the scientific evidence base. Investigations have been carried out on the effects of treated municipal wastewater on soil chemical properties and crop quality, providing important data that could inform future national guidelines. Collaboration with international partners has further enriched this field, bringing in methodologies for risk assessment, One Health perspectives, and emerging contaminant monitoring.

Ukraine's ongoing process of European integration provides a strategic window for developing a modern regulatory framework for wastewater reuse. Alignment with the principles of Regulation (EU) 2020/741 would enable the country to adopt risk-based management, define water quality classes, and establish monitoring protocols that could support both food safety and environmental sustainability. Ukrainian scientific institutions, particularly the Institute of Climate-Smart Agriculture of NAAS, can play a key role in adapting EU best practices to local agro-climatic conditions and in providing the evidence base for national standards.

Conclusions. This study demonstrates that the reuse of treated wastewater and biosolids holds significant potential for strengthening agricultural resilience in Ukraine at a time when the country faces overlapping challenges of freshwater scarcity, climate change, and war-related destruction of infrastructure. The bibliographic analysis makes clear that these resources can provide substantial agronomic benefits, supplying essential nutrients, reducing dependency on costly synthetic fertilizers, and improving the long-term fertility of soils. At the same time, the risks associated with their use are complex and multifaceted. They include microbiological hazards, chemical contaminants, and, no less importantly, socio-economic barriers related to consumer acceptance and the absence of regulatory clarity.

The analysis also shows that regulatory and institutional frameworks remain underdeveloped. In Ukraine, harmonized standards for wastewater and biosolid reuse in agriculture are still lacking, despite the fact that European directives and regulations already offer clear benchmarks. The absence of such standards creates uncertainty both for farmers and for investors, limiting the opportunities for scaling up new practices. Furthermore, while technological solutions exist, they are not universally applicable. Each context–whether a drought-prone southern region or a war-affected area where infrastructure has been damaged–requires different approaches, ranging from low-cost natural treatment systems to advanced multi-stage technologies capable of ensuring pathogen and contaminant removal.

Another critical gap concerns knowledge and monitoring. Emerging pollutants such as pharmaceutical residues, microplastics, and antibiotic resistance genes remain insufficiently studied in Ukraine, and there is little systematic surveillance to track their accumulation in soils and crops. Without robust monitoring and risk assessment frameworks, it is impossible to guarantee safety or to build long-term confidence in these practices. Taken together, these findings confirm the central hypothesis of this study: although wastewater and biosolids reuse offers a viable alternative to conventional water and fertilizer sources, its safe and effective application demands a comprehensive risk management system that integrates international standards with Ukraine's specific recovery and climate adaptation needs.

In light of these results, several priorities emerge for Ukraine. The modernization of regulatory frameworks must be placed at the center of national policy, with the development of clear standards that reflect both conventional and emerging risks while aligning with European legislation, particularly Regulation 2020/741. Alongside regulatory reform, pilot projects are urgently needed in war-affected and drought-prone regions to test treatment technologies, evaluate risk mitigation strategies, and generate the practical evidence required for broader adoption. These efforts should be closely linked to the selection of adaptive technologies that balance cost, context, and safety, ranging from precision irrigation methods such as drip systems to advanced disinfection techniques like ozonation or ultraviolet treatment for high-risk effluents.

Equally important is the creation of national monitoring systems capable of tracking chemical, microbial, and ecotoxicological parameters, not only individually but in terms of their cumulative and interactive effects. Expanding this type of monitoring will provide a more accurate picture of long-term risks to human health and ecosystem integrity. At the same time, success will depend on building the knowledge and trust of those who will ultimately implement these practices. Training programs for farmers, utilities, and local authorities, combined with broader public awareness campaigns, can help establish a culture of safe reuse while reducing societal resistance.

Finally, the reuse of treated wastewater and biosolids should not be seen in isolation, but as part of Ukraine's broader recovery and climate adaptation strategy. Integrating these practices into national policies on agriculture, food security, and environmental protection supported by coordination across ministries and active international cooperation can transform what has often been considered a waste problem into a valuable resource. By embracing this approach, Ukraine can move closer to building a resilient agricultural system that not only meets immediate needs but also lays the foundation for long-term sustainability.

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Пілярська О.О., Жеребчук С.В., Шабля О.С., Полагенько О.С. Бібліографічний аналіз визначення ризиків та управління ними при повторному використанні очищених стічних вод для сільськогосподарського зрошення як метод імплементації найкращих практик для України

Стаття має на **меті** провести комплексний бібліографічний аналіз існуючих досліджень щодо ідентифікації та управління ризиками, пов'язаними з повторним використанням очищених стічних вод для сільськогосподарського зрошення, з метою формування рекомендацій для впровадження найкращих практик, адаптованих до специфіки України з урахуванням екологічних, соціальних та нормативних аспектів. **Методи.** Проведено систематичний огляд наукових публікацій із міжнародних баз даних за останні два десятиліття. Аналізувалися ключові тематичні напрями, зокрема біологічні, хімічні, фізичні, екологічні та соціально-економічні ризики. Особлива увага приділялася технологіям очищення, нормативній базі, методам моніторингу та стратегіям зниження ризиків, а також виявленню прогалин і викликів, актуальних для України. **Результати.** Аналіз показує, що повторне використання очищених стічних вод має суттєві переваги, такі як циркуляція поживних речовин і збереження водних ресурсів, але також пов'язане з різноманітними ризиками. Біологічні загрози представлені патогенними мікроорганізмами, які можуть зберігатися після очищення. Хімічні забруднювачі включають важкі метали, залишки фармацевтичних препаратів, мікропластик і гени антибіотикорезистентності. Фізичні ризики стосуються засолення та накопичення осадів. Ефективне управління ризиками базується на багаторівневих процесах очищення, ретельному моніторингу та гармонізації нормативної бази. В Україні досліджень у цій сфері небагато, що підкреслює необхідність локалізованих досліджень і адаптації міжнародних практик. **Висновки.** Для України впровадження безпечного та сталого використання очищених стічних вод у сільському господарстві вимагає міждисциплінарного підходу, що поєднує сучасні технології очищення, системи моніторингу, чіткі регуляторні стандарти, які відповідають директивам ЄС, та навчальні програми для зацікавлених сторін. Бібліографічний огляд підкреслює важливість індивідуальних рішень, що враховують регіональні виклики, зокрема дефіцит води та відновлення інфраструктури у постконфліктних регіонах. Ця робота є важливим кроком до науково обґрунтованої політики та практичних рекомендацій для стійкого управління водними ресурсами в аграрному секторі України.

Ключові слова: повторне використання очищених стічних вод, сільськогосподарське зрошення, оцінка ризиків, управління ризиками, біосоліди, якість води, екологічне здоров'я, Україна, стале сільське господарство.

Piliarska O.O., Zherebchuk S.V., Shablia O.S., Polahenko O.S. Bibliographic Analysis of Risk Identification and Management in Treated Wastewater Reuse for Agricultural Irrigation as a Method for Implementing Best Practices in Ukraine

This article **aims** to provide a comprehensive bibliographic analysis of existing research on risk identification and management related to the reuse of treated wastewater for agricultural irrigation, with the goal of informing the implementation of best practices adapted for Ukraine's specific environmental, social, and regulatory context. **Methods.** A systematic review of scholarly publications from international databases was conducted, focusing on studies published in the last two decades. Key thematic areas including biological, chemical, physical, environmental, and socio-economic risks were examined. The analysis emphasizes treatment technologies, regulatory frameworks, monitoring approaches, and risk mitigation strategies, identifying gaps and challenges relevant to Ukraine. **Results.** The analysis reveals that treated wastewater reuse offers significant benefits such as nutrient recycling and water resource sustainability but also presents diverse risks. Biological hazards mainly involve pathogenic microorganisms that may persist despite treatment. Chemical contaminants include heavy metals, pharmaceutical residues, and emerging pollutants such as microplastics and antibiotic resistance genes. Physical risks include salinization and sediment accumulation. Effective risk management relies on multi-barrier treatment processes, rigorous monitoring, and harmonized regulations. Few studies focus on Ukrainian conditions, highlighting the need for localized research and adaptation of international best practices. **Conclusions.** For Ukraine, implementing safe and sustainable treated wastewater reuse in agriculture requires an interdisciplinary approach integrating advanced treatment technologies, robust monitoring, clear regulatory standards aligned with EU directives, and capacity-building programs for stakeholders. Bibliographic synthesis underscores the importance of tailored solutions addressing regional challenges such as water scarcity and post-conflict infrastructure recovery. This review serves as a foundational step toward evidence-based policy-making and practical guidelines that support resilient agricultural water management in Ukraine.

Key words: treated wastewater reuse, agricultural irrigation, risk assessment, risk management, biosolids, water quality, environmental health, Ukraine, sustainable agriculture.

Дата першого надходження статті до видання: 27.02.2026
Дата прийняття статті до друку після рецензування: 27.03.2026
Дата публікації (оприлюднення) статті: 28.04.2026