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Review

Systematic review on the effects of wastewater chemical composition on crop yield under fertigation practices

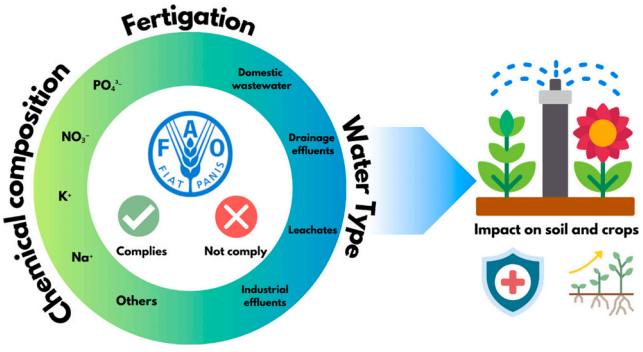
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HIGHLIGHTS

- Fertigation requires precise adjustment soil conditions for optimal effectiveness.
- Wastewater reuse enhances agricultural sustainability.
- Elevated Na^+ and K^+ levels in wastewater limit nutrient uptake and yield.
- Consistent NO_3^- and PO_4^{3-} levels in treated wastewater boost plant growth.

GRAPHICAL ABSTRACT



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ABSTRACT

The escalating global demand for freshwater resources poses significant challenges to sustainable agricultural practices. This systematic review examines the influence of inorganic ions' concentration in wastewater on crop yields under fertigation, with a particular focus on compliance with the recommendations of FAO water quality standards. The review reveals that key nutrients, such as nitrates (NO_3^-) and phosphates (PO_4^{3-}), largely meet established thresholds, while sodium (Na^+) and potassium (K^+) frequently exceed permissible levels, threatening crop productivity, especially in salinity-sensitive species. Additionally, the study explores the effects of nutrient variability on crop performance across different soil types and cultivation environments. Statistical analyses were performed to assess chemical composition and their correlation with agricultural yields. The findings emphasize the critical need to adapt fertigation practices to the specific characteristics of soil and environmental conditions to optimize the benefits of wastewater reuse.

1. Introduction

The global growing freshwater demand poses increasingly relevant challenges, as the availability of this resource diminishes progressively. Projections indicate a significant increase of demand by 2030, expected to exceed 160 % of the total available volume (Ricart and Rico, 2019).

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This exponential rise is exacerbated by both degradation and depletion of freshwater resources (Busico et al., 2021; Gleick and Cooley, 2021), posing significant threats to the sustainability of crops, heavily reliant on this resource (Sidhu et al., 2019). The growing competition for water resources among agricultural, industrial, and domestic sectors represent a critical challenge to achieve a sustainable water management, driving the search for innovative solutions (Jeong et al., 2020).

Among these solutions, the utilization of treated urban wastewater stands out as a valuable resource to meet agricultural needs, including irrigation (Gava et al., 2023). This shift in focus highlights the importance of adopting sustainable practices such as fertigation, a method that combines the application of fertilizers with irrigation systems, delivering nutrients directly to the root zone to enhance crop growth and resource efficiency.

Fertigation emerges as a multifaceted strategy that simultaneously addresses various agricultural challenges. Fertigation relieves pressure on drinking water sources, and harnesses nutrient-rich wastewater to improve agricultural productivity. This method effectively exploits the high nutrients presence in effluents, particularly biogenic compounds such as total nitrogen (N) and phosphorus (P) (Mainardis et al., 2022). The effluents from wastewater treatment plants are often abundant of macronutrients like N, P, and potassium (K^+) and therefore they could serve as fertilizer for plants' growth (Silva et al., 2016).

In agricultural practices, fertigation with treated wastewater presents challenges related to public health and regulatory compliance as wastewater may contain harmful pathogens and organic and inorganic micropollutants. This makes it essential to implement effective treatment protocols that adequately mitigate health risks, ensuring the safety of both crops and consumers (Radini et al., 2023). However, one of the most critical issues is represented by the presence of emerging contaminants, such as pharmaceuticals, hormonal compounds, industrial chemicals (Kasonga et al., 2021), and microplastics (Viaroli et al., 2022). These contaminants can accumulate in soil, water, and ultimately in the food chain, requiring specialized management and treatment to avoid environmental and health risks (Chojnacka et al., 2020; Mainardis et al., 2022).

Furthermore, to ensure the safety of fertigation practices, the use of treated wastewater must strictly comply with regulatory standards, such as those established by European legislation, including the Regulation (EU) 2020/741 of the European Parliament and of the Council (25th May 2020), which sets minimum requirements for water reuse in agriculture. These standards are complemented by the Food and Agriculture Organization (FAO) guidelines for wastewater reuse in agriculture, which provide a detailed framework to ensure sustainable and safe practices (Radini et al., 2023).

FAO has developed specific water quality recommendations adapted for agricultural applications, emphasizing the importance of regulating nutrient levels in irrigation water to prevent negative effects on soil quality and crop productivity. These guidelines set permissible limits on critical nutrients such as N and P dissolved compounds, ensuring that fertigation with treated wastewater does not result in soil degradation, water contamination, or harmful accumulation of toxic elements (FAO, 1992).

Data from the European Environment Agency (EEA) indicate that up to 90 % of urban wastewater undergoes treatment, highlighting a substantial potential for its safe reuse in agriculture, provided that nutrient concentrations also comply with FAO standards. Adhering to FAO recommendations ensures the protection of public health and the environment while fostering confidence in fertigation as a sustainable strategy for water management and agricultural production (EEA, 2021).

The relevance of this approach becomes even more pronounced when considering that agricultural reuse of effluent from wastewater treatment plants can significantly reduce nutrient loads to surface waters (Lahlou et al., 2021) and groundwater (Azad et al., 2020). Moreover, fertigation offers a promising strategy for mitigating greenhouse gas emissions by optimizing nutrient supply and minimizing the need for energy-intensive wastewater treatments (Lahlou et al., 2020). However, extensive adoption of this technique necessitates a thorough understanding of its environmental and ecological impacts across diverse agricultural systems (Alessandrino et al., 2023; Chauhan and Kumar, 2020). This requires careful evaluation of its effects on water resources, including potential water pollution and its broader consequences for aquatic ecosystems.

As indicated by Chojnacka et al. (2020), the use of secondary effluents for fertigation reduces the amount of nutrients discharged into surface waters, thus decreasing their environmental load. The application of biogenic compounds to soil could potentially increase groundwater pollution, making monitoring necessary. This effect can be offset by lower doses of N and P in the form of chemical fertilizers applied to crops (Ebrahimian et al., 2014). Thus, it is essential to examine the potential associated risks, such as nutrient loss and agrochemical leaching, and their implications for water quality and ecosystem health.

In the soil domain, it is crucial to understand the effects of fertigation on health, fertility, and sustainability. Special attention should be given to soil microbiota, as they play a key role in nutrient cycling and soil ecosystem function (Raza et al., 2019; Torres et al., 2023). Microbial activity contributes to organic matter decomposition, nutrient release, and soil structure improvement (Ahmed et al., 2024).

Investigating fertigation effects on plant physiology and growth implies examining nutrient absorption mechanisms and the biochemical responses involved in these processes (Aftab and Hakeem, 2020). Nutrient availability in soil, influenced by fertigation, directly affects crop growth, development, and production. Understanding plant responses to fertigation with treated wastewater is essential for optimizing yield and promoting sustainable agricultural systems (Ahmed et al., 2024).

A thorough review of the literature was conducted for this study to investigate the effects of nutrients as well as other inorganic ions' concentration in wastewater on crop yield when applied to plants in greenhouses and fields, comparing their concentration with that recommended by FAO standards for water quality in agriculture. The specific objectives of this review are: i) to corroborate potential correlation between inorganic ions' concentration in wastewater and crop yield under fertigation; ii) to identify whether nutrients concentration in the wastewater used for fertigation comply with water quality standards established by FAO; iii) to discuss how this correlation varies across different soil types and growing conditions; and iv) to assess the impact of wastewater fertigation on the long-term sustainability of agricultural systems. The structure of a systematic review was maintained to ensure objectivity in literature screening and to facilitate a critical discussion of the collected data.

2. Methodology

2.1. Search strategy and data sources

This systematic study started with a preliminary investigation in the academic databases Scopus and Web of Science, utilizing the phrases "fertigation" and "wastewater reuse" to assess the consistency and comparability of the results from both platforms. Upon verifying the consistency of the results, it was resolved to utilize Scopus as the primary database for the compilation of the search.

A comprehensive search method was developed to incorporate pertinent papers about the utilization of wastewater in fertigation and its effects on crop yield. The search focused on studies published from 2005 to 2024, intending to include both contemporary advancements and studies that illustrate the evolution of technology and approaches over time. The search string was specifically designed to answer the key research questions and ensure that the selected studies adequately addressed the objectives of the systematic review. These questions are:

- How does the concentration of inorganic ions' concentration in wastewater affect the yield of different crops under fertigation in field and greenhouse conditions?
- Is inorganic ions' concentration in the wastewater used for fertigation in line with the established quality standards, and how does this impact crop yield?
- What is the correlation between the concentration of inorganic ions in wastewater and crop yield in different soil types and growing conditions?

Studies that provided quantitative data on the inorganic ions' concentration such as N, P, and K^+, and analyzed their impact on different crop types, both in greenhouses and open fields, were prioritized. In addition, studies that evaluated the effect of inorganic ions on various soils and growing conditions were included, to establish a clear correlation between wastewater quality and crop yield. The final search string was as follows:

(ALL (fertigation AND fertiliz) AND ALL (wastewater OR reuse OR sewage OR sewer* OR effluent) AND ALL (yield OR produc* OR crops) AND ALL (concentration OR impact)) AND PUBYEAR > 2004 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (LANGUAGE, "English"))*

The search string returned 2440 papers, which were exported in .ris format and integrated into the Rayyan platform (https://www.rayyan.ai/) to simplify the systematic screening of the studies. A verification of the search string was subsequently done, identifying benchmark studies in the research field of interest. The benchmark studies employed in this phase are reported in Table 1. This verification was crucial to confirm that the search terms effectively covered the pertinent and representative literature on the topic.

2.2. Selection process

The articles' selection procedure is divided into multiple stages, adhering to the criteria set by the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). Fig. 1 shows the methodology employed for articles' selection. In the selection process, inclusion and exclusion criteria were implemented at every stage, from the preliminary assessment of abstracts to the comprehensive reading of full articles, to guarantee that the chosen articles sufficiently addressed the research questions. Table 2 reports the inclusion and exclusion criteria applied at this stage.

2.3. Analysis procedure

The analysis procedure for the selected studies began with the organization of studies into a database, where essential information was recorded to enable a quantitative and structured evaluation of the results. The parameters extracted were the concentrations of inorganic ions present in wastewater, such as N, P, K^+, and other essential elements for crops. Additionally, data on crop yield under different fertigation conditions, the types of crops studied, and the soil types were included, as well as growth conditions, whether in greenhouses or open fields.

To analyze the relationship between the occurrence of inorganic ions in wastewater and crop yield, descriptive and graphical methods were used to identify patterns and correlations in the data. Independent cross-checks were performed to ensure data accuracy, resolving discrepancies and assessing potential outliers using graphs and statistics to ensure uniformity and consistency of the database. Additionally, an initial assessment of the diversity of the studies was performed through comparative schemes. Missing data were addressed using the mean of similar parameters in the study set and included comparative analyses of various water types and culture conditions to validate the robustness and consistency of the results.

Table 1
Summary of benchmark articles on fertigation with wastewater in agricultural systems.

Reference	Keywords	Study Objective	Conclusions
Chojnacka et al. (2020)	Fertigation, Wastewater, Transition, Challenges, Opportunities.	Analyze the transition from conventional irrigation to fertigation with reclaimed wastewater, identifying opportunities and challenges.	Fertigation with reclaimed wastewater offers significant advantages but requires overcoming technical, regulatory, and social challenges for effective implementation.
Garcia-Caparros et al. (2017)	Water management, Fertigation, Intensive horticulture, Sustainability.	Evaluate the integral management of irrigation water in intensive horticultural systems, focusing on water and nutrient use efficiency.	Fertigation increases water and nutrient use efficiency and is essential for sustainability in arid and semi-arid regions.
Gava et al. (2023)	Reuse, Drainage water, Sustainability, Greenhouses.	Evaluate the reuse of drainage water and substrate in Mediterranean greenhouse crops to improve environmental and economic sustainability.	Reusing water and substrate improved environmental sustainability and reduced resource use in greenhouses.
Groenveld et al. (2019)	Nutrient efficiency, Fertigation, Aquaculture, Agriculture, Nitrogen.	Optimize nitrogen use efficiency through fertigation management in an integrated aquaculture-agriculture system.	Controlled fertigation improves nitrogen efficiency, reducing losses and environmental impact.
Jiménez-Benítez et al. (2020)	Wastewater, Fertigation, Economic viability, CO_2 emissions.	Evaluate the economic and technological feasibility of fertigation with treated wastewater, considering CO_2 emissions in EU case studies.	Fertigation with treated wastewater is economically viable and can reduce CO_2 emissions though it requires significant initial investment.
Mainardis et al. (2022)	Wastewater, Fertigation, Water management, Circular economy.	Analyze the challenges and opportunities of using wastewater in fertigation, focusing on water management and the circular economy.	Wastewater fertigation improves agricultural sustainability but faces technical and social barriers.
Savvas et al. (2023)	Recycling, Fertigation, Effluents, Greenhouse crops, Water use efficiency.	Explore new technologies to recycle fertigation effluents in soilless greenhouse systems to maximize water and nutrient use efficiency.	Emerging technologies improve water and nutrient use efficiency in greenhouses, promoting sustainability in intensive crop production.

To ensure data consistency and comparability, a process of unit homogenization was conducted for each parameter analyzed. For crop yield, all units were standardized to tons per hectare (ton/ha). Similarly, inorganic ions' concentrations were normalized to milligrams per liter (mg/L). Furthermore, error values were included for each measurement, covering both concentrations and crop yield, to provide an accurate assessment of data variability and reliability.

The collected data undergo statistical analysis and descriptive graphs, allowing the visualization of trends and correlations between

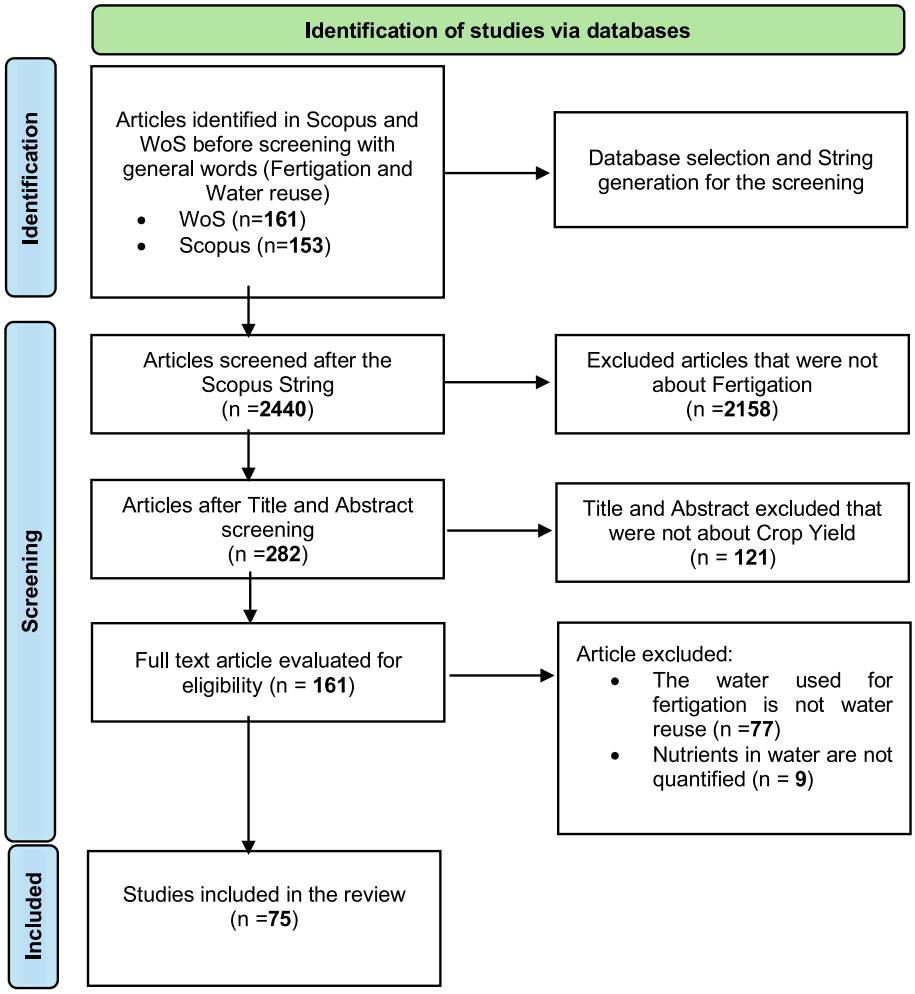


Fig. 1. The PRISMA flow diagram for the systematic review detailing the database searches, the number of abstracts screened, and the full texts retrieved.

Table 2
Inclusion and exclusion criteria applied in the selection.

Criteria	Included	Excluded
Type of water	Studies using wastewater, greywater, or industrial effluents in fertigation	Studies using only irrigation water with fertilizers or conventional water
Nutrient concentration	Studies providing quantitative data on nutrients in wastewater	Studies not presenting quantitative data on nutrient concentration
Impact on crop yield	Studies evaluating the impact of fertigation with wastewater on crop yield	Studies not including results on crop yield or not using fertigation
Growth conditions	Studies detailing growth conditions (greenhouse, field) and soil type	Studies not specifying growth conditions or soil type
Water quality	Studies including an analysis of the chemical composition of the wastewater used	Studies not providing details on the quality of water used
Type of document	Research articles and reviews published in scientific journals	Conference papers, book chapters, non-peer-reviewed reports
Language	Studies published in English	Studies in other languages

inorganic ions' concentrations and crop yield in different agricultural contexts. The graphs included comparative analyses of inorganic ions' concentrations in relation to: (i) productivity, (ii) yield according to different crop types and types of water used, and (iii) the influence of growing conditions. Additionally, an analysis of the compliance of the water used was carried out, using the FAO *Guidelines for irrigation water quality* as a reference to assess the quality of wastewater after the articles' selection. Detailed information on all measured parameters as well as the graph generated are available in the Supplementary Material.

3. Results and discussion

This section presents the results obtained from the systematic review, focusing on the analysis of inorganic ions' concentrations in wastewater used for fertigation and their impact on the productivity of various crops under different agricultural conditions. An evaluation is conducted on the effects of adequacy to FAO water quality standards on the crop yield. Additionally, fluctuations in water quality based on its source are investigated, examining the effects of these variations on both agricultural productivity and soil health, depending on the type of crop. Lastly, the correlation among the concentration of essential nutrients and agricultural performance in different soil types and growth conditions is explored, offering a holistic perspective on the feasibility and sustainability of using wastewater for fertigation in the context of long-term sustainable agriculture.

3.1. Compliance of inorganic ions in wastewater according to FAO guidelines

Fig. 2 is a graphical representation of the studies examined, which demonstrate a high level of non-compliance with the FAO guidelines for irrigation water quality regarding the concentration of inorganic ions present in wastewater used for fertigation. To provide a clearer

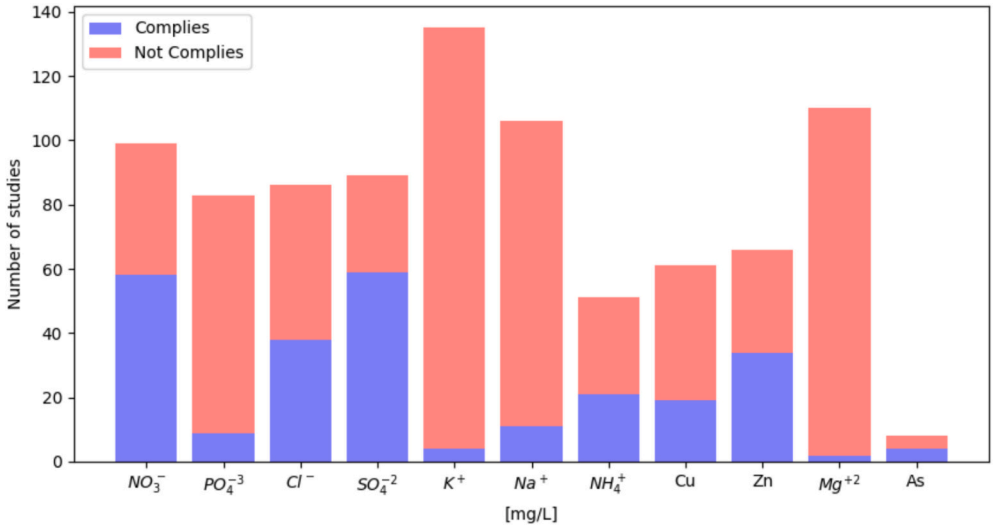


Fig. 2. Recommendations compliance of the reviewed literature.

comparison, the FAO establishes maximum recommended concentrations for key inorganic ions in irrigation water, which include NO_3^- (15 mg/L), PO_4^{3-} (2 mg/L), Cl^- (250 mg/L), SO_4^{2-} (500 mg/L), K^+ (2 mg/L), Na^+ (40 mg/L), NH_4^+ (5 mg/L), Cu (0.2 mg/L), Zn (2 mg/L), Mn (0.2 mg/L), and As (0.1 mg/L).

Essential micronutrients for plant development, such as K^+ and Na^+, are particularly notable for their high rates of non-compliance (Odone et al., 2024). This discrepancy raises significant concerns regarding the variability in wastewater composition and the multiple factors influencing elevated ion concentrations. The disparities observed suggest that wastewater characteristics are strongly influenced by its source, the efficiency of treatment processes, and local agricultural practices (Chojnacka et al., 2020; Elgallal et al., 2016). In regions where secondary and tertiary treatments are inadequate or inconsistently applied, excessive ion accumulation can be exacerbated, leading to progressive soil degradation (Rezapour et al., 2021). Persistent exposure to high concentrations of these ions may alter soil physicochemical properties, affecting water retention capacity, nutrient availability, and overall soil fertility, with potentially long-term consequences for sustainable agricultural productivity (Azad et al., 2020; Mainardis et al., 2022).

In contrast, nutrients such as NO_3^- and PO_4^{3-} showed higher compliance with the guidelines, which may be associated with the implementation of optimized wastewater treatment practices in certain regions or the effectiveness of treatment systems in reducing the concentrations of these compounds. This constitutes a positive finding, as NO_3^- is an essential nutrient for plant development, thus its presence at appropriate levels can promote healthy plant growth and adequate production (Aftab and Hakeem, 2020; Ahmed et al., 2024).

This contrast in compliance may indicate that, although some wastewater meets specific recommendations, selective non-compliance with other inorganic ions may significantly diminish the potential benefits of using such water for fertigation. For example, Na^+ can hinder the assimilation of other essential micronutrients, disrupting the soil's ionic balance and reducing the long-term effectiveness of fertilization (Abdel-Aziz et al., 2016). Additionally, the accumulation of salts from the use of wastewater with high Na^+ and Cl^- content can reduce soil permeability, adversely impacting crop health and agricultural sustainability (Penserini et al., 2024).

An additional point to highlight is the high Na^+ and Cl^- content detected in certain studies, which underlines the need to optimize wastewater management practices before its use in the agricultural sector. It is important to consider mitigation strategies, such as dilution or alternation with freshwater sources, to minimize the impact that these elements could have on soil and plants (Radini et al., 2021).

Non-compliance with FAO recommendations for certain inorganic ions could affect agricultural yield in the short term and have detrimental long-term repercussions for soil health and the viability of agricultural systems. Therefore, it is important to implement appropriate management strategies that enable the efficient and responsible use of wastewater in fertigation, ensuring agricultural productivity without compromising available natural resources.

3.2. *Correlation between inorganic ions' concentrations and yield in field and greenhouse conditions*

The correlation between inorganic ions' concentrations in wastewater and crop productivity under fertigation in field and greenhouse conditions is a crucial aspect of contemporary agriculture, especially in systems where effective water management and nutrient and micronutrient optimization are fundamental for maximizing productivity (Yasuor et al., 2020). Fig. 3 illustrates the influence of various inorganic ions' concentrations on agricultural productivity, particularly showing the effects of either compliance or non-compliance with FAO water quality recommendations. The numerical data corresponding to this figure can be found in the Supplementary Materials.

When analyzing NO_3^-, it is evident that appropriate concentrations tend to optimize yields in both greenhouse and field conditions. In greenhouse environments, yields are higher and more consistent, reflecting improved N uptake by plants. In open-field conditions, environmental factors introduce greater variability in yields due to challenges in controlling processes such as leaching, mineralization, and denitrification, which depend on soil conditions and temperature (Savvas et al., 2023). This can explain the observed fluctuations in productivity when optimal conditions are not maintained.

Regarding PO_4^{3-}, as depicted in Fig. 3, especially in greenhouse environments, yields are more stable when concentrations of this inorganic ion fall within recommendations. This suggests a direct relationship between PO_4^{3-} availability and plant uptake efficiency in a controlled environment. In field conditions, PO_4^{3-} can be subject to fixation processes in the soil, particularly in soils high in Ca^{2+}, Fe^{2+}, or Al^{+3}, which tend to immobilize this nutrient, reducing its availability to plants (Ahmed et al., 2024). Additionally, soil pH plays a crucial role in PO_4^{3-} solubility. For example, in acidic soils, PO_4^{3-} may settle out as Fe- or Al-PO_4, which could explain why yields vary more in the field when the recommended limits are not met (Penn and Camberato, 2019).

This observation aligns with research indicating that applying P fertilizers in open-field environments may require additional management techniques, such as localized application, to increase PO_4^{3-} use

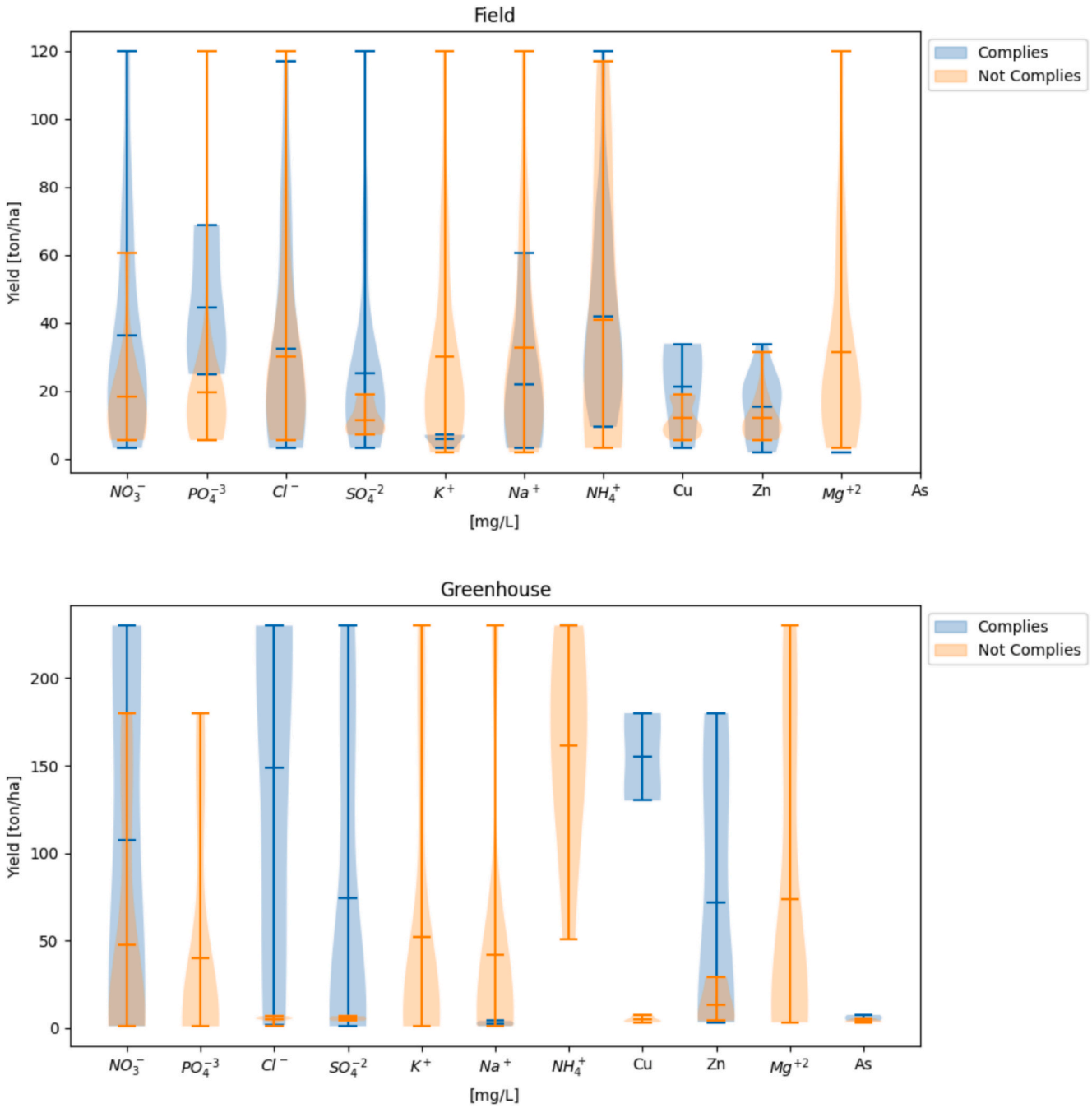


Fig. 3. Distribution of crop yield (ton/ha) as a function of chemical composition in wastewater under greenhouse and field conditions. Violin plots show the difference between studies that comply (blue curve) and do not comply (orange curve) with FAO water quality guidelines.

efficiency (Bindraban et al., 2020; Ibrahim et al., 2022). In this context, the application of fertilizers through irrigation with wastewater containing high PO_4^{3-} levels may be insufficient if other soil factors, such as pH and organic matter content, are not considered, as they can affect the availability of this nutrient.

K^+ and Na^+, which are essential in plant osmotic regulation, exhibit different behaviors depending on the cultivation environment, as shown in Fig. 3. Both graphs show a notable variability in production outcomes when concentrations exceed the established recommended limits, particularly detrimental in field environments. Salt accumulation in the soil, a common occurrence when using wastewater with high Na^+ concentrations, may be the cause of this behavior. Na^+ accumulation can increase soil salinity, affecting soil composition and, consequently, the roots' ability to absorb water and nutrients (Dagianta et al., 2014).

In greenhouse studies, although variability is also observed, the controlled environment seems to buffer some negative effects. However, the dispersion in yields suggests that even under optimal conditions, an excess of Na^+ or K^+ can reduce the efficiency of other essential nutrients' absorption. This result is consistent with the literature, where excess soil salts have been associated with reduced hydraulic conductivity and water availability for plants, potentially leading to induced water stress, even in soils with sufficient moisture (Chtouki et al., 2024; Rápalo-Cruz et al., 2024).

NH_4^+ is an essential nutrient in soil nitrification and ammonification. In greenhouses, its behavior is more predictable, leading to stable yields when recommended thresholds are met. In open-field conditions, studies that do not adhere to these recommendations show greater yield variability, likely due to NH_4^+ volatilization or its conversion to NO_3^- under

suboptimal conditions (Hurtado et al., 2024). Cl^- and SO_4^{2-} are necessary in small concentrations but can be harmful when they are present in large amounts. In field conditions, for instance, high Cl^- concentrations may be related to soil salinization, reducing the roots' ability to absorb water and causing osmotic stress in plants (Ahmed et al., 2024). In greenhouse studies, while variability in yields is also observed, it is smaller, suggesting that the controlled environment may mitigate some of the negative effects of salt accumulation, allowing for more efficient nutrient management (Dousova et al., 2016; Michael et al., 2015).

Finally, from the graphs obtained by analyzing the studies, micronutrients such as Zn, Cu, and Mn, while having a lower impact compared to macronutrients, show lower variability in both environments. This observation suggests that their concentration in wastewater may be more constant over time (Masunaga and Marques Fong, 2018; Plaza et al., 2021). This stability could be attributed to their lower solubility or reduced reactivity in wastewater treatment systems, often resulting in more predictable residual concentrations (Chauhan and Kumar, 2020).

In addition, plants require these elements in significantly lower quantities compared to macronutrients, which may further contribute to the observed stability in their uptake patterns (Ahmed et al., 2024). Previous studies have shown that the accumulation of these micronutrients in soils fertigated with wastewater tends to remain within relatively stable ranges, without significantly affecting the absorption of other essential elements (Bindraban et al., 2020; Vandecasteele et al., 2018). However, the appropriate concentration of these micronutrients is crucial to avoid both deficiencies and toxicities that can compromise vital processes such as protein synthesis and plant energy metabolism.

3.3. Correlation between yield and crop type

Fig. 4 presents the result of a thorough analysis of the yield reported in the reviewed studies, categorized by crop type. It illustrates the distribution of agricultural outputs for different crop categories under fertigation. The graphical representation indicates significant variability in yields across several crop types. It can be noted that crops such as fruits and vegetables show a higher variability in yields throughout the assessed articles, indicating a more sensitive reaction to the chemical composition of wastewater (Ali et al., 2024). These crops, which have elevated nutritional demands, exhibit greater variability in yield, suggesting that the efficacy of fertigation with wastewater may be enhanced.

This variability is largely influenced by the interactions among different ionic species present in the wastewater. Essential macronutrients such as N, P, and K interact dynamically, affecting their bioavailability and uptake efficiency (Chauhan and Kumar, 2020). High Na^+ concentrations, for instance, can induce antagonistic effects, particularly limiting K^+ absorption due to competitive inhibition at the root level (Yasuor et al., 2017). This phenomenon is critical for K^+-dependent crops like tomatoes and peppers, where K^+ plays a key role in enzymatic activation and osmotic regulation (Nikolaou et al., 2021). Furthermore, imbalances in the Ca^{2+}: K^+ ratio can weaken cell wall structure, increasing susceptibility to biotic stressors and physiological disorders (Alves et al., 2017). Mg^{2+} plays a key role for chlorophyll synthesis, influencing yield outcomes, while an excess of SO_4^{2-} can potentially reduce PO_4^{3-} solubility in soil, further impacting nutrient uptake (Bindraban et al., 2020; Ibrahim et al., 2022).

Crop categories including grains and legumes demonstrate less yield variability, suggesting that these crops are more resilient to variations in the chemical composition of wastewater. This could be due to their ability to adapt to varying nutritional conditions or their lower dependence on certain essential nutrients compared to other plants (Dutta et al., 2022). The increased stability observed in these groups may indicate improved nutrients' utilization, thus reducing their dependence on external factors.

The yields variability observed in certain crops may also be affected by the soil or environmental conditions, including greenhouse and field crops. As previously stated, factors such as N retention capacity, leaching, and soil pH significantly influence nutrients' availability and in turn agricultural productivity (Yasuor et al., 2020). Still, this resilience does not necessarily imply optimal growth conditions. While cereals and legumes may exhibit lower yield fluctuations, their ability to maintain stable productivity might be linked to long-term physiological adaptations, including modifications in root exudation patterns and rhizosphere interactions that influence nutrient solubilization and microbial activity (Arcas-Pilz et al., 2021; Ibrahim et al., 2022). The presence of certain ions, particularly in excess, can trigger adaptive mechanisms such as increased root biomass allocation or differential expression of transport proteins, allowing these crops to cope with fluctuations in nutrients' availability (Hashmat et al., 2021). Nevertheless, these

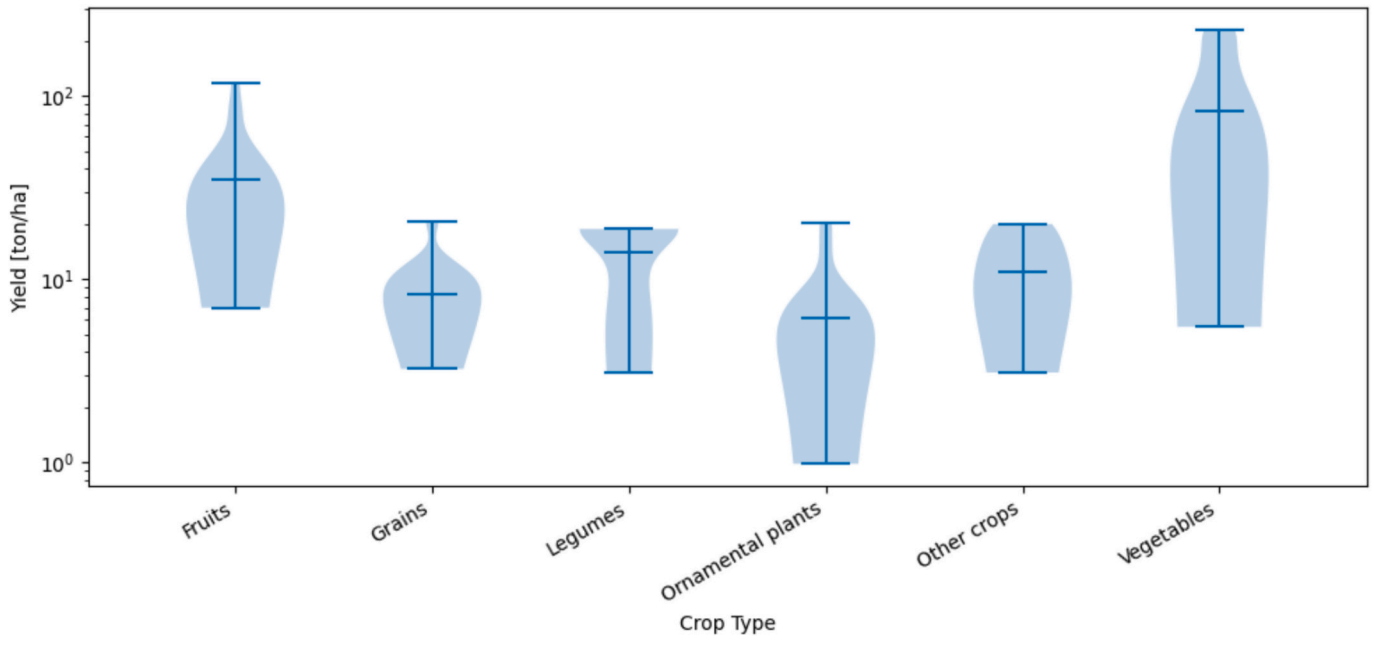


Fig. 4. The violin plots show the yields (ton/ha) for different crop groups under fertigation with wastewater.

adaptations may not be sufficient under prolonged exposure to imbalanced ionic compositions, warranting further investigation into the cumulative effects of wastewater fertigation on soil-plant dynamics (Gava et al., 2023; Plaza et al., 2016).

Some plants can be stressed by the type of wastewater used in fertigation. This stress response is not only linked to the absolute concentration of nutrients but also to their relative proportions and temporal availability. Crops with high metabolic demands require precise nutrient ratios at different developmental stages, and deviations from optimal concentrations can trigger physiological imbalances, reducing nutrients' use efficiency. For example, an excess of NH_4^+ relative to NO_3^- can acidify the rhizosphere, altering root respiration and microbial community structure, further impacting nutrients' assimilation. This shows the relevance of carefully control the chemical composition in soil to obtain better productivity results and maintain high yields. By incorporating a deeper understanding of ion interactions and plant physiological responses, fertigation strategies can be optimized to minimize nutrients' antagonism, prevent soil degradation, and enhance yield stability across different cropping systems (Azad et al., 2020; Chauhan and Kumar, 2020). Studies have demonstrated that different irrigation techniques and N management strategies can significantly influence soil quality and nutrients' efficiency, impacting long-term agricultural sustainability (Demir and Özbahçe, 2021). Future research should focus on developing predictive models that account for seasonal variations in wastewater composition and their long-term effects on plant health and productivity, ensuring more sustainable and effective wastewater reuse in agriculture (Jeong et al., 2020).

3.4. Effect of the water source on yield

The results obtained from the analysis of the agricultural yield in the reviewed articles are presented in Table 3 and Fig. 5. These indicate that crops irrigated with domestic wastewater exhibit higher yields, with an average of 62.31 tons/ha and a median of 33.57 tons/ha. The high yield observed can be attributed to the abundant presence of essential macronutrients for plant growth, such as N, P, and K^+ in various bioavailable forms, which can partially meet crop nutritional needs (Rietra et al., 2022).

The classification of domestic wastewater is critical, as untreated wastewater, despite its high nutrient content, poses risks due to organic load, pathogens, and heavy metals (Silva et al., 2016). It frequently exceeds permissible limits for COD, BOD, and microbial contamination under EU legislation 2020/741 (Jiménez-Benítez et al., 2020; Penserini et al., 2024). Additionally, emerging contaminants and persistent organic pollutants may accumulate in soil and enter the food chain, making untreated wastewater unsuitable for safe agricultural use (Hänel et al., 2022; Tzortzakis et al., 2020).

In comparison, crops irrigated with industrial effluents show an average yield of 15.95 tons/ha, suggesting that nutrient concentrations are insufficient to fully meet crop requirements without additional fertilization (Chojnacka et al., 2020).

Analyzing the composition of water used in irrigation systems reveals that its origin directly influences its chemical and nutritional properties. Domestic wastewater contains organic matter and essential plant nutrients derived from food waste and human metabolism byproducts, giving it significant agronomic potential (Libutti et al., 2018). In contrast, industrial effluents come from treatment processes that remove a large portion of organic and inorganic compounds, lowering its nutrient content but also reducing the presence of unwanted contaminants (Elgallal et al., 2016; Mainardis et al., 2022). Meanwhile, effluents such as drainage water and leachates have a highly variable composition, reflecting the accumulation of nutrients, salts, and potentially toxic elements (PTEs) from agricultural runoff, industrial discharges, and other human activities, which does not make them optimal for irrigation in most cases (Rezapour et al., 2021).

The detailed analysis of water quality used in these irrigation systems reinforces the idea that domestic wastewater provides adequate concentrations of essential inorganic ions, such as NO_3^- and PO_4^{3-}, optimizing crop growth without causing significant nutritional imbalances. Additionally, it has been demonstrated that using reclaimed wastewater can reduce the need for commercial fertilizers, thereby decreasing energy demand and greenhouse gas emissions (Barbosa et al., 2022), contributing to more sustainable agriculture (Perulli et al., 2019). Although, the long-term impact of using wastewater from different sources must be carefully considered. While nutrient-rich effluents, like domestic wastewater, may initially enhance crop productivity, prolonged use can lead to unintended consequences, such as soil nutrient imbalances, salinity accumulation, and alterations in microbial communities (Coelho et al., 2020). The high Na^+ and Cl^- concentrations in industrial effluents, for instance, pose a significant risk of osmotic stress, which reduces plant water uptake and can lead to yield decline over time (Yasuor et al., 2020). Furthermore, heavy metals and emerging contaminants present in certain wastewater types may gradually accumulate in soil, affecting soil fertility and food safety (Tzortzakis et al., 2020). Although fertigation employing wastewater shows many advantages, there is still a chance that water contaminants, like PTEs will accumulate in soil. This is a critical concern that must be managed properly (Dagianta et al., 2014). The presence of elements such as Cu, Zn, and As, particularly in drainage effluents and leachates, suggests a potential risk of soil contamination that could compromise long-term

Table 3
Summary of median and average chemical composition (mg/L) and crop yields (ton/ha) by irrigation water type from the systematic review.

	Median			
Type of water	Domestic wastewater	Drainage effluents	Leachates	Industrial effluents
Yield[ton/ha]	33.57	5.58	5.66	9.49
Compound				
NO_3^- [mg/L]	16.59	285.8	328.6	236.0
PO_4^{3-}[mg/L]	13.30	54.13	31.70	123.7
Cl^-[mg/L]	257.50	17.73	443.2	358.7
SO_4^{2-}[mg/L]	165.1	120.1	307.2	348.6
K^+[mg/L]	29.8	982.4	136.84	113.1
Na^+[mg/L]	135.7	204.8	345.0	138.4
P[mg/L]	11.46	57.73	45.00	17
N[mg/L]	60.00	286.9	900.0	84.34
NH_4^+[mg/L]	18.04	18.04	n.d*	118.7
Cu[mg/L]	0.05	1.63	0.02	2.38
Zn[mg/L]	0.29	0.55	0.02	4.11
Mg^{2+}[mg/L]	24.31	48.49	6.46	76.2
As[mg/L]	0.02	0.67	n.d*	n.d*
COD [mg/L]	163.1	n.d*	n.d*	1135.52
BOD [mg/L]	55.5	n.d*	n.d*	764.5
Average				
Yield[ton/ha]	62.31	6.95	4.45	15.95
Compound				
NO_3^- [mg/L]	143.8	368.0	385.0	326.6
PO_4^{-3}[mg/L]	25.71	54.13	60.59	150.9
Cl^-[mg/L]	281.5	17.73	467.9	565.1
SO_4^{2-}[mg/L]	388.6	120.1	658.0	631.0
K^+[mg/L]	67.53	2052	332.6	304.9
Na^+[mg/L]	149.6	339.7	573.3	307.8
P[mg/L]	12.55	80.29	45.00	78.25
N[mg/L]	54.7	591.3	900.0	143.0
NH_4^+[mg/L]	36.17	23.06	n.d*	377.8
Cu[mg/L]	0.20	3.01	0.06	3.19
Zn[mg/L]	2.03	0.58	0.43	6.60
Mg^{2+}[mg/L]	37.84	80.66	10.42	105.5
As[mg/L]	0.02	0.82	n.d*	n.d*
COD [mg/L]	743.31	n.d*	n.d*	1717.98
BOD [mg/L]	147.67	n.d*	n.d*	865.47
Total Studies	28	8	8	21

* *n.d = this information has not been found in the reviewed articles.*

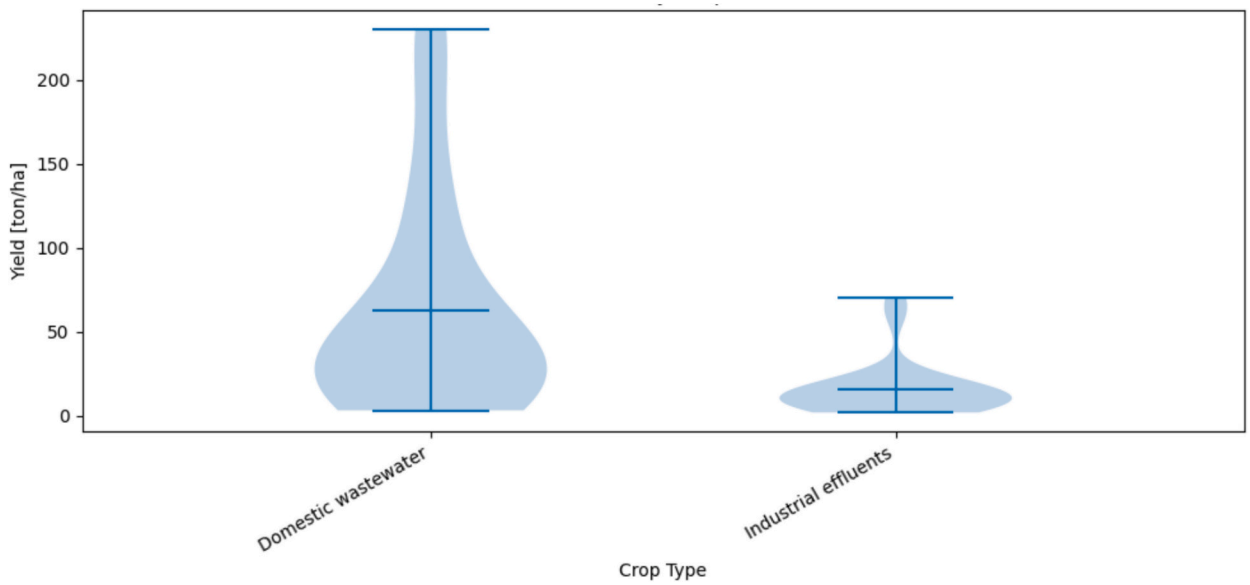


Fig. 5. The violin plots illustrate the yield dispersion (ton/ha) when using domestic wastewater and industrial effluents, highlighting variations for different crop types.

agricultural sustainability (Dousova et al., 2016). Variations in metal concentrations between different wastewater sources indicate that their origins and treatment methods play a crucial role in determining their suitability for fertigation (Rezapour et al., 2021). The accumulation of these compounds, particularly in fields irrigated with leachates and drainage effluents, could decrease productivity and jeopardize food safety due to the bioaccumulation of PTEs in agricultural products (Libutti et al., 2018; Naveed et al., 2018).

Treated wastewater can supply between 50 % and 100 % of the N and P requirements in crops such as wheat and maize, reducing production costs and greenhouse gas emissions (Lahlou et al., 2021; Maestre-Valero et al., 2019). However, the results of this review indicate that the N/P ratio (Table 3) in these effluents is unbalanced according to the needs for crops. This imbalance can affect fertigation efficiency, as N is generally sufficient to meet crop needs, while P may be inadequate without additional supplementation (Penserini et al., 2024).

In domestic wastewater, for example, the average N concentration (54.7 mg/L) is considerably higher than that of P (12.55 mg/L) and during treatment this gap tends to increase reflecting differences in the transformation and retention processes of these nutrients. While N, primarily in soluble forms such as NO_3^-, is highly mobile and remains in treated effluents at high concentrations, P tends to precipitate and adsorb, especially in the presence of coagulants used to remove solids (Chauhan and Kumar, 2020).

The insufficient reporting on wastewater treatment levels in most of the reviewed studies hinders the establishment of clear correlations between treatment processes and their effects on fertigation. 36 % of the articles analyzed did not report whether the water had been treated, while 64 % provided details. Regarding treatment levels, 37 % of the studies indicated that no treatment had been conducted, 16 % reported the application of primary treatment, 28 % mentioned secondary treatment, and 19 % referred to tertiary treatment. This omission represents a significant limitation, since the quality of wastewater used in irrigation directly depends on the treatment received.

Nevertheless, the average and median values of macronutrients reported in Table 3 suggest that domestic wastewater tended to present lower concentrations of NO_3^-, PO_4^{3-}, and K^+, suggesting that, in several cases, these waters could have been subjected to some level of treatment, although this was not explicitly reported. When considering domestic wastewater, 25 % of the studies indicated no treatment, 7 % reported primary treatment, 39 % referred to secondary treatment, and 29 % mentioned tertiary treatment. In contrast, industrial effluents showed relatively high concentrations of these nutrients, suggesting that treatment processes did not always result in a uniform reduction of key compounds for soil fertility (Mainardis et al., 2022). Within this category, 38 % of the cases reported no treatment, 33 % indicated primary treatment, 21 % referred to secondary treatment, and 8 % documented tertiary treatment.

Leachates and drainage effluents showed high variability in nutrient concentrations, with high dispersion likely influenced by factors such as localized fertilizer accumulation and variable runoff dynamics (Dousova et al., 2016). The absence of data on the treatment of these water sources hinders their accurate characterization and limits the assessment of their suitability for agricultural use. The significant proportion of studies that did not report treatment levels shows the necessity for more accurate and standardized documentation to better assess the implications of wastewater reuse in fertigation.

3.5. Correlation between soil type and yield

Soil texture is a critical factor influencing the retention and release of nutrients in the context of fertigation with wastewater. This textural variability, reflected in different combinations of sand, silt, and clay, directly affects the efficiency of nutrient supply and, consequently, agricultural productivity (Elgallal et al., 2016).

The reviewed studies indicate that nutrient supply through wastewater depends on soil heterogeneity, impacting crop yields. While clay and silt soils show higher nutrient retention due to their heterogeneous dual-domain structure, sandy soils, considered more homogeneous, tend to increase NO_3^- leaching, especially under high rainfall conditions, reducing nutrients' efficiency. This phenomenon, widely documented, is particularly significant in soils with low nutrient retention capacity, where essential compounds for plant growth are lost (Ogbenna and Tesfamariam, 2023). The rapid movement of NO_3^- through the soil profile limits its availability to plants, leading to variations in agricultural yield.

On the other hand, clayey soils, which have higher water and nutrient retention capacities, enable more stable nutrient absorption, potentially contributing to more consistent crop yields (Śpitalniak et al., 2021). However, this type of soil also presents an elevated risk of salt accumulation when nutrient-rich irrigation water is used. According to Tahir and Marschner (2017), soils with high cation exchange capacity,

typical of clayey soils, are effective at retaining specific nutrients like NH_4^+. However, this retention capacity may lead to salinization issues, which, in turn, affects soil structure and its ability to retain both nutrients and water (Yasuor et al., 2017). Moreover, salt accumulation can induce osmotic stress and ionic toxicity in plants, reducing photosynthetic capacity and, consequently, crop growth (Khan et al., 2022).

Fig. 6 presents a soil texture diagram that classifies and distributes soils used in the studies included in this systematic review. A marked diversity is observed in the percentages of sand, silt, and clay across the different studies, revealing extensive textural variability.

Although this texture-focused approach provides fundamental information to explain the physical dynamics of nutrient retention, future research should also incorporate the analysis of soil fertility and biological activity to obtain a more comprehensive view of their response to fertigation provided by wastewater (Coelho et al., 2018; Haddon et al., 2023; Hashmat et al., 2021). Aspects such as the presence of robust microbial communities and the amount of available organic matter play a key role in essential processes such as nitrification and P solubilization, favoring better nutrient utilization and higher agricultural yields (Moursy et al., 2022; Tzortzakis et al., 2020). In contrast, soils with low organic matter content or impoverished microbial communities may present greater nutrient leaching or immobilization, which would reduce the efficiency of fertigation (Savvas et al., 2023).

Integrating these variables (cation exchange capacity, key nutrient content, and microbial diversity, among others) in future studies will allow a more accurate understanding of the effects of physical, chemical, and biological factors on soil interaction in agricultural productivity and will contribute to the design of management strategies that optimize the use of wastewater in fertigation, thus minimizing risks such as salinization and contamination by excess nutrients (Chtouki et al., 2024).

4. Conclusions

The concentration of inorganic ions in wastewater used for fertigation exerts a considerable influence on the performance of various crops, both under field and greenhouse conditions. The results indicate that crop yields are more consistent and generally higher in controlled environments, such as greenhouses. This is because inorganic ions, especially NO_3^- and PO_4^{3-}, are better absorbed by plants. However, under field conditions, crop yields exhibit greater variability due to exogenous factors such as leaching and mineralization, which affect nutrients' availability. This behavior emphasizes the need for careful nutrients' management in open agricultural environments, where natural soil processes and changing environmental conditions can make challenging to ensure efficient nutrients' absorption by plants. To mitigate these uncertainties, site-specific fertigation strategies should be developed, integrating real-time soil monitoring and adaptive nutrients' dosing to optimize plant uptake while minimizing environmental risks.

In terms of compliance with the quality standards for wastewater used in fertigation, the findings indicate that while certain essential inorganic ions, such as NO_3^- and PO_4^{3-}, fall within the limits recommended by FAO, others, such as Na^+ and K^+, often exceed the suggested thresholds. This non-compliance adversely affects agricultural productivity, particularly in crops sensitive to salinity. The elevated concentration of Na^+ and Cl^- in wastewater, associated with increased soil salinization, generates osmotic stress in plants, reducing their ability to absorb water and other essential nutrients. This indicates that although wastewater may satisfy a portion of crop nutrients' requirement, its extended use without appropriate management could compromise both agricultural productivity and the long-term sustainability of soil health. To counteract these negative effects, strategies such as periodic freshwater irrigation cycles and crop rotation with salt-tolerant species should be considered to maintain soil structure and mitigate salinity buildup.

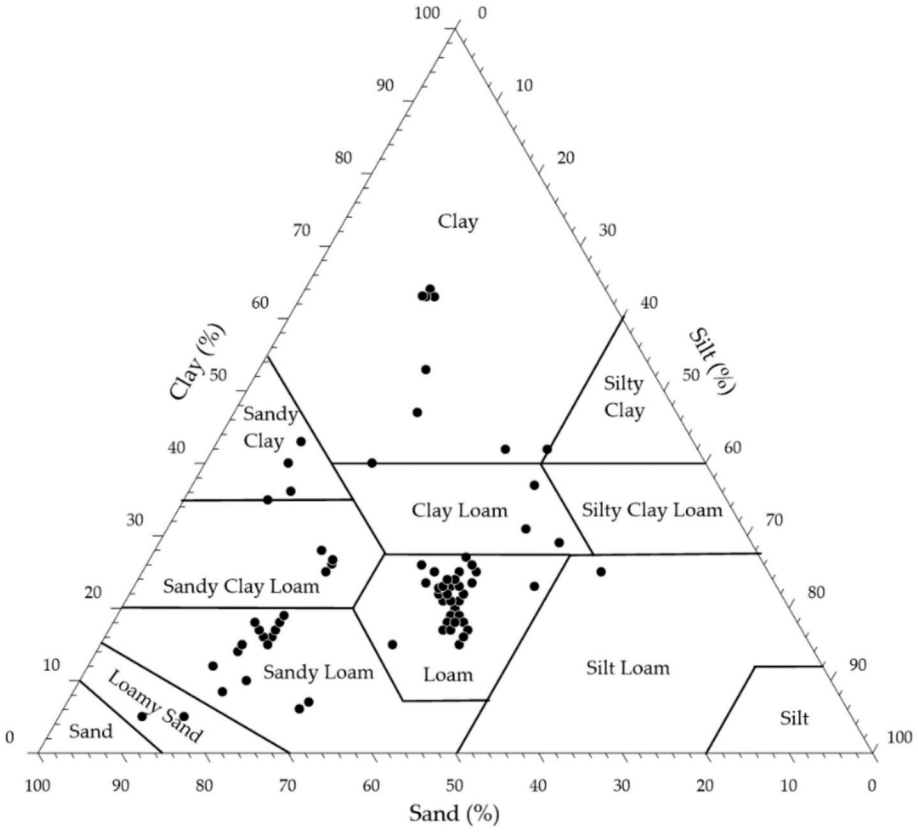


Fig. 6. Soil textural triangle displaying the classification and distribution of soil samples evaluated in this systematic review.

The correlation between nutrients' concentrations in wastewater and agricultural productivity also exhibits significant variation depending on soil type and cultivation conditions. NO_3^- leaching is more pronounced in sandy soils, reducing the availability of this essential nutrient for plants, potentially affecting yields and posing a threat to the environment. In contrast, crops yield in clayey soils characterized by a higher nutrient retention capacity may be more stable. However, the risk of salt accumulation is elevated, which could lead to salinization issues and long-term degradation of soil quality.

The recent update to the Urban Wastewater Treatment Directive (EU 2024/3019) establishes more stringent limits on inorganic contaminants, prompting the adoption of advanced treatment technologies such as membrane filtration, ozonation, and granular activated carbon filtration. These processes enhance water quality and facilitate its reuse; however, they can also alter nutrients' concentration, potentially affecting their suitability for agricultural fertigation. While the reduction in nutrients is not always substantial, it remains a factor to consider when optimizing wastewater reuse strategies.

The findings from this systematic review highlight the critical importance of adapting fertigation practices to the specific characteristics of soil types as well as crop growing conditions to maximize the benefits of wastewater use in agriculture. Future research should focus on optimizing fertigation protocols through precision agriculture techniques, evaluating microbial responses to wastewater irrigation, and assessing long-term impacts on soil health to ensure both productivity and environmental sustainability. Additionally, it is crucial to investigate the effects of advancements in wastewater treatment, particularly the implementation of nutrients' recovery and selective separation processes, on the suitability of industrial effluents for fertigation.

CRediT authorship contribution statement

Aahilyn Osorio: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Antonio Panico:** Writing – review & editing, Validation, Supervision, Conceptualization. **Gianluigi Busico:** Writing – review & editing, Validation, Methodology, Investigation. **Micòl Mastrocicco:** Writing – review & editing, Validation, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179257.

Data availability

Data will be made available on request.

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