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GEOCHEMICAL AND PHYSICOCHEMICAL RESPONSES OF AGRICULTURAL SOILS TO LONG-TERM TREATED WASTEWATER IRRIGATION IN DAVANAGERE, INDIA

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ABSTRACT
Reuse of treated municipal wastewater for irrigation is increasingly practiced in water-scarce regions; however, its long-term impacts on soil physicochemical and geochemical properties require systematic evaluation. This study investigates the effects of prolonged treated wastewater irrigation on agricultural soils in Davanagere, Karnataka, India. Thirty composite surface soil samples (0-15 cm) were collected from agricultural fields located within Zone 3 (2-3 km) of the municipal sewage treatment plant (STP). The samples were analysed for physicochemical properties, macronutrients, micronutrients, and heavy metals using standard analytical techniques, including pH and Electrical Conductivity (EC) measurements, wet oxidation for organic carbon, Olsen's method for phosphorus, flame photometry for potassium, and atomic absorption spectrophotometry for micronutrients and trace metals. The soils exhibited moderately alkaline pH (7.50-7.97; mean 7.80) with low salinity (EC 0.03-0.46 dS/m). Organic carbon ranged from 0.97-1.45%, indicating enrichment due to organic inputs from treated wastewater. Macronutrients showed substantial accumulation, with Total nitrogen ranging from 1258-1854 kg/ha, phosphorus 145.83-322.81 kg/ha, and potassium 105.5-278.55 kg/ha. Micronutrients were within agronomically optimal ranges. Trace metals including Pb (0.98-2.15 ppm), Cr (0.17-0.32 ppm), Cd (0.19-0.405 ppm), and Ni (1.46-2.22 ppm) were detected but remained within permissible soil quality limits. The findings indicate that treated wastewater irrigation enhances soil fertility through increased organic matter and nutrient availability while causing gradual accumulation of trace metals. Although current levels remain within acceptable limits, continuous monitoring is necessary to ensure the long-term sustainability of wastewater reuse in agriculture.

Keywords: Treated wastewater irrigation; Soil fertility; Heavy metals; Nutrient enrichment; Soil quality assessment.

Introduction
The shortage of freshwater has become one of the most significant challenges facing agricultural and environmental systems worldwide. Rapid urbanisation, population growth, climate variability, industrial expansion, and increasing food demand have intensified pressure on limited freshwater resources. Agriculture accounts for a major share of global freshwater consumption, making sustainable water resource management essential for ensuring long-term food security. In this context, the reuse of treated municipal wastewater for irrigation has gained increasing attention as a viable alternative water resource, particularly in arid, semi-arid, and peri-urban regions where conventional freshwater supplies are insufficient. The utilisation of treated municipal wastewater for irrigation offers several advantages. It contributes to water conservation, reduces the discharge of untreated effluents into natural water bodies, and supplies essential nutrients such as nitrogen, phosphorus, and potassium that can enhance soil fertility and crop productivity. Wastewater reuse also supports circular economy principles by promoting the recovery and reuse of water and nutrients within agricultural systems. Consequently, many countries have incorporated wastewater reuse into integrated water resource management strategies. However, despite these agronomic benefits, long-term irrigation with treated wastewater may alter soil physicochemical properties and pose potential risks to soil health and environmental sustainability.

Municipal wastewater typically contains a complex mixture of dissolved salts, organic matter, nutrients, microorganisms, and trace metals. While these constituents can increase soil organic carbon and nutrient availability, continuous irrigation with treated effluent may also lead to undesirable effects such as soil salinisation, sodicity, nutrient imbalance, and accumulation of potentially toxic elements. These processes may influence soil structure, microbial activity, nutrient cycling, and metal mobility, thereby affecting soil productivity and ecological stability. Previous studies have reported significant differences in soil physicochemical properties and heavy metal concentrations between wastewater-irrigated soils and freshwater-irrigated soils, highlighting the dual role of wastewater reuse as both a beneficial resource and a potential environmental concern.Despite increasing adoption of treated wastewater irrigation worldwide, limited studies have examined the spatial variability of soil quality in relation to distance from sewage treatment plants, particularly in medium-sized urban regions of developing countries. Understanding how soil properties respond to varying levels of wastewater exposure is essential for evaluating the long-term sustainability of wastewater irrigation practices. However, comprehensive spatial assessments that integrate soil physicochemical properties, nutrient enrichment, and trace metal accumulation remain relatively scarce in the Indian context.

An important yet often overlooked aspect of wastewater irrigation is its spatial variability. The intensity and composition of effluent exposure generally decrease with increasing distance from sewage treatment plants, resulting in heterogeneous patterns of soil modification. Soils located closer to treatment facilities are typically subjected to higher concentrations of nutrients and contaminants, whereas soils at greater distances experience diluted effects due to mixing with surface or groundwater sources.

Against this background, the present study adopts a zonal framework based on distance from a municipal sewage treatment plant (STP) to evaluate the physicochemical and geochemical characteristics of soils subjected to long-term treated wastewater irrigation in Davanagere, Karnataka, India. The study area was divided into three zones: Zone 1 (0-1 km from the STP), Zone 2 (1-2 km), and Zone 3 (2-3 km). The objective of this study is to evaluate the physicochemical properties, nutrient status, and trace metal accumulation in agricultural soils irrigated with treated municipal wastewater in Zone 3 (2-3 km from the STP). By analysing soil physicochemical parameters, macronutrients, micronutrients, and trace metals within a spatial framework, this study aims to provide insights into the long-term impacts of treated wastewater irrigation on soil quality. The findings are expected to contribute scientific evidence for sustainable wastewater reuse practices and support informed decision-making in agro-environmental management.

STUDY AREA
Davanagere is located in central Karnataka, India, at approximately 14.50° N latitude and 75.91° E longitude. The region has experienced rapid population growth and urban development, leading to increased generation of municipal wastewater. To manage this wastewater, the city operates STPs, and the treated effluent is discharged into irrigation canals that supply water to surrounding agricultural lands. The study area experiences a semi-arid tropical climate, with an average annual rainfall of approximately 600-650 mm, most of which occurs during the southwest monsoon season. The mean annual temperature ranges between 20°C and 36°C. The soils in the region are clay and red loamy soils, which are moderately fertile and suitable for a variety of agricultural crops. Figure 1 shows the geographical location of the study area and the surrounding agricultural lands irrigated with treated wastewater.

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Agricultural fields located near the STP are commonly irrigated with treated wastewater conveyed through canal systems. Farmers in nearby villages frequently use this treated effluent as a primary irrigation source, particularly during periods of freshwater scarcity. Major crops cultivated in the area include paddy, maize, sugarcane, and vegetable crops, which benefit from the nutrient-rich characteristics of treated wastewater. Consequently, wastewater irrigation has become an important factor influencing soil fertility and agricultural productivity in the region.

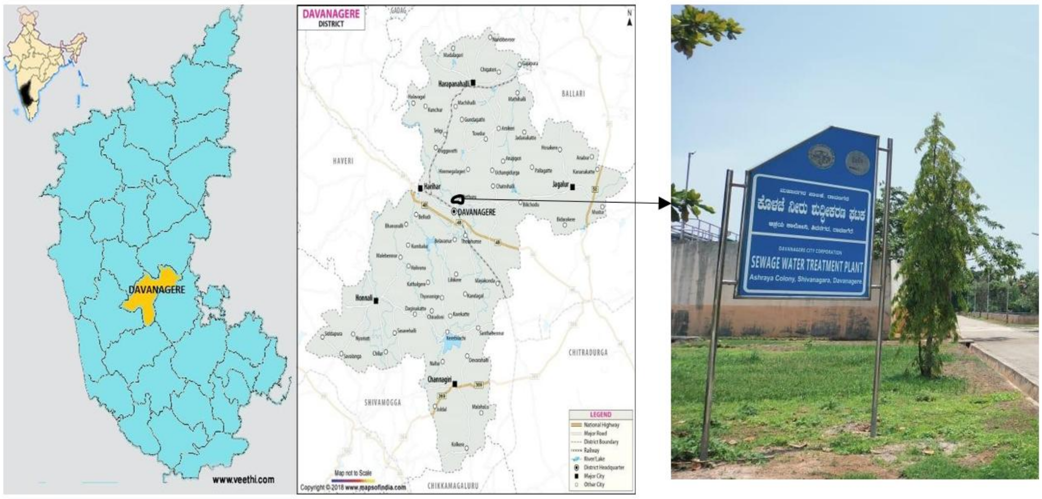

Fig 1: Study area

MATERIALS AND METHODS

Study Design and Zonal Framework: The study was designed to evaluate the impact of long-term treated wastewater irrigation on soil quality using a spatial zonation approach. Agricultural fields irrigated with treated effluent from the municipal STP were categorised based on their distance from the STP. Zone 3, located at a distance of 2-3 km from the STP, was selected to assess the residual and cumulative effects of treated wastewater irrigation under comparatively reduced exposure conditions. This zonal framework enabled the assessment of spatial variability in soil physicochemical and geochemical properties under long-term effluent influence.

Soil Sampling: Soil samples were collected from agricultural fields regularly irrigated with treated wastewater within Zone 3 (2-3 km from the STP). Soil sampling was carried out in June 2025 during the post-harvest period. A V-shaped sampling approach was adopted to ensure representative spatial coverage of each field. In this method, soil samples were collected along a V-shaped transect across the field to capture spatial variability in soil properties as per Indian Council of Agricultural Research (ICAR) Standards. Within each sampling site, soil was collected from multiple points in a zigzag pattern and homogenised to form composite samples.

The quartering method was employed to obtain representative subsamples, and approximately 0.5 kg of soil was retained from each composite sample for laboratory analysis. In total, thirty composite soil samples were collected from different farms within the study area, providing a statistically meaningful dataset for evaluating soil quality parameters. Surface soil samples from 0-15 cm depth were collected, as this layer is most responsive to irrigation-induced changes and directly influences crop growth and nutrient dynamics. All samples were air-dried, gently crushed, and sieved through a 2 mm mesh before analysis to ensure uniformity and analytical accuracy.

Analytical Procedures: Soil samples were analysed for physicochemical properties, macronutrients, micronutrients, and heavy metals using standard and widely accepted analytical procedures at the Bio Centre Laboratory, Shivamogga, India. Soil parameters and their corresponding analytical methods are presented in Table 1. Soil pH was measured in a soil-water suspension using a calibrated digital pH meter, while electrical conductivity (EC) was determined using a conductivity meter to assess soil salinity. Organic carbon (OC) was estimated using the wet oxidation method, which provides an index of soil organic matter content.

Total Nitrogen (TN) was determined by Kjeldahl's Method, Available phosphorus was determined using the Olsen method, which is suitable for neutral to alkaline soils, and potassium was measured using a flame photometer. Micronutrients including Iron (Fe), Manganese (Mn), Zinc (Zn), and Copper (Cu), along with Calcium (Ca) and Magnesium (Mg), were quantified using Atomic Absorption Spectrophotometry (AAS).

For heavy metal analysis, soil samples were subjected to acid digestion using a nitric-perchloric acid mixture prior to analysis, and the concentrations of Lead (Pb), Chromium (Cr), Cadmium (Cd), and Nickel (Ni) were determined using Atomic Absorption Spectrophotometry (AAS). To ensure analytical reliability, all analyses were performed in triplicate, and standard calibration procedures were followed. Quality control measures included the use of reagent blanks, standard reference materials, and repeated measurements to minimise analytical errors. Descriptive statistical parameters such as minimum, maximum, mean, and standard deviation were calculated to characterise the variability of soil properties across the study area.

Table 1. Soil parameters and analytical methods

Parameter	Method
pH	Digital pH meter
EC	Electrical conductivity meter
Organic Carbon	Wet Oxidation Method (Walkley-Black)
Total Nitrogen	Kjeldahl's Method
Phosphorous	Olsen's method
Potassium	Flame photometer
Micro-nutrients, Ca and Mg	Atomic Absorption Spectrophotometer
Heavy metals	Acid digestion followed by Atomic Absorption Spectrophotometer (AAS)

RESULTS AND DISCUSSION

This section presents a comprehensive evaluation of soil physicochemical and geochemical characteristics in Zone 3 under long-term treated wastewater irrigation. A total of thirty soil samples were collected from agricultural lands located within a 2-3 km radius of the STP and analysed to assess the influence of effluent irrigation on soil quality. The results are interpreted in the context of soil fertility, environmental sustainability, and potential ecological risks, with reference to relevant standards. Table 2 presents the statistical summary of analysed soil parameters.

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Table 2: Analysed Soil Characteristics

Parameter	Zone 3			
	Min	Max	Mean	± SD
pH	7.5	7.97	7.80	0.11
EC (dS/m)	0.03	0.46	0.30	0.10
OC %	0.97	1.45	1.21	0.12
TN (kg/ha)	1258	1854	1570.83	152.77
P (kg/ha)	145.83	322.81	229.86	50.52
K (kg/ha)	105.5	278.55	203.82	45.20
Fe (ppm)	24.97	37.22	31.12	3.65
Mn (ppm)	9.18	24.24	15.46	4.24
Zn (ppm)	0.67	3.31	2.02	0.83
Cu (ppm)	1.11	4.69	3.57	0.75
Ca (ppm)	244.37	945.32	619.87	181.19
Mg (ppm)	99.37	266.2	205.27	35.99
B (ppm)	0	0.16	0.1	0.03
Pb (ppm)	0.98	2.15	1.56	0.34
Cr (ppm)	0.17	0.32	0.22	0.03
Cd (ppm)	0.19	0.405	0.29	0.06
Ni (ppm)	1.46	2.22	1.87	0.22

Soil Physicochemical Properties: Soil pH in the study area ranged from 7.50 to 7.97, with a mean value of 7.80 ± 0.11, indicating moderately alkaline soil conditions typical of wastewater-irrigated agricultural fields. The observed alkalinity may be attributed to the presence of bicarbonates, carbonates, and dissolved salts in treated wastewater, which influence soil buffering capacity and nutrient dynamics. Moderately alkaline soils generally favour the growth of many agricultural crops; however, persistent alkalinity may affect the solubility and availability of certain micronutrients and trace metals over time. EC values ranged from 0.03 to 0.46 dS/m, with a mean of 0.30 ± 0.10 dS/m, indicating low salinity levels and minimal immediate risk of salt stress in the study area. These findings suggest that treated wastewater irrigation in Zone 3 has not yet resulted in significant salt accumulation in soils. However, the variability in EC values across sampling locations indicates spatial heterogeneity in salt distribution, which may increase with prolonged effluent irrigation. Therefore, periodic monitoring of soil salinity is essential to prevent potential long-term soil degradation. OC content varied from 0.97% to 1.45%, with a mean value of 1.21 ± 0.12%, reflecting enrichment of soil organic matter due to continuous inputs of organic residues from treated wastewater. Increased organic carbon enhances soil structure, water-holding capacity, microbial activity, and nutrient retention. The relatively high OC levels observed in Zone 3 soils therefore indicate the beneficial contribution of treated wastewater irrigation to soil fertility. Similar increases in soil organic matter under wastewater irrigation have been reported in previous studies. Overall, the physicochemical characteristics of soils in Zone 3 suggest that treated wastewater irrigation has contributed to improved soil fertility while influencing soil chemical properties. Although current conditions remain within acceptable ranges, prolonged wastewater application may gradually modify soil reaction and salinity levels. Therefore, continuous monitoring and appropriate management practices are necessary to ensure the sustainable use of treated wastewater in agricultural systems.

Macronutrient Status: Macronutrient concentrations in the study area indicated substantial enrichment under treated wastewater irrigation. Total nitrogen ranged from 1258 to 1854 kg/ha with a mean value of 1570.83 ± 152.77 kg/ha, phosphorus ranged from 145.83 to 322.81 kg/ha (mean 229.86 ± 50.52 kg/ha), and potassium ranged from 105.5 to 278.55 kg/ha (mean 203.82 ± 45.20 kg/ha). The elevated concentrations of these essential macronutrients indicate the continuous supply of nutrients through treated wastewater irrigation, reflecting its significant fertilising effect on soil. The enrichment of N, P, and K contributes to improved soil fertility and enhanced crop productivity while reducing dependence on synthetic fertilisers. From an agronomic perspective, treated wastewater acts as an additional nutrient source that supports nutrient cycling and improves resource-use efficiency in agricultural systems. However, long-term accumulation of macronutrients, particularly nitrogen and phosphorus, may lead to nutrient imbalance and increase the risk of nutrient losses through leaching and surface runoff. Such losses may contribute to groundwater contamination and eutrophication of nearby water bodies, posing potential environmental concerns.

The observed variability in macronutrient concentrations across the sampling locations suggests that nutrient enrichment is influenced by factors such as irrigation intensity, soil texture, and organic matter content. These findings are consistent with previous studies reporting higher nutrient levels in wastewater-irrigated soils compared with soils irrigated using freshwater. Therefore, balanced nutrient management and regular soil monitoring are essential to maximise the agronomic benefits of treated wastewater while minimising potential environmental risks.

Micronutrients: Micronutrient concentrations in the soils indicated adequate availability of essential elements required for plant growth. Fe concentrations ranged from 24.97 to 37.22 ppm with a mean value of 31.12 ± 3.65 ppm, Mn ranged from 9.18 to 24.24 ppm (mean 15.46 ± 4.24 ppm), Zn ranged from 0.67 to 3.31 ppm (mean 2.02 ± 0.83 ppm), and Cu ranged from 1.11 to 4.69 ppm (mean 3.57 ± 0.75 ppm). These concentrations indicate sufficient levels of micronutrients necessary for plant growth and metabolic functions. Ca concentrations varied from 244.37 to 945.32 ppm with a mean value of 619.87 ± 181.19 ppm, while Mg ranged from 99.37 to 266.20 ppm (mean 205.27 ± 35.99 ppm). The relatively higher concentrations of Ca and Mg may be associated with the mineral composition of treated wastewater and its influence on soil buffering capacity and nutrient balance. Boron concentrations ranged from 0.00 to 0.16 ppm with a mean of 0.10 ± 0.03 ppm, indicating low accumulation and minimal risk of boron toxicity in the study area. Overall, the micronutrient profile suggests that treated wastewater irrigation contributes positively to soil nutrient availability. Adequate micronutrient levels can enhance crop growth and productivity; however, prolonged wastewater application may lead to excessive accumulation of certain elements over time. The variability observed in micronutrient concentrations among the sampling locations reflects the influence of site-specific factors such as soil characteristics, irrigation intensity, and management practices. Therefore, periodic monitoring and appropriate soil management strategies are essential to maintain balanced nutrient levels and ensure sustainable agricultural production.

Heavy Metals

Trace metals, including Pb, Cr, Cd, and Ni, were detected at relatively low concentrations in the analysed soil samples. Pb concentrations ranged from 0.98 to 2.15 ppm with a mean value of 1.56 ± 0.34 ppm, while Cr varied from 0.17 to 0.32 ppm (mean 0.22 ± 0.03 ppm). Cd concentrations ranged from 0.19 to 0.405 ppm (mean 0.29 ± 0.06 ppm), and Ni ranged from 1.46 to 2.22 ppm with a mean value of 1.87 ± 0.22 ppm. All measured concentrations were within the permissible limits suggested by international soil quality guidelines.

Although the concentrations remained within acceptable limits, the presence of Cd and Ni indicates a gradual accumulation that may be associated with long-term application of treated wastewater. The distribution and retention of heavy metals in soils are strongly influenced by soil physicochemical properties such as pH and organic carbon content. In the present study, the moderately alkaline pH and relatively high organic carbon content may have enhanced the adsorption and immobilisation of metals within the soil matrix, thereby reducing their mobility.

While the current concentrations do not pose immediate environmental risks, continued application of treated wastewater may result in gradual accumulation of trace metals in soils. Over time, this accumulation may increase the potential for metal transfer to crops and entry into the food chain. Therefore, periodic monitoring of heavy metal concentrations and implementation of appropriate soil management practices are essential to ensure the sustainable use of treated wastewater in agricultural systems.

The analysed soil parameters were compared with the fertility rating standards recommended by the Indian Council of Agricultural Research (ICAR), and the comparison is presented in Table 3.

Table 3: Comparison of Soil Fertility Parameters with ICAR Soil Fertility Rating Standards

Parameter	Observed Mean Value	ICAR Standard Range	Interpretation
pH	7.80	6.5-7.5 (neutral); 7.5-8.5 (slightly alkaline)	Slightly alkaline soil
EC (dS/m)	0.30	<1.0 (non-saline)	Non-saline
Organic Carbon (%)	1.21	<0.5 low; 0.5-0.75 medium; >0.75 high	High
Total Nitrogen (kg/ha)	1570.83	<280 low; 280-560 medium; >560 high	High
Phosphorus (kg/ha)	229.86	<22 low; 22-56 medium; >56 high	High
Potassium (kg/ha)	203.82	<108 low; 108-280 medium; >280 high	Medium
Fe (ppm)	31.12	>4.5 sufficient	Sufficient
Mn (ppm)	15.46	>2 sufficient	Sufficient
Zn (ppm)	2.02	>0.6 sufficient	Adequate
Cu (ppm)	3.57	>0.2 sufficient	Adequate
B (ppm)	0.10	<0.5 low	Low

Implications for Agro-Environmental Sustainability: The findings of this study indicate that the use of treated wastewater for irrigation can provide considerable agronomic benefits through the enrichment of soil nutrients and enhancement of organic matter content. These improvements contribute to better soil fertility, increased microbial activity, and enhanced crop productivity, thereby reducing the reliance on synthetic fertilisers in agricultural systems. However, the gradual accumulation of dissolved salts and trace metals observed in the soils highlights potential long-term risks to soil quality and environmental sustainability. Continuous application of treated wastewater may lead to progressive buildup of contaminants, which could affect soil health, groundwater quality, and the safety of agricultural produce if not properly managed.Therefore, sustainable management of wastewater irrigation requires regular soil quality monitoring, optimisation of irrigation practices, and balanced nutrient management strategies. Integrating these measures can help maximise the agronomic benefits of treated wastewater while minimising potential environmental risks, thereby ensuring the long-term sustainability of wastewater reuse in agricultural systems.

Conclusion

This study assessed the physicochemical and geochemical characteristics of agricultural soils subjected to long-term treated wastewater irrigation in Zone 3 (2-3 km from the sewage treatment plant) in Davanagere. The results indicate that treated wastewater irrigation has positively influenced soil fertility by increasing organic carbon and essential macronutrients while maintaining soil pH and salinity within acceptable ranges. These findings highlight the potential of treated wastewater as a supplementary irrigation resource capable of enhancing soil productivity in water-scarce regions. However, the analysis also revealed a gradual accumulation of trace metals, particularly cadmium and nickel, although their concentrations remained within permissible limits. The interaction between soil pH, organic carbon content, and metal adsorption processes appears to play an important role in regulating the mobility and retention of metals in wastewater-irrigated soils. While the current levels do not pose immediate environmental risks, continuous application of treated wastewater may lead to progressive accumulation of contaminants over time. Overall, treated wastewater irrigation offers significant agronomic benefits but also requires careful management to avoid potential environmental impacts. Therefore, sustainable utilisation of treated wastewater in agriculture should involve regular soil quality monitoring, balanced nutrient management, and optimised irrigation practices. Spatially based soil quality assessments such as the present study are essential for supporting safe and long-term wastewater reuse in agricultural systems.

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