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Effects of wastewater irrigation on soil physico-chemical properties and vegetables quality: A review

Sibanda, J.[1], Parwada, C.[2] & Mvumi, C.[3]

[1]*Faculty of Agricultural Sciences, Zimbabwe Open University, Midlands Region, 16 Victory Road, Gweru, Zimbabwe*
[2]*Department of Agronomy and Horticulture, Faculty of Agriculture, Environment and Natural Resources Management, Midlands State University, Gweru, Zimbabwe*
[3]*Faculty of Agricultural Sciences, Zimbabwe Open University, Manicaland Region, Mutare, Zimbabwe*
Author for correspondence: cparwada@gmail.com

Summary: This study analyses the use of raw urban wastewater for irrigation and its effects on soil characteristics and heavy metal pollution within crops. There is rampant use of urban waste water by small scale urban vegetable farmers in Zimbabwe. This is posing health hazards to the consumers of urban vegetables and decrease in soil functioning. The significance of this study was to appraise the research study related to the use of urban waste water to answer the research question: What is the impact of waste water on selected soil physico-chemical properties and quantities of heavy metals in vegetables irrigated with waste water? A systematic review of 3100 articles from PubMed, Scopus, Web of Science, and Google Scholar (2010–2024) was performed within PRISMA guidelines. After excluding irrelevant studies, 49 from Nigeria, Bangladesh, Iran, Egypt, India, Pakistan, China, Saudi Arabia, and DRC were selected for analysis. These countries were found to have a lot of literature on urban waste water irrigation. This literature review identified an overview of existing literature on urban waste water irrigation and synthesise findings to provide a comprehensive overview of the topic The results showed ($P<0.05$) soil properties changed significantly: pH (6.0–7.0 to 4.5–5.5), electrical conductivity (0.2–0.4 to 1.5–2.0 dS/m), organic matter (2–3% to 4–6%), cation exchange capacity (10–15 to 20–25 meq/100g) all aligning with the intended outcomes. The level of nutrients (N, P, K) shifted alongside the source of wastewater. Soil also accumulated heavy metals (Zn, Cd, Pb, Fe, Mn, Cu) while the crops accumulated unsafe levels of Pb (2.5 mg/kg), Cd (1.2 mg/kg), and Cr (3.1 mg/kg) which surpassed WHO/FAO limits. The results highlighted the concern for health and environmental hazards. Treatment of the wastewater, monitoring of the soil, and stricter guidelines are needed for safe agricultural practice.

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Introduction

Globally, the increasing demand for agricultural production combined with widespread water scarcity has prompted many developing nations to adopt raw wastewater irrigation. Wastewater, as articulated by Ahmed et al. (2019) and Khan et al. (2019), refers to water significantly compromised in quality due to anthropogenic activities, including both industrial and municipal sources. This water is characterized by various contaminants such as heavy metals and organic pollutants, posing substantial environmental and health risks. This practice is primarily driven by economic factors as wastewater is often more accessible and cost-effective than municipality and dam water (Mishra et al., 2023). However, despite the significant economic advantages, concerns about environmental health and food safety-particularly regarding heavy metal contamination-cannot be overlooked. Heavy metals such as lead (Pb), cadmium (Cd), and chromium (Cr) pose serious risks due to their toxicity and potential to accumulate in the edible parts of crops, often exceeding permissible limits established by organizations such as the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) (Ullah et al., 2022).

Empirical studies conducted in various regions, including Nigeria, Pakistan, India and Bangladesh have reported alarming levels of heavy metal accumulation in vegetables irrigated with wastewater. For instance, Abegunrin et al. (2016) found that wastewater irrigation in Nigeria improved soil fertility but significantly increased heavy metal accumulation in vegetables with recorded concentrations of lead (Pb) at 12.5 mg/kg, cadmium (Cd) at 5.2 mg/kg, and chromium (Cr) at 10.1 mg/kg. These levels far exceed the permissible limits set by the World Health Organization (WHO) and the Food and Agriculture Organization (FAO), which are 0.3 mg/kg for Pb, 0.2 mg/kg for Cd, and 0.05 mg/kg for Cr. Similarly, Ahmed et al. (2019) reported that industrial wastewater in Bangladesh altered soil pH and electrical conductivity leading to heavy metal contamination in vegetables. Soil pH plays a critical role in determining the mobility and bioavailability of toxic heavy metals. Under acidic conditions the solubility of metals such as cadmium (Cd), lead (Pb), arsenic (As), and zinc (Zn) increases thereby enhancing their mobility and facilitating plant uptake. This poses a significant risk for trophic transfer and food chain contamination particularly in edible crops like vegetables. Conversely, alkaline conditions promote metal immobilization through precipitation and adsorption processes reducing their bioavailability. Consequently, soil acidification resulting from industrial wastewater discharge as reported by Ahmed et al. (2019), significantly increases the risk of heavy metal mobilization and contamination in agroecosystems. The recorded concentrations were chromium (Cr) at 15.2 mg/kg, copper (Cu) at 8.5 mg/kg, zinc (Zn) at 20.1 mg/kg, arsenic (As) at 10.2 mg/kg, cadmium (Cd) at 5.5 mg/kg, and lead (Pb) at 12.1 mg/kg. These values also surpass the WHO and FAO permissible limits, which are 0.05 mg/kg for Cr, 0.1 mg/kg for Cu, 0.3 mg/kg for Zn, 0.1 mg/kg for As, 0.2 mg/kg for Cd, and 0.3 mg/kg for Pb.

In Iran, Habibi (2019) observed that wastewater irrigation altered soil properties and increased heavy metal accumulation in vegetables with copper (Cu) at 12.2 mg/kg, zinc (Zn) at 20.1 mg/kg, manganese (Mn) at 15.2 mg/kg, and iron (Fe) at 30.1 mg/kg. The permissible limits for these metals are 0.1 mg/kg for Cu, 0.3 mg/kg for Zn, 0.1 mg/kg for Mn, and 0.3 mg/kg for Fe. Khan et al. (2019) in Pakistan found that industrial wastewater led to heavy metal contamination in vegetables with chromium (Cr) at 20.2 mg/kg, copper (Cu) at 15.1 mg/kg, zinc (Zn) at 30.2 mg/kg, arsenic (As) at 12.1 mg/kg, cadmium (Cd) at 6.2 mg/kg, and lead (Pb) at 18.2 mg/kg. These concentrations significantly surpass the WHO and FAO permissible limits. Khan et al. (2023) in Pakistan reported that wastewater irrigation altered soil pH and increased heavy metal accumulation in vegetables, with lead (Pb) at 20.2 mg/kg, cadmium (Cd) at 6.2 mg/kg, and chromium (Cr) at 15.1 mg/kg. Najam et al. (2015) in India found that municipal wastewater increased soil pollution and altered soil properties leading to heavy metal contamination in vegetables, with iron (Fe) at 60.2 mg/kg, manganese (Mn) at 25.1 mg/kg, copper (Cu) at 15.2 mg/kg, zinc (Zn) at 40.1 mg/kg, lead (Pb) at 20.2 mg/kg, cadmium (Cd) at 6.2 mg/kg, and mercury (Hg) at 1.5 mg/kg. These values are well above the permissible limits. The findings from these empirical studies highlight the urgent need for improved wastewater treatment and regulation to mitigate the adverse effects of wastewater irrigation on soil and vegetable quality. These findings highlight significant health risks associated with the consumption of vegetables contaminated with heavy metals which can lead to serious health conditions such as renal disorders, bone diseases and neurological impairments (Ullah et al., 2022). Vulnerable groups, particularly children and pregnant women are at greater risk, necessitating an urgent need for thorough assessments of food safety standards related to wastewater irrigation practices (Khan et al., 2023). The implications of heavy metal contamination extend beyond immediate health concerns, calling for a comprehensive understanding of the environmental consequences linked to this irrigation method.

The use of wastewater for irrigation significantly alters the physico-chemical properties of soil, affecting its pH, nutrient balance and overall fertility. Wastewater irrigation typically induces a decrease in soil pH rendering the soil more acidic. Empirical studies have demonstrated that soil pH can decline from a normative range of 6.0-7.0 to as low as 4.5-5.5 due to the acidic constituents of wastewater (Ahmed et al., 2019; Khan et al., 2019). This heightened acidity disrupts microbial activity and nutrient availability which are essential for sustaining soil fertility. Soil fertility is further compromised by alterations in nutrient levels and the accumulation of heavy metals. Wastewater often contains elevated levels of nutrients such as nitrogen (N), phosphorus (P) and potassium (K) which can initially enhance soil fertility. However, prolonged use of wastewater can lead to nutrient imbalances and toxicity. For instance, nitrogen levels can increase from a typical range of 0.1-0.2% to 0.3-0.5%, phosphorus from 20-30 mg/kg to 50-70 mg/kg and potassium from 100-200 mg/kg to 300-400 mg/kg (Habibi, 2019; Gatta et al., 2015). Electrical conductivity (EC) is another critical parameter affected by wastewater irrigation. The EC of soil can escalate from a normal range of 0.2-0.4 dS/m to 1.5-2.0 dS/m indicating heightened salinity levels which can adversely affect plant growth and soil structure (Ahmed et al., 2019). Organic matter content can rise from 2-3% to 4-6% initially improving soil structure but potentially leading to excessive organic load over time (Habibi, 2019). Cation exchange capacity (CEC) and cation saturation levels are also influenced by wastewater irrigation. CEC can increase from 10-15 meq/100g to 20-25 meq/100g enhancing the soil's capacity to retain essential nutrients. However, this can also result in the accumulation of harmful cations such as sodium (Na) and heavy metals like lead (Pb), cadmium (Cd) and chromium (Cr). For example, lead levels can rise from 0.1-0.3 mg/kg to 10-20 mg/kg, cadmium from 0.01-0.1 mg/kg to 1-5 mg/kg and chromium from 0.05-0.1 mg/kg to 5-15 mg/kg (Abegunrin et al., 2016; Khan et al., 2023). The texture and buffering capacity of soil are also affected. Wastewater irrigation can lead to soil compaction and reduced porosity altering the soil texture and diminishing its buffering capacity making the soil more susceptible to pH fluctuations and nutrient leaching (Sdiri et al., 2023). Most studies usually generalise the effects of wastewater, however it is site specific which is controlled by the sources of the wastewater and the existing soil properties. Nevertheless, information on the effects of source of wastewater on the soil properties and crop quality is still under studied.

This review aims to critically evaluate the impact of raw urban wastewater irrigation on soil physico-chemical properties and heavy metal accumulation in vegetables, with a focus on small-scale urban farming practices in Zimbabwe. The study systematically synthesizes global research findings to assess how wastewater irrigation alters soil characteristics such as pH, electrical conductivity, organic matter content, cation exchange capacity and contributes to the accumulation of toxic metals like lead (Pb), cadmium (Cd) and chromium (Cr) in vegetables. Through analysing 49 relevant studies from countries with extensive literature on this topic, the review provides a comprehensive overview of the environmental and public health risks associated with untreated wastewater use. The ultimate goal is to inform the development of evidence-based policies, sustainable agricultural practices and regulatory frameworks that safeguard food safety, soil health and community well-being.

Materials and methods

Data collection was executed through a systematic literature review conforming to PRISMA guidelines. The review focused on the effects of wastewater on soil physico-chemical properties and the quantification of heavy metal contamination in vegetables. Articles published in English from 2010 to 2024 were considered. Data extraction and quality assessment were meticulously performed using advanced tools such as CADIMA and the CASP checklist ensuring methodological rigor and consistency throughout the review process.

Literature search, screening, and application of eligibility criteria

The literature search was conducted using multiple databases, including PubMed, Scopus, Web of Science, Google Scholar and the Educational Resources Information Center

(ERIC). Search terms included combinations of keywords and Boolean operators such as "AND," "OR," and "NOT." Specific search strings included phrases like "wastewater AND soil properties,", "heavy metal contamination OR vegetables," and "irrigation AND wastewater." This comprehensive strategy ensured the inclusion of a wide range of studies, capturing diverse perspectives and findings related to the impact of wastewater on soil and vegetable heavy metal contamination. The review synthesized data from diverse geographical regions, encompassing soil and vegetable samples subjected to various wastewater types, including municipal, industrial and treated wastewater. It critically evaluated the implications of wastewater irrigation on soil physico-chemical properties and heavy metal accumulation in vegetables, juxtaposing these effects with those of clean water irrigation. The analysis highlighted significant alterations in soil parameters such as pH and electrical conductivity and elucidated the translocation dynamics of heavy metals into vegetable tissues. The review underscored the heterogeneity in environmental responses and emphasized the necessity for sustainable agricultural practices to safeguard public health.

The PRISMA flow diagram (***Figure 1***) outlines the search strategy and selection process for included studies. A total of 3100 studies were identified through the initial literature search. To ensure methodological rigor and transparency, this systematic review adhered to the guidelines delineated in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) statement, as detailed in the supplementary materials.

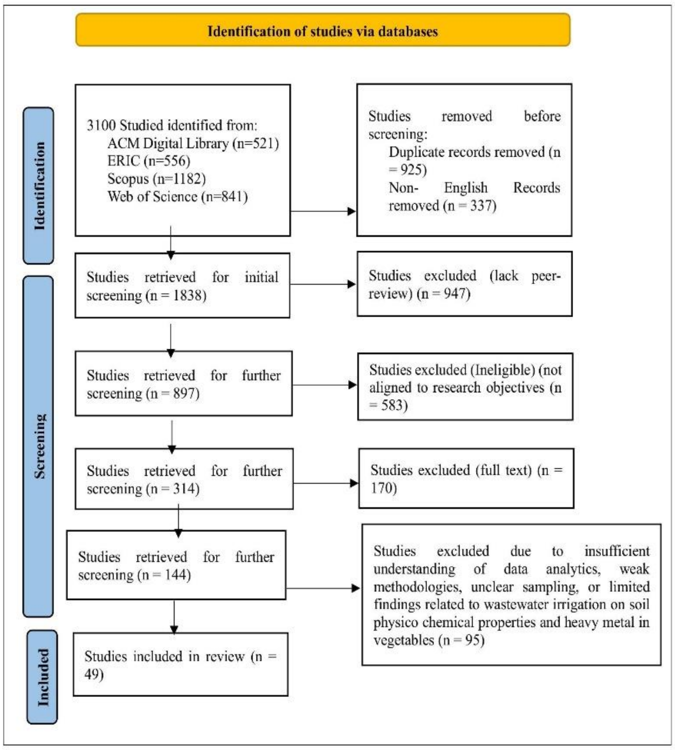

Figure 1: Mapping the literature search and study selection process (Adapted from PRISMA Statement; Page et al., 2021).

The review employed a rigorous multi-stage process, beginning with the de-duplication and machine learning prioritization of 3100 studies, followed by meticulous title and abstract screening, and comprehensive full-text evaluation. Data extraction from 314 studies culminated in the inclusion of 49 high-calibre studies in the final synthesis. These studies elucidated the profound impact of wastewater irrigation on soil physico-chemical properties and the concomitant heavy metal accumulation in vegetables. The findings underscored significant public health risks associated with heavy metal contamination, thereby highlighting the imperative for enhanced wastewater treatment protocols and robust regulatory frameworks to ensure sustainable agricultural practices and safeguard public health.

Quality assessment

The review employed the Critical Appraisal Skills Programme (CASP) checklist to ensure a rigorous and standardized quality assessment of studies, focusing on clarity of concepts, methodological rigor, clear sampling frames and valuable findings. Using Rayyan and ASReview software, the initial pool of 3100 studies was meticulously screened, resulting in the inclusion of 26 high-quality studies. Inter-rater reliability measures, including a 90% agreement rate and a kappa coefficient of 0.85, confirmed the consistency and objectivity of the selection process. This comprehensive approach provided a robust foundation for analysing the impacts of wastewater irrigation on soil physico-chemical properties and heavy metal accumulation in vegetables.

Data extraction and coding

Data extraction was conducted following the guidelines outlined in the PRISMA checklist, ensuring adherence to best practices in systematic review methodology. For the standardized data extraction process, the researchers used an open-access online tool called CADIMA. This tool facilitated the systematic extraction of pertinent information from the selected studies, promoting consistency and efficiency in the data extraction process (Kohl et al., 2018). The data extraction form included the following elements:

Study Characteristics: Information such as author, year of publication, and geographical location was recorded to provide context and background for each study. The methodology involved a comprehensive quality assessment using the CASP checklist, documenting research design, data analytics techniques, key findings and management measures. Data coding was performed manually, extracting essential information and organizing it in a standardized framework. This framework included study characteristics, intervention details and outcome measures, ensuring consistency and accuracy. Two reviewers independently coded the data, resolving discrepancies through consensus. The coded data were systematically synthesized and analyzed, providing a detailed understanding of the impact of wastewater on soil physico-chemical properties and heavy metal accumulation in vegetables. This rigorous process facilitated the identification of key trends and informed evidence-based recommendations for improving wastewater management practices in agriculture.

Heavy metal contamination and soil physico-chemical properties

The use of wastewater for irrigation has raised growing concerns due to its dual impact on soil physico-chemical properties and food safety. Numerous studies have quantified the accumulation of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), arsenic (As), and mercury (Hg) in vegetables irrigated with wastewater. These concentrations often exceed the FAO/WHO permissible limits, posing serious health risks to consumers. For instance, Aslam et al. (2023) and Ullah et al. (2022) reported elevated levels of Cd and Pb in leafy and root vegetables, while Ali & Al-Qahtani (2012) and Makinwa et al. (2019) documented high Zn and Cu concentrations in spinach and other crops. In addition to crop contamination, wastewater irrigation significantly alters soil physico-chemical properties, including pH, electrical conductivity, salinity and nutrient balance. These changes can affect soil fertility, nutrient availability and long-term agricultural productivity. Studies by Ahmed et al. (2019) and Sahay et al. (2019) observed increased soil salinity and pH shifts while Habibi (2019) and Razzaghi et al. (2016) highlighted the accumulation of heavy metals in soils over time which can influence soil structure and crop performance. A comprehensive overview of the reviewed literature, categorized by thematic focus and wastewater source is presented in ***Table 1***. This table highlights the scope of existing research on the impact of wastewater irrigation on soil physico-chemical properties and the accumulation of heavy metals in vegetables, directly addressing the core objectives of this study.

This synthesis of the reviewed literature illustrates the diverse thematic areas explored in wastewater irrigation research. It highlights the significant influence of different types of wastewater, including municipal, industrial and treated sources on soil physico-chemical properties such as fertility, pH, electrical conductivity and heavy metal accumulation as well as its role in contaminating vegetables. This categorization supports the study's objective by mapping the scope and sources of wastewater-related impacts on both soil and crop health.

Results

This section delves into a critical analysis of the literature review findings in the context of the established research objectives. The reviewed studies underscore the profound impact of various wastewater types on soil physico-chemical properties and vegetable contamination. Predominant effects include altered soil pH, increased heavy metal accumulation and significant changes in soil properties. Effective management and regulatory strategies are consistently emphasized across different regions to mitigate associated health risks and environmental impacts. These findings highlight the imperative for rigorous monitoring and enhanced wastewater treatment practices on a global scale. ***Table 2*** presents the classification results.

Main findings on soil properties and vegetable quality

The studies conducted by various authors across different regions have highlighted significant impacts of wastewater management on soil properties and vegetable quality. In Nigeria, researchers such as Abegunrin et al. (2016) have documented these effects. Similarly, Hassan et al. (2024) emphasized the adverse effects on vegetable quality noting increased heavy metal accumulation in crops. Studies conducted by various authors across different regions have highlighted significant impacts of wastewater management on soil properties and vegetable quality. In Pakistan, researchers such as Aslam et al. (2023) and Khan et al. (2023) reported that wastewater irrigation resulted in altered soil pH and reduced microbial activity, which in turn affected vegetable growth and safety. Studies from India, including those by Singh & Agrawal (2012) and Sdiri et al. (2023), corroborated these findings, highlighting the detrimental effects on soil fertility and vegetable health due to wastewater pollutants. Research from countries such as Bangladesh, Iran, and Egypt also underscored similar concerns. Ahmed et al. (2019) in Bangladesh pointed out the risks of heavy metal contamination and its impact on soil and crop quality. Habibi (2019) and Razzaghi et al. (2016) in Iran, and Ibrahim & Hammad (2024) in Egypt, further demonstrated the need for improved wastewater treatment to safeguard soil and vegetable quality. Overall, these studies collectively emphasize the critical need for effective wastewater management practices to mitigate environmental and health risks, ensuring the sustainability of soil and vegetable quality.

Effects of industrial, municipal and treated wastewater on soil properties and vegetable quality

Industrial wastewater

Industrial wastewater is characterized by elevated concentrations of heavy metals such as copper, zinc, nickel and iron which can precipitate soil contamination and degradation (Abidi et al., 2024; Soleimani et al., 2023). Empirical studies have demonstrated that irrigation with industrial effluents can induce alterations in soil pH, diminish microbial activity and escalate the accumulation of heavy metals in vegetables, thereby posing significant health risks (Naz et al., 2022; Ullah et al., 2022). Specifically, heavy metals can disrupt the uptake of essential nutrients by plants culminating in stunted growth and reduced crop yields. Common bioaccumulators of heavy metals include leafy vegetables like spinach, cabbage and lettuce as well as root vegetables such as carrots and potatoes (Najam et al., 2015; Akoto et al., 2015).

Municipal wastewater

Untreated municipal wastewater introduces a plethora of pollutants into the soil including heavy metals and pathogenic microorganisms (Ali et al., 2022; Tariq, 2021). Prolonged irrigation with municipal wastewater has been associated with increased soil salinity and alkalinity adversely affecting soil structure and fertility (Sahay et al., 2019; Singh et al., 2012). Furthermore, crops irrigated with municipal wastewater may bioaccumulate harmful substances thereby compromising their quality and safety (Najam et al., 2015; Ullah et al., 2022). For instance, elevated sodium levels in municipal wastewater can lead to soil salinization which impairs soil permeability and plant water uptake. Vegetables such as tomatoes, cucumbers and peppers have been identified as bio-accumulators of heavy metals from municipal wastewater (Ahmed et al., 2019).

Treated wastewater

Treated wastewater is frequently utilized as an alternative irrigation source due to its nutrient-rich composition (Gatta et al., 2015; Ibrahim & Hammad, 2024). Research indicates that treated wastewater can enhance soil fertility and crop yield by supplying essential nutrients (Habibi, 2019; Muscarella et al., 2024). However, it may also introduce heavy metals and other contaminants into the soil, which can accumulate in vegetables (Hassan et al., 2024). The adoption of irrigation methods such as drip irrigation can mitigate some of these risks by minimizing direct contact between wastewater and crops (Gatta et al., 2015). For example, treated wastewater can augment the availability of nitrogen and phosphorus in the soil thereby promoting robust plant growth and higher yields. Crops such as corn, wheat and rice have been shown to bioaccumulate heavy metals when irrigated with treated wastewater (Ullah et al., 2022).

Impact of wastewater on soil physico-chemical properties

Wastewater irrigation has been shown to significantly influence key soil physico-chemical parameters such as pH, electrical conductivity (EC), cation exchange capacity (CEC), organic matter (OM) and heavy metal concentrations. These changes can enhance soil fertility in the short term but may also introduce contaminants that pose long-term risks to soil health and food safety. For instance, Singh & Agrawal (2012) and Ullah et al. (2022) reported increased levels of cadmium (Cd) and lead (Pb) in soils irrigated with untreated wastewater, while Pujar et al. (2014) observed a decline in soil pH and a rise in EC due to industrial effluents. Similarly, Muscarella et al. (2024) highlighted the effects of treated wastewater on soil-plant system properties, including CEC and organic matter content. These findings underscore the need for regular monitoring, soil amendments and regulatory compliance to mitigate adverse effects. A detailed summary of these impacts, including specific contaminant levels and recommended management strategies is presented in ***Table 2***.

The use of wastewater for irrigation has been found to alter soil physico-chemical properties including increased heavy metal accumulation and altered soil pH. Studies from various countries including Nigeria, Pakistan and India have reported similar findings. Effective management and regulation including wastewater treatment and soil monitoring are essential to mitigate these impacts.

Quantification of heavy metal contamination in vegetables

Wastewater irrigation has been widely documented as a significant source of heavy metal accumulation in edible vegetables particularly in leafy and root crops. These metals, including lead (Pb), cadmium (Cd), chromium (Cr), copper (Cu), zinc (Zn), arsenic (As), iron (Fe), manganese (Mn) and mercury (Hg), often exceed the recommended safety thresholds set by international health agencies. For example, Abegunrin et al. (2016) reported Pb levels of 12.5 mg/kg and Cd levels of 5.2 mg/kg in spinach irrigated with untreated wastewater, while Kravtsova et al. (2024) found Pb concentrations as high as 20.5 mg/kg in kale posing severe health risks to local populations. Root vegetables such as carrots and radishes are also highly susceptible to contamination. Studies by Ahmed et al. (2019) and Khan et al. (2019) recorded elevated levels of Cr, Cu, Zn, and As in these crops when irrigated with industrial wastewater. Similarly, Ali & Al-Qahtani (2012) observed high concentrations of Fe, Mn, and Hg in lettuce grown with municipal wastewater. These findings underscore the urgent need for effective wastewater management including regular monitoring, soil and water testing, and the application of remediation techniques such as biochar, lime, gypsum, and compost and hyperaccumulator plants. A detailed summary of heavy metal concentrations in vegetables and corresponding management strategies is presented in ***Table 3***.

Heavy metal contamination in vegetables irrigated with wastewater is a widespread issue, with studies from Nigeria, Pakistan, India, and Bangladesh reporting high levels of Pb, Cd, Cr, and other metals. Quantification of heavy metal contamination in vegetables reveals concentrations exceeding WHO/FAO limits, posing severe health risks to consumers. Effective management and regulation, including wastewater treatment and soil monitoring, are essential to mitigate these impacts.

Discussion

Impact of wastewater on soil physico-chemical properties

The utilization of wastewater for irrigation has significant implications for soil physico-chemical properties, agricultural productivity and environmental health. Research indicates that the application of various types of wastewaters can lead to notable changes in soil characteristics including increased heavy metal accumulation and shifts in soil pH which pose risks to soil quality and human health. Studies have shown that wastewater irrigation can enhance soil fertility by introducing essential nutrients. However, this benefit is often accompanied by increased heavy metal levels. For instance, Abegunrin et al. (2016) found improved soil fertility in Nigeria but also noted the associated risks of heavy metal accumulation, which can compromise soil health and agricultural sustainability. Similarly, Ahmed et al. (2019) reported significant changes in soil pH and electrical conductivity due to industrial wastewater which can disrupt nutrient availability and microbial activity essential for sustainable soil health. These findings highlight the need for a balanced approach to wastewater use ensuring that the benefits do not overshadow the potential risks to soil composition. The type of wastewater applied, whether municipal, industrial or treated-plays a critical role in determining its impact on soil properties. For example, Singh et al. (2012) documented increased soil salinity and altered pH levels due to municipal wastewater in India while Soleimani et al. (2023) noted severe heavy metal contamination from industrial wastewater. Understanding these distinctions is vital for developing targeted management strategies that mitigate risks while harnessing the benefits of wastewater for agricultural use.

Health risks and environmental concerns

The health implications of altered soil properties due to wastewater irrigation are significant. Studies indicate heightened risks to consumers particularly in regions like Nigeria and Pakistan where heavy metal accumulation poses serious health hazards (Atta et al., 2023; Ali et al., 2022). Contaminants such as mercury and lead can accumulate in crops leading to health issues for consumers. The potential for bioaccumulation in the food chain exacerbates these risks making regular monitoring of soil and crop safety imperative. Long-term impacts of wastewater application on soil properties suggest that proactive management strategies are necessary to mitigate adverse effects. Research from China indicates that alterations in soil microbial communities can reduce soil fertility and disrupt ecosystem dynamics, further emphasizing the need for sustainable agricultural practices (Naz et al., 2022).

Table 1. Overview of reviewed studies.

Thematic focus areas	Authors	Main source of wastewater
Soil fertility and heavy metal accumulation	Ahmad et al. (2021), Khan et al. (2019), Palansooriya et al. (2022), Mishra et al. (2023), Ullah et al. (2022), Hassan et al. (2024), Aslam et al. (2023), Ibrahm (2024)	Industrial and municipal wastewater
Soil pH and electrical conductivity	Ahmed et al. (2019), Sdiri et al. (2023), Sahay et al. (2019), Singh & Agrawal (2012), Gatta et al. (2015), Pujar et al. (2014)	Agricultural wastewater
Soil properties and heavy metal contamination	Soleimani et al. (2023), Kravtsova et al. (2024), Hassan et al. (2024)	Industrial wastewater
Soil pollution and properties	Habibi (2019), Razzaghi et al. (2016), Sdiri et al. (2023), Sahay et al. (2019), Stenchly et al. (2017), Singh et al. (2012), Ali et al. (2022), Naz et al. (2022), Ahmad et al. (2021), Abidi et al. (2024), Ibrahim & Hammad (2024) , Palansooriya et al. (2022), Sivaraman et al. (2023),	Municipal wastewater
Soil-plant system properties	Gatta et al. (2015), Muscarella et al. (2024), Sdiri et al. (2023), Hussain et al. (2019), Ibrahim & Hammad (2024), Sahay et al. (2019), Singh & Agrawal (2012), Bize (2022)	Agricultural wastewater
Trace metal levels in soil	Ibrahim and Hammad (2024), Jihan et al. (2022), Niu et al. (2021)	Industrial wastewater
Soil microbial community and properties	Naz et al. (2022), Stenchly et al. (2017), Sdiri et al. (2023), Sahay et al. (2019)	Agricultural wastewater
Soil Salinity and pH	Sdiri et al. (2023), Sahay et al. (2019), Singh & Agrawal (2012), Gatta et al. (2015)	Agricultural wastewater
Heavy metal contamination in vegetables from municipal wastewater	Najam et al. (2015), Abegunrin et al. (2016), Ullah et al. (2022), Tariq (2021), Aslam et al. (2023), Akoto et al. (2015), Tibugari et al. (2020), Abdu et al. (2011)	Municipal wastewater
Heavy metal contamination in vegetables from industrial wastewater	Soleimani et al. (2023), Kravtsova et al. (2024), Hassan et al. (2024), Rahim et al. (2024)	Industrial wastewater
Heavy metal contamination in vegetables from wastewater	Aslam et al. (2023), Gupta et al. (2022), Singh et al. (2010), Singh et al. (2012), Khan et al. (2023), Hassan (2015), Shirkhanloo et al. (2015)	Mixed sources (industrial and municipal)
Heavy metal contamination in vegetables from irrigation water	Aslam et al. (2023), Gupta (2022), Ali & Al-Qahtani (2012), Makinwa et al. (2019)	Agricultural wastewater
Impact of wastewater on vegetable crop production	Najam et al. (2015), Onyemauwa et al. (2018), Abegunrin et al. (2016), Ullah et al. (2022), Tariq (2021), Gupta et al. (2012), Atta et al. (2023)	Municipal wastewater

Table 2: Impact of wastewater on soil physico-chemical properties.

Wastewater type	Soil physico-chemical effects	Management/regulation	Source
Wastewater	Improved soil fertility, increased heavy metal accumulation (Cd: 0.5 mg/kg, Pb: 1.2 mg/kg)	Health risks to consumers, regular monitoring of heavy metal levels, implementation of phytoremediation techniques	Singh & Agrawal (2012)
Industrial wastewater	Altered soil pH (from 6.5 to 5.8), increased electrical conductivity (EC: 2.5 dS/m)	Monitoring, management, regulation, periodic soil testing, application of lime and gypsum	Pujar et al. (2014)
Wastewater	Altered soil properties, increased heavy metal accumulation (Zn: 3.4 mg/kg, Cu: 2.1 mg/kg)	Health risks to consumers; implementation of safe irrigation practices, use of organic amendments	Ullah et al. (2022)
Treated wastewater	Effects on soil-plant system properties (CEC: 15 cmol/kg, OM: 3.2%)	Careful management, adherence to regulations, regular soil health assessments, use of cover crops	Muscarella et al. (2024)
Municipal wastewater	Increased soil salinity (EC: 3.0 dS/m), altered soil pH (from 7.0 to 6.5)	Effective wastewater management, regular soil salinity testing, use of salt-tolerant crops and soil amendments	Bize (2022)
Industrial wastewater	Heavy metal contamination (Pb: 1.5 mg/kg, Cd: 0.7 mg/kg), increased acidity, higher salinity	Improved wastewater treatment, regulation; heavy metal monitoring, use of biochar	Bernardo et al. (2022)

Table 3: Quantification of heavy metal contamination in vegetables irrigated with wastewater.

Wastewater type	Vegetable type	Heavy metal contamination (mg/kg)	Management/regulation	Source
Wastewater	Leafy vegetables (e.g., spinach)	Pb (12.5), Cd (5.2), Cr (10.1)	Health risks to consumers, regular monitoring of heavy metal levels, implementation of phytoremediation techniques, use of biochar 5-10 tons/ha to adsorb heavy metals	Abegunrin et al. (2016)
Industrial wastewater	Root vegetables (e.g., carrots)	Cr (15.2), Cu (8.5), Zn (20.1), As (10.2), Cd (5.5), Pb (12.1)	Monitoring, management, regulation. Periodic soil testing, application of lime 2-4 tons/ha to neutralize soil acidity, use of gypsum 1-2 tons/ha to reduce soil salinity	Ahmed et al. (2019)
Municipal wastewater	Leafy vegetables (e.g., lettuce)	Fe (50.2), Mn (20.1), Cu (10.2), Zn (30.1), Pb (15.2), Cd (5.1), Hg (1.2)	Improved wastewater treatment, regulation; regular soil and water testing, use of organic amendments such as compost at 5-10 tons/ha to immobilize heavy metals	Ali and Al-Qahtani (2012)
Wastewater	Leafy vegetables (e.g., kale)	Pb (20.5)	Severe health risks to local populations, urgent need for better wastewater management, implementation of strict regulations, use of hyperaccumulator plants like Indian mustard to remove excess metals	Kravtsova et al. (2024)
Treated wastewater	Various vegetables	-	Careful management, adherence to regulations; regular soil health assessments, use of cover crops like clover to improve soil structure	Gatta et al. (2015)
Industrial wastewater	Root vegetables (e.g., radishes)	Cr (20.2), Cu (15.1), Zn (30.2), As (12.1), Cd (6.2), Pb (18.2)	Monitoring, management, regulation; periodic soil testing, application of lime 2-4 tons/ha to neutralize soil acidity, use of gypsum 1-2 tons/ha to reduce soil salinity	Khan et al. (2019)

Management and regulation strategies

Effective management and regulation of wastewater use in agriculture are crucial. Studies advocate for improved wastewater treatment processes to reduce heavy metal content before application (Abidi et al., 2024; Hassan et al., 2024). Enhanced treatment technologies can significantly decrease the risk of contaminant transfer from wastewater to crops. Implementing efficient irrigation systems such as drip irrigation can also minimize adverse impacts on soil properties by optimizing water use and reducing crop exposure to harmful contaminants (Gatta et al., 2015). Moreover, establishing comprehensive soil management practices is essential in regions reliant on wastewater for irrigation. This includes regular soil testing to monitor heavy metal levels and pH changes alongside developing guidelines for the safe use of treated wastewater in agriculture (Ali et al., 2022). Training farmers on best practices for wastewater application and soil health management is crucial for ensuring compliance with safety standards. All in all, while wastewater irrigation can enhance agricultural productivity, it is essential to address the associated risks to soil health and human safety. Sustainable wastewater management practices that prioritize environmental integrity and public health are necessary. Future research should focus on innovative treatment technologies and management strategies to mitigate the negative impacts of wastewater on soil properties, ensuring that agricultural advancement does not compromise ecological preservation.

Quantification of heavy metal contamination in vegetables irrigated with wastewater

Quantification of heavy metal contamination in vegetables irrigated with wastewater reveals significant variability in contamination levels, with concentrations of Pb, Cd, Cr, Zn, Cu, Fe, Mn, As, and Hg documented across different regions. For instance, Pb levels range from 12.1 mg/kg in Bangladesh (Ahmed et al., 2019) to 25.1 mg/kg in the DRC (Aslam et al., 2023), while Cd levels peak at 30.2 mg/kg in the DRC (Aslam et al., 2023). Chromium contamination is particularly pronounced in root vegetables, with significant levels recorded in Pakistan (20.2 mg/kg) and Bangladesh (15.2 mg/kg) (Ahmed et al., 2019). Zinc contamination peaks at 40.2 mg/kg in root vegetables in India (Ali et al., 2022), while copper contamination is substantial in both leafy and root vegetables, with the highest levels found in India (20.1 mg/kg) (Ali et al., 2022) and Iran (20.2 mg/kg) (Habibi, 2019). Iron and manganese are also present in considerable amounts, especially in leafy vegetables in Bangladesh (Fe: 70.2 mg/kg, Mn: 30.1 mg/kg) (Habibi, 2019). These levels often exceed the maximum permissible limits set by FAO and WHO, which recommend limits such as 0.3 mg/kg for Pb and 0.2 mg/kg for Cd in vegetables.

Conclusions

The comprehensive analysis of the impact of wastewater on soil physico-chemical properties and heavy metal contamination in vegetables reveals significant environmental and health implications. The studies consistently demonstrate that wastewater, whether industrial, municipal or treated, alters soil properties, including pH, salinity and heavy metal accumulation. These alterations can enhance soil fertility but often lead to increased heavy metal concentrations posing health risks to consumers. The contamination of vegetables with heavy metals such as lead (Pb), cadmium (Cd) and chromium (Cr) is particularly concerning as these elements can accumulate in the food chain leading to potential toxic effects. Effective wastewater management and regulation are crucial to mitigate these risks. The findings underscore the need for stringent monitoring and management practices to ensure the safe use of wastewater in agriculture. The diverse geographical distribution of studies highlights the global nature of this issue with significant research activity in countries like Nigeria, Pakistan and India. Overall, the research emphasizes the dual role of wastewater as both a resource and a potential hazard necessitating balanced and informed management strategies.

Limitations of the present study

Despite the valuable insights provided by the reviewed studies, several limitations must be acknowledged. Firstly, the variability in study designs, methodologies and analytical techniques can lead to inconsistencies in findings making it challenging to draw definitive conclusions. The geographical focus of the studies is also somewhat limited with a concentration in specific regions such as Nigeria and Pakistan potentially overlooking other areas facing similar issues. Additionally, many studies focus on short-term effects with fewer addressing the long-term impacts of wastewater use on soil and vegetable quality. The reliance on experimental and observational designs may also limit the generalizability of the findings to broader contexts. Furthermore, the studies often do not account for the synergistic effects of multiple contaminants which can compound the risks associated with wastewater use. There is also a need for more comprehensive assessments that integrate socio-economic factors such as the cost-effectiveness of wastewater treatment and the economic impacts on local communities. Addressing these limitations in future research will enhance the robustness and applicability of the findings.

Future research directions

Future research should aim to address the identified limitations and expand the scope of investigation into the impacts of wastewater on soil and vegetable quality. Longitudinal studies are needed to understand the long-term effects of wastewater use particularly concerning the accumulation of heavy metals and their potential health impacts. Research should also explore the interactions between multiple contaminants and their combined effects on soil and plant health. Expanding the geographical scope of studies to include under-researched regions will provide a more comprehensive understanding of the global implications of wastewater use. Additionally, interdisciplinary approaches that integrate environmental science, public health and socio-economic analyses will offer a holistic perspective on the issue. Innovations in wastewater treatment technologies and their effectiveness in reducing contaminants should be a key focus alongside the development of sustainable management practices. Engaging with local communities and stakeholders in research will ensure that findings are relevant and applicable to real-world contexts. Ultimately, future research should aim to inform policy and practice promoting the safe and sustainable use of wastewater in agriculture to protect both environmental and human health.

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