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Impacts of Wastewater Irrigation on Soil Carbon-Nutrient Cycling and Environmental Sustainability: Systematic Review

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Abstract

Background: Wastewater irrigation is widely utilized to address water scarcity and enrich soil fertility, yet its impacts on soil carbon-nutrient cycling and environmental sustainability remain complex and multifaceted.

Methods: In this systematic review of 89 peer-reviewed studies published between 2000 and 2025, we synthesized data on soil organic carbon (SOC), nitrogen dynamics, crop yields, and greenhouse-gas (GHG) emissions (CO_2, N_2O, and CH_4) under various wastewater irrigation regimes.

Results: The findings indicated that wastewater irrigation can boost SOC by up to 164% and increase soil nitrogen content by up to 152%, driving short-term crop-yield gains of up to 56% through enhanced nutrient availability. However, prolonged application frequently leads to soil salinization, heavy-metal accumulation, and elevated CO_2 and N_2O emissions, with several studies reporting eventual declines in yield over time.

Conclusion: These results reveal a dual effect: immediate agronomic benefits counterbalanced by long-term environmental risks. Sustainable implementation requires advanced wastewater treatment, continuous soil monitoring, and optimized irrigation practices to mitigate negative impacts while preserving soil health and carbon sequestration potential. Future research should prioritize strategies that minimize GHG emissions and maximize nutrient retention to ensure long-term agricultural and environmental sustainability.

Keywords: Soil, Nitrogen cycle, Carbon, Wastewater, Environment

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Introduction

Water scarcity poses a critical challenge for agriculture, particularly in arid and semiarid regions, leading to increased use of treated municipal and industrial effluents for crop irrigation (1). This practice can augment water supplies and enrich soils with organic matter and nutrients (e.g., carbon and nitrogen), potentially enhancing fertility and yields. However, the long-term effects of treated wastewater irrigation on soil biogeochemical cycles remain uncertain. Some studies report sustained increases in soil carbon and nutrient status, while others highlight risks of salinization, heavy metal accumulation, altered greenhouse gas emissions, and other adverse outcomes (2). Given these complex and conflicting findings, a systematic review is warranted to synthesize the evidence using transparent, reproducible methods. Accordingly, this review addresses how treated wastewater irrigation influences soil organic carbon sequestration and nitrogen cycling across agricultural ecosystems, and what sustainability trade-offs arise from this practice(3-6).

Soil carbon and nitrogen play fundamental roles in maintaining soil fertility, structure, and overall ecosystem stability. Carbon, primarily in the form of soil organic carbon (SOC), influences soil aggregation, water retention, and microbial activity; while nitrogen governs nutrient cycling and plant growth. The application of wastewater to agricultural soils introduces dissolved organic carbon (DOC), which can contribute to SOC accumulation and enhance microbial biomass and enzymatic activities. Simultaneously, wastewater is a major source of nitrogen, typically in the forms of ammonium (NH_4^+) and nitrate (NO_3^-), which can boost crop productivity but also alter microbial processes such as nitrification and denitrification (3,7-9). These changes have significant implications for soil health, nutrient availability, and environmental sustainability.

One of the key concerns regarding wastewater irrigation is its potential impact on greenhouse gas emissions. The alteration of nitrogen cycling due to excessive nitrogen inputs from wastewater can increase emissions of nitrous oxide (N_2O), a potent greenhouse gas that contributes to global warming. Furthermore, wastewater irrigation can modify the carbon balance of soils, affecting CO_2 emissions and long-term carbon sequestration potential. While some studies report increased carbon stabilization due to the enhanced microbial transformation of organic matter, others suggest that labile carbon from wastewater accelerates microbial respiration, leading to carbon losses in the form of CO_2 (Figure 1). Additionally, the potential for nitrate leaching and groundwater contamination raises environmental and public health concerns, necessitating careful management of wastewater irrigation practices (10-14).

The physicochemical properties of wastewater, including its organic load, salinity, and heavy metal content, further complicate its effects on soil carbon and nitrogen dynamics. The quality and composition of wastewater vary depending on its source (e.g., domestic, industrial, or agricultural effluents), treatment level, and irrigation frequency. High concentrations of salts and heavy metals in wastewater can negatively impact soil microbial communities, potentially reducing microbial efficiency in nutrient cycling and organic matter decomposition. Additionally, long-term wastewater application can lead to soil salinization, sodicity, and the accumulation of potentially toxic elements, thereby affecting soil structure and plant health (9,15-21).

The valorization of wastewater treatment by-products addresses water scarcity and soil nutrient depletion by enabling water reuse and nutrient recycling. Research shows that co-composting sewage sludge with organic waste yields Class A compost with optimal C/N ratios (15–25), germination indices exceeding 100% for major crops, and low heavy-metal risks, highlighting its potential as a sustainable soil amendment (22).

Previous research examined sludge accumulation and agricultural potential in a 14-year-old aerated lagoon wastewater treatment plant in Ouargla, Algeria. The study found that the accumulated sludge exhibited high dry matter content (96.73% DM), low fermentability, and substantial nutrient levels (2.58% N, 0.55% P). Critically, heavy metal concentrations were within safe limits, and no fecal contamination was detected. These findings suggested the sludge's potential suitability for amending arid soils, though salinity management was identified as a necessary precaution. The authors highlighted significant valorization opportunities but emphasized the imperative for ongoing monitoring and strategies to mitigate salinity to ensure sustainable application (23).

Given the increasing reliance on wastewater irrigation, a comprehensive understanding of its impact on soil carbon and nitrogen dynamics is crucial for optimizing sustainable agricultural practices. This review synthesizes current research on the subject, focusing on the influence of wastewater irrigation on soil organic carbon sequestration, nitrogen transformations, microbial activity, and potential environmental trade-offs. By analyzing studies from diverse agroecosystems, this review aims to identify key trends, highlight knowledge gaps, and suggest future research directions. Furthermore, it explores how different wastewater sources, irrigation regimes, and soil types influence carbon and nitrogen cycling. Through this analysis, the review provides insights that can inform policy decisions and management strategies to maximize the benefits of wastewater irrigation while minimizing its environmental risks.

Materials and Methods

This systematic narrative review was designed to

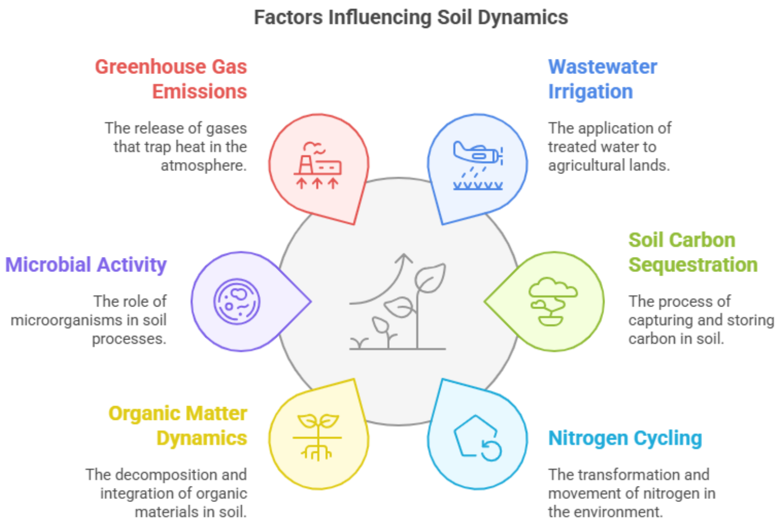

Figure 1. Factors influencing soil dynamics

synthesize the current scientific understanding of the impacts of wastewater irrigation on soil carbon and nitrogen dynamics. A comprehensive literature search was conducted using six major academic databases: Web of Science, Scopus, ScienceDirect, Google Scholar, PubMed, and Semantic Scholar. The search covered studies published between January 2000 and March 2025.

Search Strategy and Selection Criteria

The search strategy was developed using a combination of keywords and Boolean operators tailored to each database. Primary search terms included "wastewater irrigation," "treated wastewater," "soil organic carbon," "nitrogen cycling," "soil fertility," "crop yield," "greenhouse gas emissions," "microbial activity," and "environmental sustainability." Additional terms such as "soil health," "nutrient dynamics," and "agricultural ecosystems" were included to broaden the scope. Database-specific filters were applied to focus on peer-reviewed articles in environmental science, agriculture, and soil science. The search query was structured as follows (example for Scopus): ("wastewater irrigation" OR "treated wastewater") AND ("soil organic carbon" OR "nitrogen cycling" OR "soil fertility" OR "greenhouse gas emissions" OR "microbial activity") AND ("agriculture" OR "soil health" OR "environmental sustainability"). Manual searches of reference lists from key articles and relevant reviews were conducted to identify additional studies not captured in the initial database search.

The following inclusion and exclusion criteria were applied:

Inclusion Criteria

- Peer-reviewed original research articles, meta-analyses, or reviews.
- Studies that directly assessed the effects of wastewater irrigation on soil carbon and nitrogen dynamics, microbial properties, or greenhouse gas emissions.
- Research based on field trials, controlled experiments, or long-term monitoring data.
- Articles published in journals indexed in Scopus, Web of Science, or with known impact factors.

Exclusion Criteria

- Studies focusing solely on wastewater treatment or water quality without assessing soil parameters.
- Reports are lacking quantitative data.
- Grey literature, conference abstracts, or preprints without peer review.
- Duplicated publications or articles with incomplete methodology descriptions.

After title and abstract screening, followed by full-text evaluation, 89 high-quality studies were selected for in-depth review. This represents approximately 74% of the initially identified publications.

Data Extraction and Categorization

Data were extracted systematically using a structured form and categorized by:

- Type of wastewater (municipal, industrial, or agricultural).
- Soil type and texture.
- Irrigation regime and frequency.
- Climatic region and experimental duration.
- Reported outcomes: soil organic carbon (SOC) content, dissolved organic carbon (DOC), total nitrogen (TN), ammonium (NH_4^+), nitrate (NO_3^-), microbial biomass, and greenhouse gas emissions (CO_2, CH_4, and N_2O).

Quality Assessment and Bias Control

To ensure the scientific robustness of this review, two independent reviewers evaluated the methodological quality and relevance of each selected article. Journals' quartile rankings (Q1–Q4) were recorded based on the Scimago Journal Rank (SJR) and Journal Citation Reports (JCR) databases to evaluate the quality of the evidence base. Among the selected studies, 68.2% were published in Q1 journals, further supporting the reliability of the synthesized findings. As illustrated in Figure 2, the majority of the reviewed articles were published in Q1 journals.

A total of 742 articles were extracted from various databases. After removing 142 duplicates, 600 articles were screened. Four hundred twenty articles were excluded due to insufficient relevance to the subject matter. Sixty articles were excluded due to poor quality. One hundred twenty articles were thoroughly assessed. Thirty-one articles were excluded due to ambiguities in the information provided. Ultimately, 89 articles were included in the final analysis (Figure 3).

Disagreements during the review process were resolved through consensus. The risk of bias due to publication date, geographic focus, or study design heterogeneity was considered in the interpretation of results.

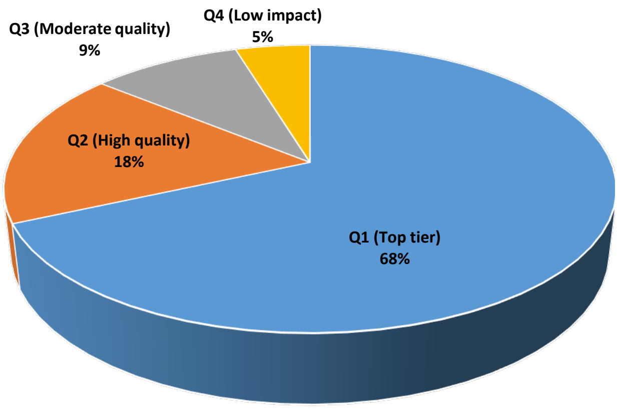

Figure 2. Distribution of journal quartiles (Q) among 89 reviewed articles

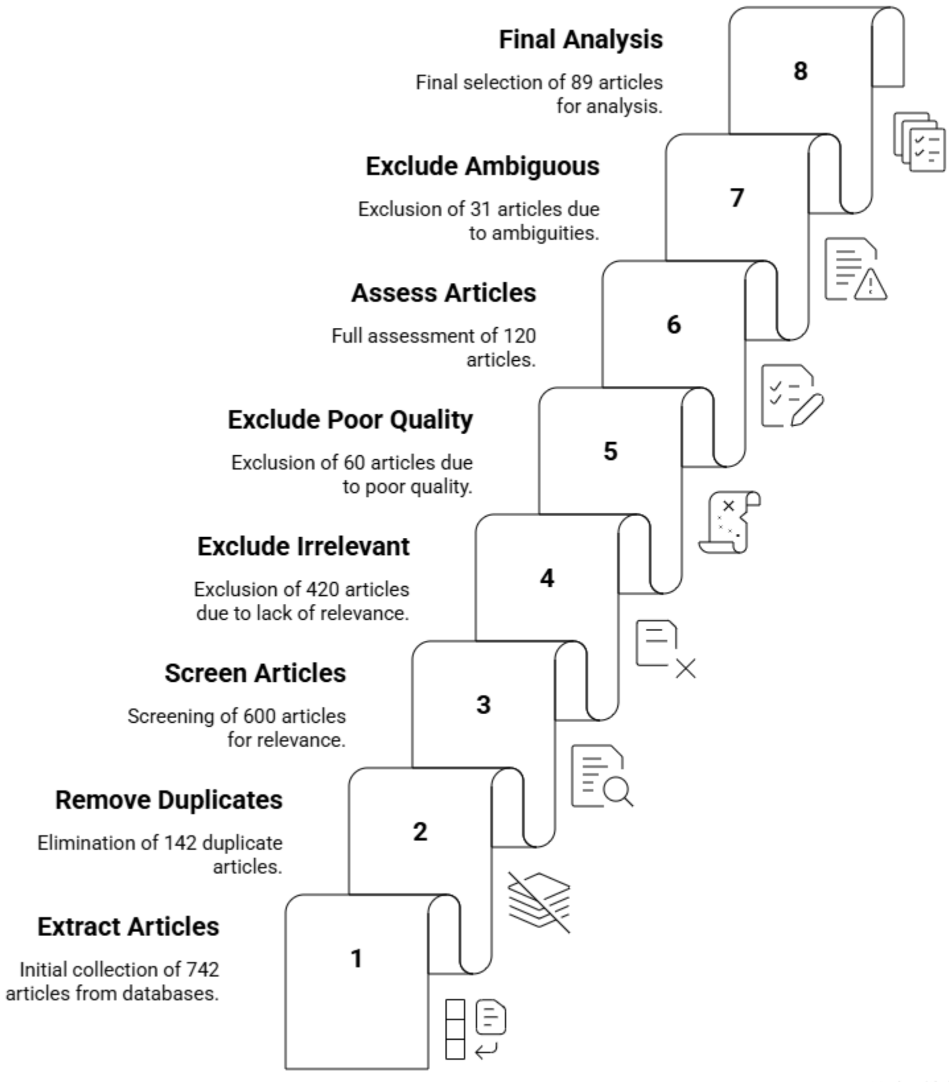

Figure 3. PRISMA flow diagram outlining the study selection process

Results

This review assessed the impacts of irrigation practices, primarily wastewater-based, on soil carbon, nitrogen, crop yield, and greenhouse gas emissions across 89 studies spanning multiple regions and durations. Soil organic carbon increased with wastewater irrigation in 28 of 29 studies (up to + 164%), with one exception of a −4.2% decrease using clean water (4) (Table 1). Soil nitrogen rose universally with wastewater, ranging from + 8% (24) to + 152% (19), while clean water effects were less quantified (Table 2). Crop yields generally improved with wastewater (e.g., + 56%) (25), though decreases occurred in some cases (e.g., −27%) (4) (Table 3). Greenhouse gas emissions (CO_2, N_2O, and CH_4) were consistently higher with wastewater irrigation compared to clean water baselines (Table 4). These results highlight wastewater irrigation's capacity to enhance soil fertility and productivity, offset by elevated GHG emissions and potential contamination risks.

Figure 4 shows Heatmap summarizing the relative impacts of various wastewater types on key agro-environmental parameters, including SOC, soil nitrogen, crop yield, and GHG emissions. Scores range from 1 (low impact) to 3 (high impact).

Discussion

Impacts of Wastewater Irrigation on Soil Carbon

Short-Term Wastewater Irrigation

The impact of wastewater irrigation on soil carbon content varies significantly depending on the duration of application. Short-term effects are generally characterized by an increase in soil organic carbon (SOC) due to the direct input of organic matter and nutrients present in wastewater. Chaganti et al reported that soils irrigated with treated wastewater (TWW) exhibited SOC levels of 3.26 g kg^{-1}, which was higher than the 2.96 g kg^{-1} observed in freshwater (FW) irrigated soils (3). This initial increase is attributed to the introduction of readily decomposable organic matter, which stimulates microbial activity and enhances carbon sequestration.

Table 1. Soil carbon change in different cities during the years 2000 to 2025

Location	Irrigation type	Soil carbon change (%)	Irrigation duration	Study reference
El Paso, Texas, USA	Treated wastewater	+10.1% (from 2.96 g kg^{-1} to 3.26 g kg^{-1} g kg^{-1})	2 years	(3)
Northern China	Long-term irrigation (clean water)	−4.2%	7 years	(4)
Turkey	Wastewater	+164% (in Vertisols after 30 years)	Up to 30 years	(19)
El Paso, Texas, USA	Treated municipal Wastewater	+16.67% (from 18 Mg ha^{-1} to 21–23 Mg ha^{-1})	6 years	(8)
Rohtak, Haryana, India	Sewage water	+2.5%	Long-term	(26)
Valley of Mezquital, Mexico	Untreated wastewater	+150%	80 years	(27)
Egypt	Treated wastewater	+8%	2 years	(28)
Afghanistan	Wastewater	+12%	1 year	(29)
Morocco	Treated wastewater	+18%	3 years	(30)
China	Reclaimed water	+10%	2 years	(31)
Egypt	Wastewater	+15%	5 years	(32)
Iraq	Treated industrial wastewater	+5%	1 year	(33)
New Zealand	Winery wastewater	+12%	1 year	(34)
China	Treated livestock wastewater	+20%	2 years	(35)
Algeria	Treated wastewater	+10%	1 year	(36)
India	Sewage water	+15%	2 years	(37)
Egypt	Treated wastewater	+10%	3 years	(38)
Morocco	Treated wastewater	+12%	1 year	(39)
China	Reclaimed water	+15%	2 years	(40)
India	Wastewater	+20%	1 year	(41)
Egypt	Treated wastewater	+10%	3 years	(42)
Iraq	Treated wastewater	+5%	1 year	(43)
New Zealand	Winery wastewater	+12%	1 year	(44)
China	Treated livestock wastewater	+20%	2 years	(26)
India	Treated wastewater Fresh water	+5% +3.7%	1 year	(45)
Spain	Sewage water	+40%	3 years	(46)
Egypt	Treated wastewater	+10%	3 years	(47)
Morocco	Treated wastewater	+12%	1 year	(48)
Algerian Sahara	Reclaimed water	+15%	2 years	(49)

Table 2. Soil nitrogen change in different cities during the years 2000 to 2025

Location	Irrigation type	Soil Nitrogen change (%)	Irrigation duration	Study reference
El Paso, Texas, USA	Wastewater	+21%	2 years	(3)
Jinan, China	Wastewater	+10%	Summer maize growing season	(49)
Shijiazhuang, China	Wastewater	+15%	Long-term (exact duration not specified)	(13)
Egypt	Wastewater	+30%	30 years	(18)
Turkey	Wastewater	+152%	Long-term (over 30 years)	(19)
North China Plain	Wastewater	+20%	1 year	(50)
Karachi, Pakistan	Wastewater	+18%	Not specified	(51)
Texas, USA	Clean water	0	6 years	(8)
Tongliao, China	Clean water	0	Not specified	(52)
Central Mexico	Clean water	0	Long-term	(53)
Italy	Treated municipal wastewater	+8%	2 years	(24)
Tunisia	Treated wastewater	+15%	Long-term	(54)
China	Drip irrigation	+20%	2 years	(55)
India	Sensor-based wastewater	+12%	1 year	(56)
USA	No-till and crop rotation	+15%	Long-term	(57)

Table 3. Crop yield change during the years 2000 to 2025

Location	Crop type	Irrigation type	Irrigation duration	Yield change (%)	Study reference
El Paso, Texas, USA	Bioenergy sorghum	Treated wastewater	2 years	Increase: Not specified	(3)
Northern China	Various crops	Wastewater	7 years	Decrease: 27%	(4)
Various locations	Wheat	Controlled irrigation	Not specified	Decrease: 6.6%	(12)
Shijiazhuang, China	Farmland	Poultry Wastewater	Not specified	Increase: Not specified	(49)
Egypt	Various crops	Raw urban Wastewater	10-30 years	Increase: Not specified	(18)
Turkey	Various crops	Wastewater	30 years	Increase:30%	(19)
Tunisia	Various crops	Treated wastewater	4-26 years	Increase: Not specified	(20)
Karachi, Pakistan	Vegetables	wastewater	Not specified	Increase: Not specified	(26)
North China Plain	Cucumber	Piggery wastewater	Not specified	Increase: 17.5%	(50)
El Paso, Texas, USA	Switchgrass	Treated wastewater	6 years	Increase: 7.7%	(8)
Ghana	Carrots	Treated wastewater	Not specified	Increase: 39.5% (SE)	(58)
China	Winter wheat	wastewater	3 years	Increase: 12.72%	(59)
Iraq	Broccoli and Cauliflower	wastewater	2 years	Increase: Not specified	(60)
Maryland, USA	Various crops	Recycled water	Not specified	Increase: 56%	(25)
India	Summer moong	Wastewater	7 years	Decrease: 15%	(61)
Ethiopia	Maize	Deficit irrigation	2 years	Increase: 52.44%	(62)
China	Winter Wheat	Various irrigation schedules	3 years	Increase: 12.72%	(63)
India	Wheat	Various irrigation frequencies	3 years	Increase: Not specified	(64)
Turkey	Silage Maize	Grey water	2 years	Decrease: Not specified	(65)
Iran	Wheat	Wastewater	6 months	Decrease: 42%	(66)
India	Chilli Lablab bean Tomato	Treated wastewater Treated wastewater Treated wastewater	9 months	Decrease:100% (fruit abortion) +165.7 % –22.6 %	(67)
India	Chilli Lablab bean Tomato	DTWW DTWW DTWW	9 months	Decrease:100% (fruit abortion) +2.0 % +8.3 %	(67)

Additionally, studies indicate that short-term wastewater irrigation may improve soil structure and water retention, thereby indirectly influencing carbon stabilization by reducing erosion losses and promoting organic matter incorporation into soil aggregates (Table 1).

Long-Term Wastewater Irrigation

Conversely, long-term wastewater irrigation presents a more complex scenario. Ganjegunte et al. (2017) observed that after prolonged irrigation, SOC levels tended to decline (8). The primary causes include soil salinization, which inhibits microbial and plant activity, and the priming effect, wherein the introduction of labile organic matter accelerates the decomposition of native organic matter. Wei et al further supported this, noting that high salinity conditions can disrupt soil aggregation and lead to enhanced carbon mineralization (69). Furthermore, excessive accumulation of sodium ions from wastewater irrigation can lead to soil dispersion, reducing aggregate stability and making SOC more vulnerable to microbial degradation. Therefore, while wastewater irrigation can initially enhance soil carbon storage, its prolonged application may ultimately reduce SOC levels in certain soil types, particularly in arid and semiarid regions where evaporation exacerbates salinity accumulation (Table 1).

Mechanisms of Soil Carbon Transformation

Several key processes drive changes in SOC under wastewater irrigation:

Microbial Activity

Wastewater irrigation generally increases microbial biomass due to the influx of organic matter and nutrients. Angin et al reported that long-term wastewater irrigation altered microbial community structures, resulting in enhanced decomposition rates of organic matter (19). The increased microbial diversity in wastewater-irrigated soils can lead to more efficient nutrient cycling and organic matter turnover, potentially influencing long-term SOC stability.

Stabilization vs. Decomposition

The fate of SOC depends on the balance between stabilization and decomposition. The presence of clay minerals promotes SOC stabilization through organo-mineral interactions, reducing decomposition rates. However, high salinity and sodicity can degrade soil structure, making SOC more susceptible to microbial

Table 4. Greenhouse gas emissions in different cities during the years 2000 to 2025

Location	Wastewater type	Greenhouse gas type	Emission Rates (wastewater irrigation)	Emission rates (clean water irrigation)	Irrigation duration	Study reference
North China Plain	Treated municipal wastewater	CO_2, CH_4, N_2O	CO_2: 2973 μg C kg⁻¹ h⁻¹ CH_4: -0.74 μg C kg⁻¹ h⁻¹ N_2O :2.30 μg N kg⁻¹ h⁻¹	CO_2: 2578 μg C kg⁻¹ h⁻¹ CH_4: -0.84 μg C kg⁻¹ h⁻¹ N_2O :1.90 μg N kg⁻¹ h⁻¹	14 days	(68)
Jinan, China	poultry wastewater	N_2O, CO_2	Higher N_2O and CO_2 emissions in poultry wastewater irrigation	Lower emissions with regular water	Single application	(49)
Nanjing, China	Saline water	N_2O, CO_2	The GWPs for N_2O and CO_2 were affected by salinity levels: S2: 19.6% lower than CK S5: 33.3% higher than CK S8: 44.1% lower than CK	control	two months	(69)
China	Drainage ditch water	N_2O, CO_2, CH_4	Aeration decreases global warming potential (GWP) by 34.02% Nitrogen input: the overall GWP increased by 15.24%	control	1 months	(70)
Turkey	Recycled municipal wastewater + sludge	CO_2	0.12 g CO_2 m⁻² h⁻¹	0.08 g CO_2 m⁻² h⁻¹	9 months	(71)
Jordan	recycled wastewater	CO_2, N_2O	0.5 g CO_2 m⁻² d⁻¹, 0.02 g N_2O m⁻² d⁻¹	0.3 g CO_2 m⁻² d⁻¹, 0.01 g N_2O m⁻² d⁻¹	Long-term	(72)
Mexico	Treated municipal wastewater	CO_2, N_2O, CH_4	CO_2: 5.61 μg C kg⁻¹ h⁻¹	CO_2: 0.74 μg C kg⁻¹ h⁻¹	Growing season of maize	(73)
North China Plain	Treated Municipal Wastewater	CO_2, N_2O, CH_4	CO_2, ≈ 256.7 mg C kg⁻¹ soil N_2O ≈ 10.8 μg N kg⁻¹ soil CH_4≈ -0.4 to -0.2 μg C kg⁻¹ soil	CO_2, ≈ 218.4 mg C kg⁻¹ soil N_2O ≈ 6.2 μg N kg⁻¹ soil CH_4≈ ≈ -0.5 to -0.3 μg C kg⁻¹ soil	One growing season	(74)
North China	Raw Wastewater	CO_2 N_2O, CH_4	CO_2 ≈ 4.5, N_2O ≈ 4.04, CH_4: decreased sink capacity mg·kg⁻¹ dry soil	CO_2 ≈ 2.41, N_2O ≈ 2.07 mg·kg⁻¹ dry soil	14 days	(75)
Southeastern China (Ningbo)	Treated domestic sewage	CH_4, N_2O	CH_4: 58.0 kg/ha/year N_2O: 9.3 kg/ha/year	CH_4:30.2 kg/ha/year, N_2O: 4.2 kg/ha/year	One year	(76)
Valley of Mezquital, Mexico	Urban wastewater	CO_2, N_2O, CH_4	CO_2:5.61 μg C kg⁻¹ soil h⁻¹ CH_4:163.6 × 10⁻³ μg C kg⁻¹ soil h⁻¹ N_2O: 2.75 × 10⁻³ μg N kg⁻¹ soil h⁻¹	CO_2:0.74 μg C kg⁻¹ soil h⁻¹ CH_4:1.5 × 10⁻³ μg C kg⁻¹ soil h⁻¹ N_2O: 1.49 × 10⁻³ μg N kg⁻¹ soil h⁻¹	90 days	(73)
Beijing, China	treated municipal wastewater	CO_2, N_2O	N_2O: 117.97 μg N/kg dry soil CO_2: 2.21 mg C/kg dry soil	N_2O: 96.71 μg N/kg dry soil CO_2: 2.07 mg C/kg dry soil	7 days	(77)
Mexico	Untreated Wastewater	CO_2, N_2O	2.5 N_2O (nmol N_2O g⁻¹ h⁻¹) 31 CO_2 (μg g⁻¹ d⁻¹)	0.1 N_2O (nmol N_2O g⁻¹ h⁻¹) 28 CO_2 (μg g⁻¹ d⁻¹)	80 years	(27)
China	Treated municipal wastewater	CH_4, N_2O	CH_4: 11.07 μg C kg⁻¹ h⁻¹ N_2O: 0.1087 μg N kg⁻¹ h⁻¹	CH_4: 8.7 μg C kg⁻¹ h⁻¹ N_2O: 0.0692 μg N kg⁻¹ h⁻¹	The entire rice-growing season	(78)

degradation (8). Additionally, wastewater often contains dissolved organic carbon fractions that vary in stability, influencing how quickly organic carbon is mineralized or sequestered.

Priming Effect

Introduction of labile organic matter through wastewater can stimulate microbial activity, leading to increased decomposition of older, more stable organic matter pools. This effect is more pronounced in sandy soils with low organic content (79). The priming effect may be more significant in the early stages of wastewater application when microbial communities rapidly respond to increased nutrient availability.

Decomposition Rates

Initial applications of wastewater often increase microbial respiration and CO_2 emissions. Over time, as microbial communities adapt, decomposition rates may stabilize, leading to a more balanced carbon cycle. However, repeated wastewater application can also lead to the accumulation of recalcitrant organic fractions, which may slow down decomposition in the long term (53).

Impact of Wastewater Irrigation on Soil Nitrogen

Wastewater irrigation significantly influences soil nitrogen content, affecting nitrogen availability, retention, and transformations through both short-term and long-term mechanisms. The extent of these changes depends on factors such as wastewater composition, irrigation frequency, soil properties, and microbial activity.

Short-Term Effects

Short-term wastewater irrigation can lead to an

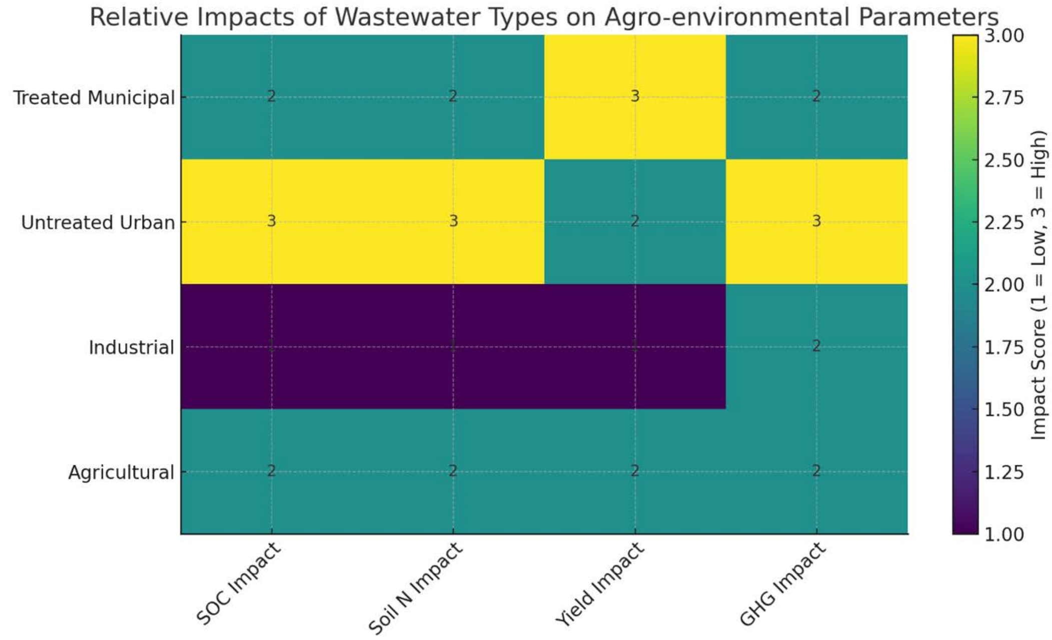

Figure4. Heatmap summarizing the relative impacts of various wastewater types on key agro-environmental parameters, including SOC, soil nitrogen, crop yield, and GHG emissions. Scores range from 1 (low impact) to 3 (high impact)

immediate increase in soil nitrogen due to the direct input of nitrogenous compounds, mainly ammonium (NH_4^+) and organic nitrogen. Zhang et al reported that poultry wastewater irrigation significantly increased soil total nitrogen (STN) in the upper 5–15 cm, enhancing soil fertility (49). Similarly, Moretti et al found that the application of treated swine wastewater led to an increase in microbial biomass nitrogen, boosting nitrogen mineralization and plant-available nitrogen levels (53).

However, the rapid availability of nitrogen can also lead to unintended consequences, such as temporary nitrogen imbalances and rapid microbial decomposition, which may reduce soil organic matter over time. Additionally, excessive nitrogen in the upper soil layers can promote nitrate leaching under high irrigation rates, increasing the risk of groundwater contamination (Table 2).

Long-Term Effects

The long-term effects of wastewater irrigation on soil nitrogen dynamics are more complex. Prolonged irrigation can lead to nitrogen accumulation in some soils, but in others, nitrogen losses through leaching, denitrification, and volatilization may offset any gains. Friedel et al found that 80 years of wastewater irrigation in Mexico resulted in a 2.5-fold increase in total organic nitrogen in Vertisols, whereas Leptosols exhibited increased nitrogen mineralization and losses (27).

Angin et al observed that 30 years of wastewater irrigation in Turkey increased organic matter and cation exchange capacity (CEC), improving nitrogen retention (19). However, soil salinity and heavy metal accumulation also increased, potentially reducing nitrogen availability over time. Moreover, long-term exposure to wastewater nutrients can alter microbial community composition, shifting nitrogen cycling pathways and affecting overall nitrogen use efficiency in soils (Table 2).

Mechanisms of Nitrogen Transformations

Several interconnected processes regulate nitrogen transformations in wastewater-irrigated soils:

Nitrification

Nitrification is the microbial oxidation of ammonium (NH_4^+) to nitrate (NO_3^-), primarily carried out by nitrifying bacteria. Wastewater rich in ammonium can enhance nitrification rates, increasing nitrate concentrations in soil. Hamsa et al found that ammonium-rich wastewater stimulated nitrification in well-aerated soils (80). However, nitrification rates vary with soil aeration, organic matter content, and pH (81).

Denitrification

Denitrification converts nitrate to nitrogen gases (N_2 and N_2O) under anaerobic conditions. Increased organic matter from wastewater can enhance denitrification rates, leading to higher nitrous oxide (N_2O) emissions. Robertson & Groffman reported that wastewater irrigation creates conditions favorable for denitrification, particularly in waterlogged soils, increasing nitrogen losses and greenhouse gas emissions (79).

Anammox (Anaerobic Ammonium Oxidation)

Anammox is a nitrogen removal process in which ammonium is oxidized using nitrite as an electron acceptor, producing nitrogen gas (N_2). Though less commonly studied in wastewater-irrigated soils, Cooper et al. (2016) suggested that anammox could contribute to nitrogen cycling in anaerobic soil environments, especially in deeper soil layers with limited oxygen (81).

Ammonia Volatilization

Ammonia volatilization occurs when ammonium (NH_4^+) is converted to ammonia gas (NH_3) under alkaline conditions. This process leads to nitrogen loss and reduces fertilizer efficiency. Hamsa et al found that high-pH wastewater enhanced ammonia volatilization, emphasizing the need for pH control in wastewater irrigation systems (80).

Nitrogen Immobilization

Microbial immobilization occurs when inorganic nitrogen is assimilated into microbial biomass, temporarily reducing nitrogen availability for plants. This process competes with nitrogen mineralization and influences long-term nitrogen cycling. The balance between immobilization and mineralization is critical for determining nitrogen use efficiency in wastewater-irrigated soils (80).

Comparative Analysis of Short-Term vs. Long-Term Effects

Short-term wastewater irrigation generally leads to increased nitrogen availability and microbial activity, benefiting crop growth. However, long-term irrigation can result in nitrogen saturation, increased leaching, and enhanced greenhouse gas emissions. While nitrogen initially accumulates in soils, prolonged wastewater use may lead to soil degradation due to salinity, organic matter depletion, and changes in microbial communities (19,27). Sustainable wastewater irrigation practices should incorporate nitrogen management strategies to mitigate long-term risks.

Environmental Impacts of Wastewater Irrigation on Agricultural Lands – A Focus on Greenhouse Gas Emissions

Wastewater irrigation is increasingly used to address water scarcity and improve soil fertility; however, its application also alters greenhouse gas (GHG) emissions relative to clean water irrigation. The following discussion synthesizes evidence on GHG emission mechanisms, compares emissions from wastewater and clean water irrigation, evaluates both short-term and long-term impacts, and examines the broader environmental implications (Table 4).

Greenhouse Gas Emission Mechanisms

Wastewater irrigation influences GHG emissions—specifically carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4)—through several interrelated microbial and biochemical processes:

Organic Matter Decomposition

The addition of organic matter contained in wastewater stimulates microbial respiration. The decomposition of this readily available organic carbon can lead to significantly elevated CO_2 emissions. In some cases, the priming effect further accelerates the breakdown of native soil organic matter, amplifying CO_2 fluxes (3, 79).

Nitrification and Denitrification

Wastewater typically contains high levels of nitrogen, especially in the form of ammonium (NH_4^+). Enhanced nitrification converts NH_4^+ to nitrate (NO_3^-), while subsequent denitrification under anaerobic conditions reduces NO_3^- to nitrogen gases (N_2O and N_2). The combined effect of these processes can result in substantially higher N_2O emissions, a greenhouse gas with a global warming potential nearly 300 times that of CO_2 (12,79,82).

Methanogenesis

Under anaerobic conditions—often created by excessive soil moisture from wastewater irrigation—methanogenic archaea convert organic substrates into CH_4. Although CH_4 emissions may be partially offset by methanotrophic activity, the net flux is typically greater than that observed under clean water irrigation (79,83).

Comparison with Clean Water Irrigation

Empirical studies consistently indicate that fields irrigated with wastewater exhibit higher GHG emissions compared to those irrigated with clean water (Table 4):

CO_2 Emissions

Research shows that CO_2 emissions from wastewater-irrigated soils can be nearly 2.5 times higher than from soils receiving clean water, primarily due to increased organic carbon inputs that fuel microbial respiration (3,79).

N_2O Emissions

Elevated nitrogen loads in wastewater intensify both nitrification and denitrification processes, leading to a marked increase in N_2O emissions. For instance, wastewater irrigation has been associated with up to a 170% increase in N_2O emissions relative to clean water irrigation (12,79).

CH_4 Emissions

The propensity for waterlogging under wastewater irrigation creates more anaerobic microsites, favoring CH_4 production. Studies comparing irrigation types have demonstrated that CH_4 emissions are significantly higher when wastewater is used, owing to enhanced methanogenic activity (79,83).

Short-Term versus Long-Term Impacts

The temporal dynamics of GHG emissions under wastewater irrigation reveal distinct short-term and long-term effects:

Short-Term Impacts
Immediately following wastewater application, rapid microbial decomposition of the introduced organic matter leads to acute spikes in CO_2, N_2O, and CH_4 emissions. These transient increases are driven by the sudden availability of labile organic substrates and nitrogen (79,83).

Long-Term Impacts
Over extended periods, the initial high emission rates may be modulated by soil adaptations. Long-term wastewater irrigation can result in the accumulation of organic matter and alterations in soil structure that stabilize microbial communities, potentially reducing the rate of GHG emissions. However, chronic exposure to wastewater also increases the risk of soil salinity and heavy metal buildup, which can impair soil health and alter GHG emission patterns in complex ways(19,20). The interplay between these factors means that while some emissions may eventually decline, others—especially N_2O—may remain elevated due to persistent nitrogen enrichment (12).

Environmental Implications
The enhanced GHG emissions associated with wastewater irrigation have far-reaching environmental consequences:

Climate Change Contributions
Increased emissions of CO_2, N_2O, and CH_4 contribute directly to global warming. The high global warming potential of N_2O, in particular, underscores the climate risks associated with wastewater reuse in agriculture (12).

Soil Health and Crop Productivity
While wastewater irrigation can improve soil fertility and water use efficiency, the concomitant increases in GHG emissions are often accompanied by adverse effects such as soil acidification, salinity, and the accumulation of heavy metals. These factors can degrade soil quality and ultimately impair crop productivity (19,20).

Mitigation and Management Strategies
To balance the benefits of wastewater reuse with its environmental drawbacks, it is critical to optimize treatment processes to reduce organic carbon and nitrogen loads and implement irrigation management practices that minimize anaerobic conditions. Enhancing soil health through practices such as biochar application may also help sequester carbon and mitigate emissions (69,70,84).

Agricultural irrigation using treated wastewater, as studied in Kerman, offers a vital alternative water source in arid regions. The Kerman treatment plant effluent showed effective removal of organic pollutants, with mean values of COD, BOD, and TSS at 64.4, 39.8, and 74.5 mg/L, respectively, aligning with Iranian environmental standards. Removal efficiencies for TSS, COD, and BOD averaged 86.86%, 80.37%, and 80.76%. However, microbial contamination remains a critical issue, with total and fecal coliforms significantly exceeding standards. Effluent EC (2.86 dS/m) and SAR (7.04) indicate severe salinity hazards and moderate limitations from specific ions, restricting use mainly to salt-tolerant crops. These findings highlight the necessity for enhanced disinfection and careful management for safe agricultural reuse (85).

Synthesis and Critical Analysis
The literature presents a consensus that wastewater irrigation generally increases GHG emissions relative to clean water irrigation; however, the magnitude and persistence of these emissions are influenced by several factors:

Irrigation Management Practices
How irrigation is managed, including the duration and frequency of water application, significantly impacts soil moisture and aeration, which in turn influence GHG emissions. Studies have shown that deficit irrigation with wastewater can be an effective strategy for reducing CO_2 emissions compared to full irrigation. The method of irrigation, such as flood, drip, or sprinkler irrigation, also plays a crucial role by affecting soil wetting patterns and oxygen availability. For example, flood irrigation, particularly in rice paddies, is known to create anaerobic conditions that lead to high CH_4 emissions. Improving water use efficiency through optimized irrigation scheduling and methods can be an effective way to mitigate GHG emissions. Short-term applications result in immediate, high emissions, while long-term irrigation may induce soil adaptations that modulate emission rates. Nevertheless, persistent nitrogen inputs tend to maintain elevated N_2O levels (19,69,70).

Wastewater Quality
Variations in organic matter and nitrogen content directly affect microbial processes, with higher nutrient loads exacerbating GHG production. The quality of irrigation water, particularly the differences between wastewater and clean water, significantly influences GHG emissions. The higher organic matter content in wastewater is a primary driver for increased CO_2 emissions from wastewater-irrigated soils. The nutrient content of wastewater, especially nitrogen and phosphorus, can affect N_2O and potentially CH_4 emissions by providing substrates for microbial processes. The salinity of wastewater can also have different effects on all three GHGs, depending on the concentration and the tolerance of the soil microbial community (12,71).

Soil Type and Conditions

Soil texture, moisture content, and pH significantly influence the balance between aerobic and anaerobic processes, thereby affecting the emission profiles of CO_2, N_2O, and CH_4. The organic matter content of the soil is a critical factor influencing greenhouse gas emissions, particularly CO_2. Studies consistently show that soils with higher organic matter levels tend to release more CO_2 due to increased microbial respiration. Wastewater irrigation, by adding organic matter to the soil, directly contributes to this effect. Soil type also plays a role; for instance, clay-loam soils have been found to exhibit higher CO_2 emissions compared to sandy-loam soils under wastewater irrigation, likely due to differences in aeration and water retention capacity affecting microbial activity. Soil moisture and temperature are directly influenced by irrigation practices and show strong correlations with CO_2 emissions. Increased soil moisture and temperature generally stimulate microbial activity, leading to higher CO_2 release. Soil salinity can have a complex impact on GHG emissions. While some studies suggest that increased salinity can inhibit microbial activity and reduce CO_2 emissions, others have found that saline soils can emit higher CO_2 under certain conditions. The effects of salinity on N_2O and CH_4 emissions are also variable and depend on the level of salinity and other soil factors (53,68,78,83).

Overall, while wastewater irrigation offers benefits such as nutrient recycling and water conservation, its potential to exacerbate GHG emissions necessitates careful management and further research to develop sustainable practices.

Wastewater irrigation markedly influences greenhouse gas emissions from agricultural lands through enhanced organic matter decomposition, intensified nitrogen cycling, and the promotion of anaerobic conditions. Compared to clean water irrigation, wastewater use is associated with significantly higher emissions of CO_2, N_2O, and CH_4, with important implications for climate change and soil health. The long-term sustainability of wastewater irrigation depends on optimizing treatment processes, tailoring irrigation practices to local soil conditions, and mitigating adverse environmental impacts through targeted management strategies.

Below is a rewritten academic English version of the section “Impact of Wastewater Irrigation on Agricultural Yields” up to the beginning of the conclusion. The reference numbers have been maintained as in the original text.

Impact of Wastewater Irrigation on Agricultural Yields

Wastewater irrigation has emerged as a viable strategy to alleviate water scarcity while simultaneously improving soil nutrient status. However, its influence on crop yields is heterogeneous and largely dependent on the duration of application and the specific characteristics of the wastewater used. This section critically examines both the short-term and long-term yield responses, explores the underlying mechanisms driving these changes, contrasts wastewater irrigation with conventional freshwater practices, and discusses the broader environmental and economic implications (Table 3).

Although wastewater can supply essential water and nutrients, under certain conditions, it may induce substantial yield reductions in sensitive crops. Documented cases include summer moong, specific wheat cultivars, and chili, which have experienced adverse effects when irrigated with wastewater characterized by high salinity and the presence of toxic elements. For instance, summer moong has been reported to suffer a 15% decline in yield, a reduction linked to elevated sodium absorption ratios, marginal boron levels, and nickel accumulation that adversely affect rhizobial symbiosis, ultimately impairing pod formation and seed development (61). Similarly, wheat cultivars irrigated with undiluted petrochemical wastewater have shown drastic grain yield declines—ranging from 38% to 42%—attributed to physiological impairments such as chlorophyll degradation, diminished sucrose synthesis, and reduced xylem vessel diameters (41,45,66). In a controlled greenhouse study, lablab bean yield responded positively to both diluted (1:1) and undiluted wastewater irrigation, increasing by 2.0% and 165.7%, respectively, compared to groundwater. In contrast, tomato yield increased by 8.3% under diluted wastewater but decreased by 22.6% under full-strength wastewater. However, chili experienced complete fruit abortion under both wastewater treatments, resulting in a 100% yield loss. These results highlight the crop-specific effects of wastewater irrigation: dilution can mitigate phytotoxicity for some species, but others, such as chili, remain highly sensitive. This underscores the need for tailored irrigation strategies and further investigation into optimal wastewater concentrations for diverse crops (67).

The primary mechanisms implicated in these yield reductions are ionic toxicity and osmotic stress. High electrical conductivity and elevated sodium adsorption ratios in wastewater can disrupt plant water uptake and deteriorate soil structure, thereby impairing crop performance. Moreover, the phytotoxicity of heavy metals such as nickel, zinc, and copper interferes with key metabolic processes by inhibiting enzyme activities and inducing nutrient deficiencies (61,66). The potential introduction of wastewater-borne microbial pathogens further exacerbates stress by reducing nutrient uptake and increasing plant mortality via secondary infections (86).

Several mitigation strategies have been proposed to counter these adverse effects. Optimizing irrigation schedules—for example, implementing nighttime irrigation—can alleviate thermal stress and enhance fruit set in sensitive crops such as chili. In addition, the application of soil amendments, including biochar-chitosan composites, has been demonstrated to effectively chelate toxic metals, improve water retention, and restore nodulation in legumes. Blending treated wastewater with freshwater is another promising approach, as it can lower both the sodium adsorption ratio and the heavy metal load, thereby helping to sustain yield potential (61,67,87).

Short-Term versus Long-Term Effects on Crop Yields

In the short term, the use of nutrient-rich wastewater frequently results in enhanced crop yields. The immediate provision of essential macro- and micronutrients—such as nitrogen, phosphorus, and potassium—improves soil fertility and stimulates vigorous plant growth. In arid regions, for example, treated wastewater has been shown to elevate soil organic carbon levels and nutrient availability, thereby improving yields in crops like wheat and alfalfa (3,26). These benefits are ascribed mainly to a reduction in reliance on synthetic fertilizers.

In contrast, long-term wastewater irrigation induces a more complex yield response. Although initial yield benefits may persist for several years, continuous application often results in adverse soil modifications, including salt accumulation and heavy metal buildup. Over time, such negative changes—namely, increased soil salinity and heavy metal toxicity—can impair root development, reduce nutrient uptake, and ultimately cause a decline in yields (18,19,25,51,88). Moreover, prolonged exposure to wastewater can alter soil microbial communities in ways that further compromise soil health and productivity (4,27).

Nutrient Enhancements and Improvements in Soil Properties

Wastewater is typically rich in essential nutrients, and its application directly enhances soil fertility by increasing the concentrations of nitrogen, phosphorus, and potassium. These nutrient inputs can significantly boost plant growth rates, with yield improvements in some instances ranging from 11% to over 20% (3, 26, 49, 50). In addition to nutrient enrichment, the organic matter present in wastewater can improve soil physical properties by enhancing soil structure, water retention, and cation exchange capacity. These improvements create a more conducive environment for root development and nutrient absorption, thereby supporting higher crop yields (19,26).

Adverse Effects: Salinity and Heavy Metal Accumulation

Despite its benefits, long-term application of wastewater often leads to the accumulation of salts and heavy metals in the soil. Elevated salinity levels impose osmotic stress and ion toxicity, which reduce water uptake and adversely affect plant growth and yield (19,88). Furthermore, even at low concentrations, heavy metals can accumulate over time, posing risks to both plant health and food safety by entering the food chain (51,88). These deleterious effects may counterbalance the short-term advantages derived from nutrient enhancements.

Comparative Analysis with Conventional Freshwater Irrigation

Comparative studies frequently reveal that fields irrigated with wastewater yield higher outputs in the short term than those irrigated with conventional freshwater, primarily due to the nutrient enrichment effect (3,26). However, the long-term benefits of wastewater irrigation may diminish or even reverse because of salinity buildup and heavy metal accumulation, issues that are less prominent under freshwater irrigation conditions (49,50). Thus, while wastewater irrigation can serve as an effective short-term strategy—particularly in water-scarce regions—its long-term sustainability depends on the implementation of appropriate management practices to mitigate negative soil alterations (Table 3).

Environmental and Economic Implications

The effects of wastewater irrigation on crop yields have significant environmental and economic ramifications. Enhanced yields can contribute to food security by reducing the need for chemical fertilizers, thereby lowering both production costs and the environmental impacts associated with fertilizer manufacture (3,26). Higher yields may improve the profitability of agricultural operations, especially in arid and semiarid regions. Conversely, long-term risks such as soil degradation due to salinity and heavy metal contamination pose environmental hazards that may undermine agricultural sustainability and public health, potentially leading to increased costs for soil remediation and more stringent regulatory measures (18,51,88).

Interpretation of Heatmap: Impact of Wastewater Types on Soil and Environmental Parameters

The heatmap (Figure 4) provides a comparative overview of the relative impacts of different wastewater types—treated municipal, untreated urban, industrial, and agricultural—on key agro-environmental parameters, including soil organic carbon (SOC), soil nitrogen (N), crop yield, and greenhouse gas (GHG) emissions. Among the wastewater sources, untreated urban wastewater demonstrates the highest overall impact, particularly on SOC, soil nitrogen, and GHG emissions, each receiving the highest score of 3. This may be attributed to the higher organic and nutrient loads typically found in untreated urban effluents, which can significantly influence soil fertility and microbial activity, albeit with potential environmental trade-offs. In contrast, industrial wastewater exhibits the lowest impact across most parameters, scoring 1 for SOC, nitrogen, and crop yield, and slightly higher (2) for GHG emissions. This likely reflects the limited nutrient content in industrial effluents but also underscores the potential risks associated with toxic compounds not captured in this scoring system.

Treated municipal wastewater, while more regulated, still shows moderate to high impacts on agro-environmental variables, particularly in terms of crop yield (score of 3), indicating its potential value in agricultural productivity enhancement when appropriately managed. Agricultural wastewater, such as livestock or poultry effluents, exhibits uniformly moderate scores across all parameters, suggesting a balanced influence that may support soil fertility and crop performance without extreme increases in emissions. Collectively, the heatmap highlights the trade-offs involved in wastewater reuse, underscoring the need to tailor irrigation strategies based on wastewater type and desired agronomic or environmental outcomes. Effective treatment and monitoring remain crucial to maximizing benefits while minimizing potential negative impacts.

Future Research Directions

Further research is warranted to optimize wastewater irrigation practices for sustainable yield improvement. Key areas include:

Long-Term Impact Studies

Comprehensive, long-term experiments are essential to assess cumulative effects on soil properties, microbial communities, and crop yields.

Crop-Specific Responses

Research should explore differential responses among crop species to better tailor irrigation practices.

Advanced Wastewater Treatment

Investigating cost-effective treatment technologies that reduce salinity and heavy metal concentrations could enhance the viability of wastewater for irrigation.

Integrated Management Strategies

Developing approaches that combine wastewater irrigation with soil amendments, crop rotation, and other agronomic practices may mitigate adverse effects and promote overall sustainability.

Economic Analysis

Detailed cost-benefit analyses are needed to evaluate the economic sustainability of wastewater irrigation relative to conventional practices.

In summary, while wastewater irrigation can offer significant short-term improvements in crop yields via enhanced nutrient availability and improved soil properties, its long-term application poses challenges that require careful management. The balance between immediate yield benefits and the potential for long-term soil degradation, alongside the associated environmental and economic implications, underscores the need for continued research and the development of integrated management strategies.

Conclusion

This systematic review provides a comprehensive synthesis of the scientific literature examining the effects of wastewater irrigation on soil carbon and nitrogen dynamics, crop productivity, and environmental sustainability. Across diverse agroecosystems, evidence consistently demonstrates that short-term wastewater irrigation enhances soil organic carbon (SOC) and nitrogen availability, leading to notable improvements in crop yields. These immediate agronomic benefits stem from the input of readily available nutrients and organic matter that stimulate microbial activity, improve soil structure, and reduce reliance on synthetic fertilizers—particularly valuable in water-scarce regions.

However, the long-term sustainability of wastewater irrigation is constrained by several environmental trade-offs. Prolonged application often results in soil salinization, heavy metal accumulation, and altered microbial communities, which collectively compromise soil health and reduce productivity over time. Furthermore, wastewater irrigation significantly elevates greenhouse gas (GHG) emissions—particularly CO_2, N_2O, and CH_4—due to intensified organic matter decomposition and nitrogen transformation processes. These emissions contribute to climate change and represent a key environmental cost of this practice.

The review underscores the importance of managing wastewater irrigation through integrated strategies. Optimized treatment processes, precise irrigation scheduling, routine soil monitoring, and the use of soil amendments (e.g., biochar or compost blends) are essential to mitigate salinity, toxicity, and GHG emissions. Furthermore, the variability in wastewater composition and soil responses necessitates localized management approaches tailored to specific crop types, soil characteristics, and climatic conditions.

Future research should prioritize long-term, field-based experiments that assess cumulative ecological impacts and explore crop-specific responses under varying wastewater qualities. Studies integrating agronomic performance, soil microbiome shifts, and economic viability will be critical to developing evidence-based guidelines for sustainable reuse. Additionally, interdisciplinary research linking wastewater reuse with food safety, regulatory policy, and climate mitigation is vital to advance holistic and resilient agricultural systems.

In conclusion, wastewater irrigation presents both opportunities and challenges. When carefully managed, it can support agricultural productivity and resource conservation. However, without appropriate safeguards, its long-term application risks undermining environmental and soil system integrity. A paradigm of adaptive, evidence-informed management is therefore essential to realize the benefits of wastewater reuse while safeguarding ecosystem health and agricultural sustainability.

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The authors declare that there is no conflict of interest.

Ethical issues

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