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Sewage water and sludge co-implementation effects on soil properties and green chili in Typic Haplustalf of southern India

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Sewage water and sludge provide a viable option to meet crop water and nutrient demands in the face of rising climatic stress. Thus, a 2-year field study (2018 and 2019) was conducted to evaluate the effect of sewage water and sludge on soil properties and the growth response of green chili. The experiment comprised nine treatment combinations involving three types of irrigation water: normal water (I₁), treated sewage water (I₂), untreated sewage water (I₃) along with three soil amendments: farmyard manure (FYM) at 25 t ha⁻¹ (SA₁), sewage sludge at 25 t ha⁻¹ (SA₂), and a mix of sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹ (SA₃). Soil-available nutrient status of N, P, and K increased by ~10%–15%, ~14%–20%, and ~13%–18%, respectively, in I₃ and SA₂. Sewage water and sludge application further improved soil microbial populations, which included actinomycetes, fungi, and bacteria. Concurrently, multivariate analysis of variance (MANOVA) demonstrated a positive influence of irrigation and soil amendments on soil properties. Across both study years, I₃ and SA₂ recorded a higher mean green chili

yield, with an improvement of approximately 25% over I_1 and SA_1 . Hence, the findings reveal the feasibility of harnessing sewage water resources as sustainable inputs, advancing both resource efficiency and short-term agricultural sustainability in the region.

KEYWORDS

ascorbic acid, green chili yield, sewage sludge, soil properties, untreated sewage water

1 Introduction

India's growing urbanization and industrialization have resulted in significant increases in wastewater creation, delivering enormous issues for waste management and environmental protection. Simultaneously, the agricultural sector faces mounting pressure to meet the food demands of a growing population while contending with the issues of soil degradation and water scarcity. In this context, the co-implementation of sewage water and sludge (SW and S) in agriculture has emerged as a feasible strategy for augmenting waste management and agricultural sustainability (Singh and Agrawal, 2008). The sewage generation in India has amplified from 7,067 million liters daily (MLD) in 1978–1979 to 62,000 MLD in 2014–2015 (Central Pollution Control Board, New Delhi, 2021), which creates the problem of safe disposal of sewage generation in the years to come with rapid urbanization. Indeed, the nutrient potential of available sewage in India is more than 33,000 tons (t) of nitrogen (N), 700 t of phosphorus (P), and 20,000 t of potassium (K) year⁻¹ (Nischitha et al., 2020). Therefore, the application of SW and S in agricultural land can ecologically link nutrient usage between urban and nearby rural agricultural landscapes (Antoniadis et al., 2015).

The Typic Haplustalf soils, commonly found in southern India, are characterized by their moderate fertility and water-holding capacity, making them suitable for a range of crops, including green chili (*Capsicum annuum* L.) (Srinivasarao et al., 2012). However, it often entails additional inputs to maintain optimal fertility and productivity, particularly under intensive cultivation. Therefore, application of SW and S has the potential to improve soil physical, chemical, and biological properties, offering a sustainable approach to enhancing soil health and crop yields. Also, adding SW and S had substantial impacts on the soil's biological properties by encouraging microbial activity and growth, which led to higher enzyme activities, microbial biomass carbon, and N mineralization

rates (Singh and Agrawal, 2010; Asghar et al., 2023). The enhanced soil biological activity further improves the nutrient cycling, organic matter decomposition, and overall soil health (Garg and Kaushik, 2005). Studies have shown that applying SW and S in a controlled manner could increase the buildup of soil organic carbon (SOC) in the soil, make nutrients more available, and increase microbial activity (Meli et al., 2002). Additionally, SW and S can serve as potential sources of viral contaminants in groundwater, thereby reducing the quality of drinking water and further affecting biogeochemical processes and overall ecosystem functioning (Baloch et al., 2025a).

Recent studies recognize wastewater reuse for agricultural irrigation as a sustainable strategy to mitigate water scarcity and enhance crop productivity while also highlighting challenges related to soil salinity, heavy metal accumulation, pathogen exposure, and associated human health risks (Lamma, 2021; Mishra et al., 2023). Human health risk assessments consistently identify ingestion as the dominant exposure pathway, with children being more susceptible to both carcinogenic and non-carcinogenic risks, particularly from metals such as Cd, Ni, Cr, and Zn, whose ecological and health impacts are strongly governed by metal speciation and wastewater treatment processes (Nyashanu et al., 2023; Tytla and Widziewicz-Rzońca, 2023; Ilić et al., 2024). Emerging evidence further indicates that wastewater irrigation influences soil microbiome structure in a water-quality-dependent manner, facilitating the transfer of waterborne bacteria to soil, increasing microbial biomass, altering dominant bacterial phyla, and affecting key nitrogen-cycling functional groups, with potential implications for soil health and nutrient dynamics (Moulija et al., 2023). However, most recent studies remain limited to sludge characterization, microbial or chemical risk indices, or short-term assessments under controlled conditions, with little integration of treated and untreated wastewater irrigation, graded sewage sludge amendments, and conventional organic inputs at the field scale. Additionally, a 6-month study conducted by Buckerfield et al. (2020) with a high-resolution spatial study of *Escherichia coli* in catchment drainage waters to evaluate wastewater-driven contamination transport and associated health risks showed that fecal contamination from wastewater remains a major pathway for pathogen exposure in developing regions. In contrast, the present study adopts a controlled factorial field experiment combined with sewage treatment plant (STP)-based irrigation water and sludge

Abbreviations: AA, ascorbic acid; BOD, biological oxygen demand; cfu, colony-forming units; COD, chemical oxygen demand; DW, dry weight; EC, electrical conductivity; *E. coli*, *Escherichia coli*; ns, non-significant; FYM, farmyard manure; g, gram; SOC, soil organic carbon; kg, kilogram; L, liter; MC, Murda complex; mg, milligram; SW and S, sewage water and sludge; t ha⁻¹, ton per hectare; WI, wilt incidence; Y, yield; SBR, sequence batch reactor; SS, sewage sludge; SW, sewage water.

characterization, providing a holistic, management-oriented evaluation of agronomic performance, soil quality, and environmental safety under realistic cropping conditions.

The co-implementation of SW and S may offer synergistic benefits for soil health and crop productivity (Lu et al., 2012). The combined application of these waste products could potentially provide a more balanced nutrient supply, improve soil physical properties, and enhance microbial diversity and activity more effectively than either of the inputs alone (Akponikpe et al., 2011). Additionally, sewage sludge can be used for reclaiming saline and alkali soils apart from increasing crop productivity (Baloch et al., 2023). However, the specific impacts of co-implementation on soil properties and crop performance may vary depending on soil type, climatic conditions, and crop species. Green chili (*Capsicum annum* L.) is an important cash crop in India, valued for its nutritional content and economic potential. The crop has shown variable responses to SW and S applications in different soil types, with some studies reporting increased yield and fruit quality, while others highlight concerns about heavy metal accumulation in plant tissues (Iqbal et al., 2014). A study conducted by Lustosa et al. (2025) reported that sewage sludge biochar enhanced the productivity of maize and wheat; however, the potential negative impacts were not given adequate attention. Likewise, a field experiment by Mlaiki et al. (2025) demonstrated that sewage sludge application increased soil organic matter, but the study primarily focused on heavy metal accumulation and did not address the potential risk of disease occurrence associated with sewage sludge use. Hence, in our current study investigating the effects of SW and S co-implementation on green chili performance in Typic Haplustalf soils could provide valuable insights for optimizing crop management practices and potential plant disease risk in this specific soil–crop system. Furthermore, the combined application of SW and S can also be explored in the present study. Understanding the impacts of the combined application of SW and S on these soils is crucial for developing sustainable management practices that balance crop productivity with environmental safety.

Therefore, the current study seeks to determine optimal application rates, assess potential synergistic effects, and evaluate their impacts on soil health and crop productivity. The study hypothesizes that co-implementation of SW and S may improve the chemical and biological properties of Typic Haplustalf soils in the southern transition zone of Karnataka, leading to improved growth, yield, and quality of green chili in comparison to conventional cultivation.

2 Materials and methods

2.1 Site and weather conditions

A 2-year field experiment was conducted at the College of Agriculture, Shivamogga, Karnataka, during the summer seasons of 2018 and 2019 to study the effect of SW and S influence on soil

chemical and biological properties and their subsequent impact on green chili performance. The experimental site was situated in the Southern Transitional Zone of Karnataka at 13°58'13.9"N latitude to 75°34'43.0"E longitude, and the sewage treatment facility was located close to the field experiment location, as shown in Figure 1.

The soil of the experimental site was sandy loam in texture and falls under Typic Haplustalf. Soil was slightly acidic (1:2 soil:water), with low KMnO_4 oxidizable N (210 kg ha^{-1}), medium 0.5 M NaHCO_3 extractable P (21.2 kg ha^{-1}), and 1 N NH_4OAc extractable K (270.1 kg ha^{-1}). During the crop growth period (March to June) in 2018 and 2019, an average of 369 mm of rainfall was received, and the actual monthly mean maximum and minimum temperatures were slightly lower than the respective normal temperatures. The rainfall was higher than normal in all the months, viz., March (+2.71 mm), April (+18.21 mm), May (+77.73 mm), and June (+23.7 mm). Excess rainfall at the later stage of the crop affected reproductive growth slightly (Supplementary Figure 1). The relative humidity during the cropping period varied between 61% and 89%.

2.2 Treatment of sewage water

The sewage collected from the College of Agriculture Shivamogga campus was first directed into the sewage treatment plant (STP) through a screen chamber, where it retained the coarse solids like paper and cloth and reduced the load on the treatment plant. The detailed process of sewage treatment is shown in the flowchart (Figure 2). After passing through screen filters, the effluent was guided to the equalization tank to maintain an equal rate of effluent flow into the reactor, which reduces biological oxygen demand (BOD) to an extent of 10%–20%. STP had a sequence batch reactor (SBR), where aeration, sedimentation, and clarification were carried out. After passing through the SBR, the excess sludge was dewatered and dried from the biological treatment process in sludge drying beds; this was used as sewage sludge (SS), serving as a source of soil amendment. The treated water was then discharged into filtered water tanks. Finally, treated water was made to pass through pressure sand filters and activated carbon filters to remove the minute suspended solids, including escaped particulate BOD from the settling tank and bad odor and improve the color of the water. Ultimately, the water was treated with chlorine to disinfect it from bacteria and fungus before being used for irrigation.

2.3 Physicochemical analysis of irrigation water and soil amendment sources

Irrigation water and soil amendment sources were analyzed for physicochemical characteristics. A minimum of three representative samples of irrigation source, viz., normal water (I_1), treated sewage water (I_2), and untreated sewage water (I_3), was collected from the outlet source and analyzed before each irrigation cycle. Similarly, soil amendments, viz., farmyard manure (FYM) and sewage sludge

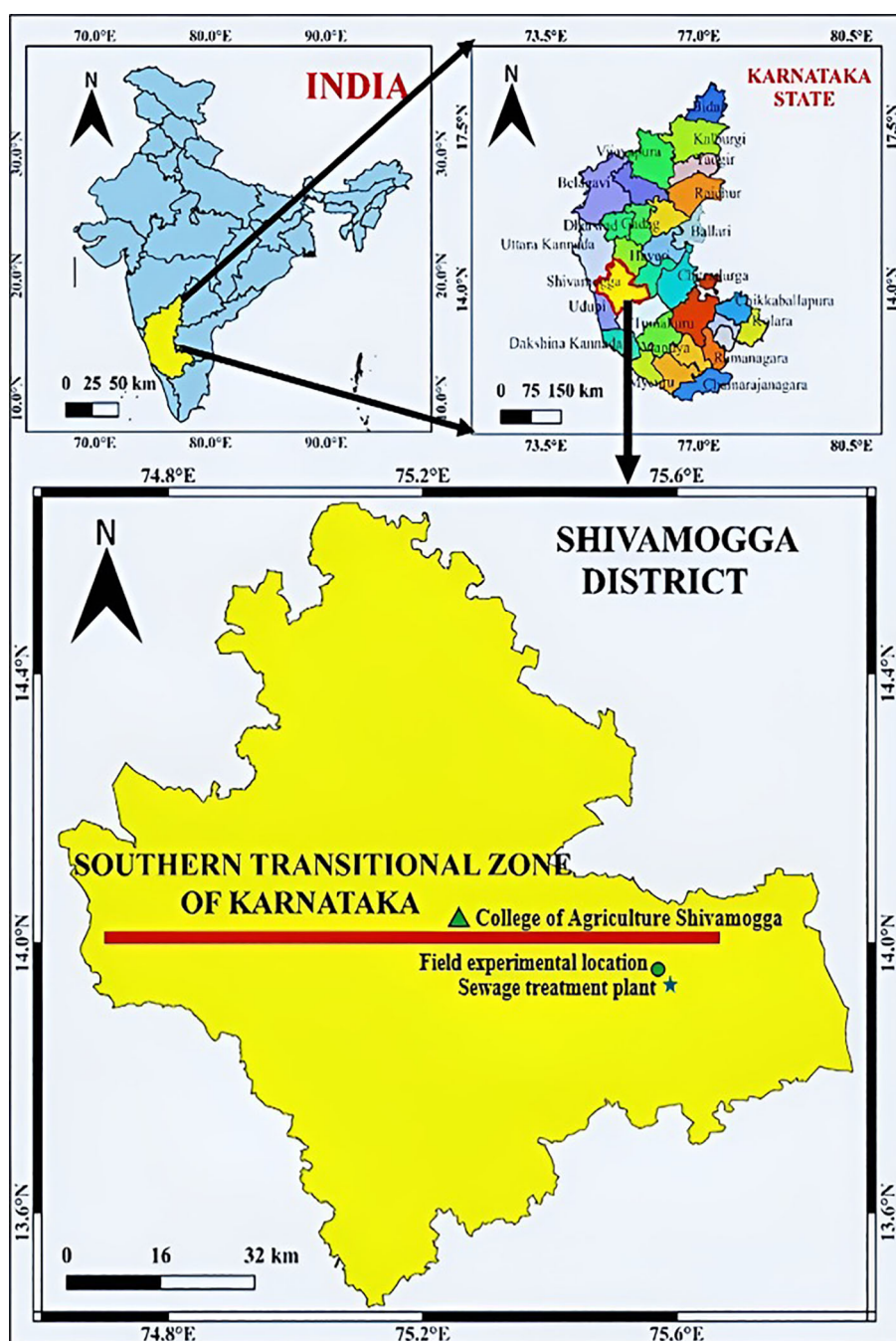


FIGURE 1

Location of the field experiment indicating the southern transition zone of Karnataka along with the experimental location and sewage treatment plant.

(SS) samples taken from the FYM pit and sludge drying beds, respectively, were dried under shade and passed through a 2-mm sieve to remove the impurities, and then the samples were finely ground to achieve homogeneity. The processed samples were stored in plastic containers for further analysis. Each sample was split into at least three replicates, and the parameters as well as the methodology used to characterize the irrigation source and soil amendment samples were adapted from [Rice et al. \(2017\)](#) as follows: pH (potentiometry), electrical conductivity (EC) (conductometry),

BOD (iodometry), chemical oxygen demand (COD) (open reflux method), carbonates (CO_3) and bicarbonates (HCO_3) (alkalinity test), sodium (Na) (flame photometry), calcium (Ca) and magnesium (Mg) (Versenate titration), heavy metals [including cobalt (Co), lead (Pb), arsenic (As), boron (B), nickel (Ni), and chromium (Cr)] (inductively coupled plasma emission spectroscopy), and total micronutrient concentration, such as copper (Cu), iron (Fe), and zinc (Zn) (atomic absorption spectrophotometry).

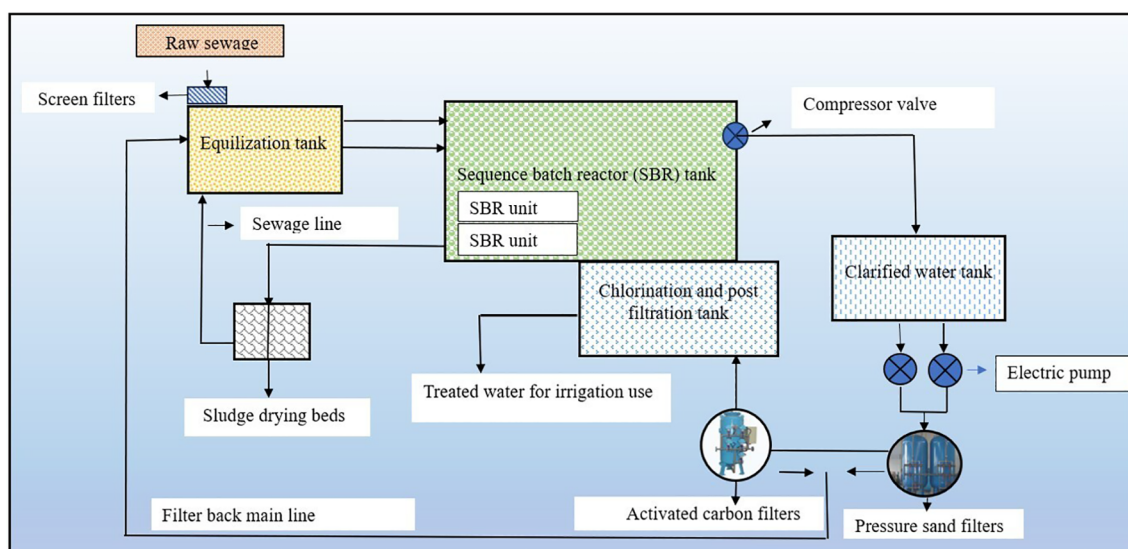


FIGURE 2

Flowchart representing treatment of sewage water through the sequence batch reactor (SBR) process in a sewage treatment plant.

2.4 Field experiment

The experiment was conducted in a factorial randomized block design, with two treatment factors: 1) irrigation water and 2) soil amendments each having three levels. Three levels of factor irrigation water included normal water (I_1), treated sewage water (I_2), and untreated sewage water (I_3), while three levels of amendments were FYM at 25 t ha^{-1} (SA_1), sewage sludge at 25 t ha^{-1} (SA_2), and sewage sludge at 12.5 t ha^{-1} + FYM at 12.5 t ha^{-1} (SA_3), resulting in nine treatment combinations each replicated three times making 27 experimental plots. Irrigation scheduling was initiated at 20 days after transplanting (DAT) with a 2-cm depth of water for the first irrigation, followed by 5 cm depth at 10-day intervals. A total of four cycles of irrigation were administered. FYM and SS were applied as per the treatment to the respective plots 15 days before transplanting for better decomposition and mineralization. The total quantity of irrigation water and nutrients added through different sources of irrigation water and manure is given in [Supplementary Table 1](#). Fertilizer was applied at the recommended rate of $150:75:75 \text{ N:P}_2\text{O}_5:\text{K}_2\text{O kg ha}^{-1}$. One week after transplanting, a basal dose of 50% of the prescribed dose of N, the entire dose of P_2O_5 and K_2O was applied, and the remaining 50% N was top-dressed at 75 DAT in all plots.

2.5 Soil analysis

2.5.1 Soil physicochemical analysis

Composite soil samples were collected to assess soil physicochemical properties. The soil samples collected from 0 to 30 cm depth were dried under shade and were powdered with a wooden pestle and mortar and passed through a 2-mm sieve, and these samples were used for analysis of soil physical and chemical properties as the standard procedure given by [Rana et al. \(2014\)](#).

2.5.2 Microbial analysis of irrigation sources, soil amendments, and soil

The microbial population in the sewage and soil was determined by the standard dilution plate count method ([Ben-David and Davidson, 2014](#)). A total of 10 mL of irrigation source (I_1 , I_2 , and I_3), 10 g of soil amendments (FYM and SS), and weighed soil were separately blended with 90 mL of sterile distilled water to obtain 10^{-1} dilution blanks for each sample. Subsequent dilutions up to 10^{-6} were made by transferring serially 1 mL of each dilution to 9 mL of sterilized water. The population of bacteria, fungi, and actinomycetes was estimated by transferring aseptically 1 mL of each dilution to 9 mL of sterilized water. The population of bacteria, fungi, and actinomycetes was estimated by transferring aseptically 1 mL of aliquots from selected dilutions of 10^{-3} , 10^{-4} , 10^{-5} , and 10^{-6} into sterile petri dishes, followed by pouring molten agar media to their respective dilutions. Plating was performed on nutrient agar, Martin's rose Bengal agar, and Kuster's agar for bacteria, fungi, and actinomycetes, respectively. The inoculated plates were kept for incubation at $30^\circ\text{C} \pm 10^\circ\text{C}$ for 1 week, and the emerged colonies were counted and expressed as colony-forming units (cfu) g^{-1} of soil. The irrigation sources and soil amendments were analyzed for harmful microbes, viz., *E. coli* and *Salmonella*, by using eosin methylene blue (EMB) agar and *Salmonella Shigella* agar media (SS agar media), respectively.

2.6 Characterization of irrigation water and soil amendments

Normal water (I_1) was found to be rather alkaline (7.22), with EC values of 0.52 dS m^{-1} and contained significant amounts of primary and secondary nutrients with good physicochemical characteristics ([Figures 3A, B](#)). The microbiological analysis of I_1 confirmed the absence of pathogenic microorganisms such as *E. coli*

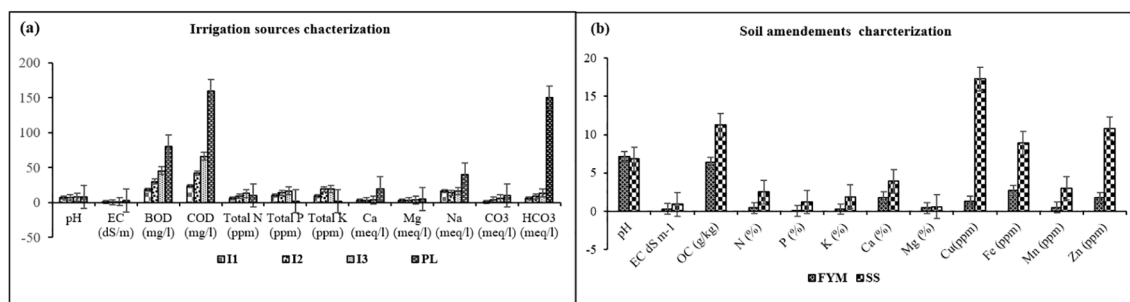


FIGURE 3

Characterization of irrigation sources (A), viz., I₁—normal water, I₂—treated sewage water, and I₃—untreated sewage water, permissible limits (PL), and soil amendments (B)—farmyard manure (FYM) and sewage sludge (SS) sources used in the study. Any treatment difference that exceeds the range of the bar is significantly different, as indicated by the LSD 0.05 bar above each column.

and *Salmonella* (Table 1). FYM analysis revealed that it has a pH of 7.12, EC value of 0.32 dS m⁻¹, and organic carbon (OC) content of 6.35 g kg⁻¹. Total N, P, and K concentrations were 0.44%, 0.051%, and 0.30%, respectively (Figure 3A). FYM contains Ca and Mg to the extent of 1.82% and 0.45%, respectively (Figure 3B). Micronutrients, such as Cu, Fe, Mn, and Zn, have respective concentrations of 1.32, 2.74, 0.52, and 1.78 ppm. Furthermore, analysis of FYM showed that it did not contain any harmful microbes (Table 1).

Analysis of SW and SS showed that SW contained a good amount of major, secondary beneficial nutrients such as N, P, K, Ca, Mg, and Na and micronutrients, viz., Fe, Mn, and Zn, and the physiochemical characteristics of SW and S such as pH, EC, BOD, and COD were well within the regulatory limits and can be safely utilized for the cultivation of crops (Figures 3A, B). Irrigation water I₂ exhibited better quality as compared with I₃ in terms of chemical and biological properties such as pH (7.45), EC (0.91 dS m⁻¹), BOD (30.21 mg L⁻¹), COD (42.23 mg L⁻¹), carbonates (4.21 meq L⁻¹), and bicarbonates (9.04 meq L⁻¹). SW collected from the campus was treated using the SBR method, wherein a slight decline (~5%–10%) in nutrient content was observed after treatment in the STP (Figure 3A). Furthermore, microbial analysis of the irrigation and

soil amendment sources confirmed that treated sewage water is free of harmful pathogens such as *E. coli* and *Salmonella* spp. (Table 1).

Heavy metal accumulation is one of the major concerns in utilizing sewage for agricultural purposes, as it affects both plant tissues and soil. Hence, a thorough analysis of heavy metal concentrations was conducted for both water and sludge samples (Table 2). Analysis of heavy metal concentrations, viz., Co, Pb, As, Ni, and Cr, showed that all heavy metals were within the permissible limits and can be safely utilized for agriculture (Table 2). Furthermore, plant tissue analysis for heavy metals was not conducted, as the domestic sewage used contained only negligible amounts of heavy metals. Nutrient budgeting of the major nutrients N, P, and K of irrigation water and soil amendment sources was carried out based on their chemical composition as done during sample characterization (Supplementary Table 1).

2.7 Biometric observations of chili plant

Five tagged plants were selected at random from each net plot at the maximum vegetative stage of chili for recording biometric

TABLE 1 Characterization of irrigation water and soil amendments for beneficial and harmful microbes.

Irrigation source (cfu mL ⁻¹ of water)	Actinomycetes	Fungi	Bacteria	<i>E. coli</i>	<i>Salmonella</i>
I ₁	4	8	12	0	0
I ₂	10	15	17	0	0
I ₃	12	37	29	5	0
Soil amendments (cfu g ⁻¹ of sample)					
Sewage sludge	6	19	22	0	0
FYM	15	39	32	7	0

I₁, normal water; I₂, treated sewage water; I₃, untreated sewage water; SS, sewage sludge; FYM, farmyard manure.

TABLE 2 Characterization of irrigation water and sewage sludge for heavy metal content (mg kg⁻¹).

Heavy metals	Permissible limit (Food and Agriculture Organization, 1985)	I ₂	I ₃	Permissible limit (Food and Agriculture Organization, 1985)	SS
Co	0.05	0.001	0.004	0.5	0.14
Pb	0.5	0	0	300	0.67
As	0.1	0.002	0.00444	50	0.32
B	0.2	0.017	0.035	3	1.92
Ni	0.1	0.004	0.005	50	2.64
Cr	0.4	0	0	400	5.56

I₂, treated sewage water; I₃, untreated sewage water; SS, sewage sludge; Co, cobalt; Pb, lead; As, arsenic; B, boron; Ni, nickel; Cr, chromium.

observations. The plant height was measured from the base of the plant to the tip of the main shoot. The total number of branches per plant was counted in five tagged plants, and the average was taken as the number of branches per plant. Dry weight was taken by oven drying the plants at 60 °C–70 °C upon arriving at constant weight; dry weight was expressed in g plant⁻¹. Yield was obtained as the cumulative of all pickings from the net plot area and expressed in t ha⁻¹.

2.8 Ascorbic acid content of green chili fruits

The ascorbic acid content of green chili was determined using the 2,6-dichloroindophenol sodium salt technique (Sadasivam and Manikam, 1996). Fresh green chili fruit weighing 5 g was ground and treated with 10 mL of 3% metaphosphoric acid and then filtered. Then, using standardized 2,6-dichloroindophenol acid, the filtrate was titrated. Formation of a pink color served as an indicator of the titration's endpoint. For each sample, a triplicate titration was performed, and ascorbic acid content was expressed as mg 100 g⁻¹ fresh weight by comparing with standard acid.

2.9 Root traits

The chili plants were grown in vegetable grow bags during 2019 and then uprooted at the maximum vegetative stage (60 DAT). The roots were carefully removed along with intact soil kept in fine meshed plastic bags, followed by gentle washing in running tap water, and all root biomass was collected after washing (Dass et al., 2016). Tap root lengths were determined by measuring the distance from the base to the longest and expressed in centimeters. Root volume was measured by immersing the fresh roots of each plant individually in a measuring cylinder, and the root volume was calculated as the rise in water level brought on by the roots' immersion and expressed in cubic centimeters (Dass et al., 2008). Furthermore, the roots were

kept in a brown paper bag and oven-dried at 70°C to a consistent weight, and the root dry weight was measured as g plant⁻¹.

2.10 Disease incidence

In the first year of the experiment (2018), there was a modest incidence of wilt and Murda complex; therefore, disease scoring was conducted to determine the impact of SW and S on the capacity to cause disease in the chili crop.

2.10.1 Wilt disease incidence

Wilted plants in the net plot were recorded, and the percent wilt incidence was calculated by using the following formula given by Thoyajakshi Bai et al. (2018).

$$\begin{aligned} & \% \text{ wilt disease incidence} \\ & = \frac{\text{Number of wilted plants}}{\text{Total number of healthy plants}} \times 100 \quad (1) \end{aligned}$$

2.10.2 Murda complex

Five plants were selected randomly from each plot and scored for leaf curling at 60 DAT by following the standard procedure developed by Niles (1980) (Table 3).

TABLE 3 Score index for Murda complex.

Score	Symptoms
0	No symptoms
1	1%–25% of leaves plant ⁻¹ showing curling
2	26%–50% leaves plant ⁻¹ showing curling
3	51%–75% of leaves plant ⁻¹ showing curling
4	>75% leaves plant ⁻¹ showing curling

2.11 Statistical analysis

Statistical methods, such as ANOVA (analysis of variance) and MANOVA (multivariate analysis of variance), were applied to evaluate the significance of each experimental variable. ANOVA assesses the variability associated with individual variables, treating each individual variable as an independent factor at the significance level of 5% probability ($p < 0.05$) (Rana et al., 2014). In contrast, MANOVA was used to assess the combined effects of all variables simultaneously at the significance levels of $p < 0.001$, $p < 0.01$, $p < 0.05$, $p < 0.1$, and $p < 1$; likewise, partial eta square (η^2) for all MANOVA results was calculated following the procedure described by Morrison (2005). Moreover, the significant difference between the two treatment means was indicated by different letters in superscript by performing Tukey's HSD test ($p < 0.05$). Multiple variate analysis and principal component analysis (PCA) were performed for a better understanding of the relationship between different growth rates, quality, disease incidence rates, yield parameters, and soil parameters using the JMP[®] software from SAS.

3 Results

3.1 Soil properties (chemical and microbiological)

Results (Supplementary Table 1) indicated that irrigation with untreated sewage water (I_3) significantly contributed to N, P, and K levels by 55.6%, 122.3%, and 56.7%, respectively, compared to normal water (I_1). Furthermore, treated sewage water (I_2) also contributed significantly, with N, P, and K levels increasing by 21.0%, 56.1%, and 22.3%, respectively. The plots receiving I_3 and I_2 treatments were supplied with irrigation water through a tractor-operated water tanker to ensure safe manual handling and to minimize the spread of persistent pathogens and heavy metals, thereby preventing shallow groundwater contamination in irrigation channels and adjacent fields. The 2-year experiment showed that varying irrigation

sources did not significantly influence ($p < 0.05$) the soil pH or EC (Table 4). However, soil pH declined by 0.5% and EC by 15.6% in I_1 irrigation. Furthermore, I_3 irrigation increased SOC by 6%–7% across both years of the study. Likewise, I_3 plots had significantly higher N (251.2 and 291.8 kg ha⁻¹), P (42.9 and 47.9 kg ha⁻¹), and K (307.5 and 350.0 kg ha⁻¹) (Table 4). Additionally, irrigation with I_3 significantly ($p < 0.05$) improved the population of actinomycetes (12.8 and 8.9 × 10² cfu g⁻¹ of soil), fungi (33.2 and 20.2 × 10³ cfu g⁻¹ of soil), and bacteria (44.4 and 29.3 × 10⁵ cfu g⁻¹ of soil) in comparison to I_1 (Table 5).

Application of sewage sludge at 25 t ha⁻¹ (SA_2) resulted in the highest total nutrient input to the soil, with N at 625 kg ha⁻¹, P at 39 kg ha⁻¹, and K at 490 kg ha⁻¹ (Supplementary Table 1). The soil pH showed a decreasing trend, with FYM at 25 t ha⁻¹ (SA_1) > sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹ (SA_3) > sewage sludge at 25 t ha⁻¹ (SA_2), whereas the reverse trend was true for the soil EC (Table 4). The available nutrient status of soil was the highest with the SA_2 -treated plots, with a percentage increment of 9.1%, 16.1%, and 7.7% for soil-available N, P, and K, respectively, during the study period (Table 4). Furthermore, a greater abundance of actinomycetes, fungi, and bacteria was recorded in the plots treated with SA_2 , whereas a minimal microbial abundance was noted in the plots treated with FYM. Microbial abundance exhibited the hierarchy of bacteria > fungi > actinomycetes throughout the study duration (Table 5).

During the first year of the field experiment, a minimal incidence of wilt and Murda complex was observed; hence, the percentages of disease incidence and Murda complex score were assessed in the initial field trial (Table 5). Nonetheless, the application of SS and sewage irrigation on chili plants did not exhibit any significant incidence of wilt disease or the Murda complex (Table 5).

MANOVA results (Wilks' lambda) showed that irrigation, soil amendment, and year significantly affected soil chemical properties (pH, EC, SOC, N, P, and K) in both years ($p < 0.001$; Table 6). Among these, year had the strongest influence (Wilks' lambda = 0.007, $p < 2.2 \times 10^{-16}$), indicating its dominant role in driving

TABLE 4 Influence of irrigation sources and soil amendments on soil pH, EC, SOC, and available N, P, and K.

Treatments	pH		EC (dS m ⁻¹)		OC (g kg ⁻¹)		N (kg ha ⁻¹)		P (kg ha ⁻¹)		K (kg ha ⁻¹)	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Sources of irrigation (I)												
I_1	6.06 ^a	7.21 ^a	0.13 ^a	0.14 ^a	3.17 ^b	2.47 ^c	230.6 ^b	260.3 ^b	37.1 ^b	42.1 ^b	267.7 ^b	313.0 ^b
I_2	6.06 ^a	7.00 ^a	0.14 ^a	0.15 ^a	3.22 ^a	2.52 ^b	244.4 ^a	270.9 ^a	42.1 ^a	47.1 ^a	297.3 ^a	347.6 ^a
I_3	6.19 ^a	7.01 ^a	0.15 ^a	0.17 ^a	3.24 ^a	2.54 ^a	251.2 ^a	291.8 ^a	42.9 ^a	47.9 ^a	307.5 ^a	350.0 ^a
Soil amendments (SA)												
SA_1	6.55 ^a	7.43 ^a	0.12 ^b	0.13 ^{bc}	3.14 ^{bc}	2.44 ^{bc}	225.0 ^c	255.3 ^{bc}	36.9 ^{bc}	41.9 ^{bc}	266.0 ^c	307.0 ^c
SA_2	5.71 ^b	6.74 ^c	0.16 ^a	0.18 ^a	3.32 ^a	2.61 ^a	258.9 ^a	297.2 ^a	46.0 ^a	51.0 ^a	317.5 ^a	361.9 ^a
SA_3	6.04 ^b	7.01 ^b	0.13 ^{ab}	0.15 ^b	3.18 ^b	2.48 ^b	242.3 ^b	267.6 ^b	39.2 ^b	44.2 ^b	288.9 ^b	341.8 ^b

I_1 , normal water; I_2 , treated sewage water (TSW); I_3 , untreated sewage water; SA_1 , FYM 25 t ha⁻¹; SA_2 , sewage sludge at 25 t ha⁻¹; SA_3 , sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹; SOC, soil organic carbon.

Values with different superscript letters in a column are significantly ($p < 0.05$) different as determined by Tukey's honest significant difference test.

TABLE 5 Influence of irrigation sources and soil amendments on soil microbial properties (cfu g⁻¹ of soil), wilt incidence (%), and Murda complex scoring in chili.

Treatments	Actinomycetes		Fungi		Bacteria		Wilt incidence (%)		Murda complex scoring	
	2018	2019	2018	2019	2018	2019	2018		2018	
Sources of irrigation (I)										
I ₁	7.9 ^b	4.8 ^b	13.0 ^b	12.8 ^b	37.2 ^b	18.0 ^b	17.9 ^a		1.2 ^a	
I ₂	13.2 ^a	7.0 ^a	30.3 ^a	17.8 ^a	42.0 ^a	24.2 ^a	19.0 ^a		1.4 ^a	
I ₃	12.8 ^a	8.9 ^a	33.2 ^a	20.2 ^a	44.4 ^a	29.3 ^a	16.9 ^a		1.4 ^a	
Soil amendments (SA)										
SA ₁	7.4 ^b	5.0 ^b	15.7 ^b	9.7 ^b	34.9 ^b	19.8 ^b	16.3 ^b		1.4 ^a	
SA ₂	15.3 ^a	9.0 ^a	36.6 ^a	24.4 ^a	49.1 ^a	27.3 ^a	19.8 ^a		1.4 ^a	
SA ₃	11.2 ^a	6.6 ^a	24.1 ^a	16.6 ^a	39.6 ^a	24.3 ^a	17.7 ^a		1.2 ^a	

I₁, normal water; I₂, treated sewage water; I₃, untreated sewage water; SA₁, FYM 25 t ha⁻¹; SA₂, sewage sludge at 25 t ha⁻¹; SA₃, sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹. Score symptoms for the Murda complex: 0, no symptoms; 1, 1% to 25% of leaves plant⁻¹ showing curling; 2, 26% to 50% leaves plant⁻¹ showing curling; 3, 51% to 75% of leaves plant⁻¹ showing curling; 4, >75% leaves plant⁻¹ showing curling.

Values with different superscript letters in a column are significantly ($p < 0.05$) different as determined by Tukey's honest significant difference test.

variability. The interaction between irrigation and soil amendment was not significant ($p = 0.129$). Partial η^2 values indicated large effects of irrigation (0.28) and soil amendments (0.46), while year showed an overwhelming effect (0.99), further supported by a high confidence interval (0.98).

MANOVA results (Table 7) indicated that irrigation, soil amendments, and year significantly influenced soil microbial parameters (actinomycetes, fungi, bacteria) and disease incidence (wilt incidence and Murda complex) ($p < 0.001$). The interaction between irrigation and soil amendments was significant but comparatively weaker ($p < 0.05$). Among the main effects, year showed the strongest influence ($\eta^2 = 0.88$), exceeding the effects of irrigation ($\eta^2 = 0.44$) and soil amendments ($\eta^2 = 0.50$), highlighting the dominant role of cumulative yearly effects on soil microbial dynamics (Table 8).

3.2 Performance of green chili (growth, yield, quality, and disease incidence)

The chili crop exhibited a pronounced differential response to the irrigation sources across both study years. The maximum plant

height (60.6 and 74.8 cm) observed under I₃ irrigation was significantly greater compared to I₁ irrigation. However, plant height was similar between I₃ (60.6 and 74.8 cm) and I₂ (58.6 and 71.6 cm) treatments in both study years (Table 8). The use of SW greatly increased the yield of green chilies, wherein the maximum yield was observed with the trend, I₃ (15.4 and 10.0 t ha⁻¹) > I₂ (14.3 and 9.2 t ha⁻¹) > I₁ (11.1 and 8.9 t ha⁻¹) (Table 8).

Furthermore, irrigation with I₃ resulted in an 18.7% increment in ascorbic acid (AA) concentration compared to I₁, while it was comparable to I₂ (6.4%) in both study years. Root traits, including taproot length, root dry weight, and root volume, were significantly impacted by SW and S co-implementation (Figure 4). The chili plants irrigated with I₃ exhibited the longest roots (48.2 cm), the highest root dry weight (17.6 g plant⁻¹), and the highest root volume (53.8 cm³) compared to those irrigated with I₂ and I₁ (Figure 5).

Among soil amendments, plant height was the highest under SA₂ (63.0 and 74.0 cm), while the lowest was recorded in SA₁ (52.9 and 67.0 cm) (Table 8). The number of branches per plant and dry matter accumulation followed a similar trend. The AA content in green chili fruits was significantly higher under SA₂, showing a 57.7% upsurge compared to SA₁ (Table 8). Additionally, the AA content of green chili showed a decreasing trend of SA₂ > SA₃ > SA₁.

TABLE 6 MANOVA statistical analysis for assessing the relative significance between soil chemical parameters (pH, EC, SOC, N, P, and K) influenced by irrigation sources and soil amendments.

Source of variance	df	Wilks' lambda	Approx. F	Num df	Den df	Pr (>F)	μ^2 (partial)	95% CI
Irrigation (I)	2	0.13375	10.69	12	74.00	6.478e ^{-12***}	0.28	0.05, 1.00
Soil amendments (SA)	2	0.03663	26.05	12	74.00	<2.2e ^{-16***}	0.46	0.27, 1.00
Year	1	0.00705	868.86	6	37.00	<2.2e ^{-16***}	0.99	0.98, 1.00
Irrigation × soil amendments	4	0.45382	1.38	24	130.29	0.12919	0.15	0.00, 1.00
Residuals	42							

df, degrees of freedom; Approx. F, approximate F statistic; Num df, numerator degrees of freedom; Den df, denominator degrees of freedom; μ^2 , partial eta square; CI, confidence interval; one-sided CI, upper bound fixed at 1.00.

Significance codes: 0; "****" 0.001; "." 0.1; 1.

TABLE 7 MANOVA statistical analysis for assessing the relative significance between microbial (actinomycetes, fungi, and bacteria) and disease incidence (% wilt incidence and MURDA complex) influenced by irrigation and soil amendment sources.

Source of variance	df	Wilks' lambda	Approx. F	Num df	Den df	Pr (>F)	μ^2 (partial)	95% CI
Irrigation	2	0.21081	8.953	10	76.00	1.492e ^{-09***}	0.44	0.25, 1.00
Soil amendments	2	0.14770	12.175	10	76.00	2.836e ^{-12***}	0.50	0.32, 1.00
Year	1	0.12314	54.116	5	38.00	2.970e ^{-16***}	0.88	0.81, 1.00
Irrigation × soil amendments	4	0.42200	1.886	20	126.98	0.1861*	0.18	0.01, 1.00
Residuals	42							

df, degrees of freedom; Approx. F, approximate F statistic; Num df, numerator degrees of freedom; Den df, denominator degrees of freedom; μ^2 , partial eta square; CI, confidence interval; one-sided CI, upper bound fixed at 1.0. Significance codes: 0; "****" 0.001; "***" 0.01; "**" 0.05; "*" 0.1; 1.

Likewise, plots applied with SA₂ significantly enhanced all root characteristics, including root length (52.9 cm), root dry weight (20.2 g plant⁻¹), and root volume (55.6 cm³) (Figures 4, 5). During the first year (2018) of the field experiment, a minimal incidence of wilt as per Equation 1 and Murda complex was observed; hence, the percentages of disease incidences and Murda complex score were assessed in the initial field trial (Table 5). Nonetheless, the application of SS and sewage irrigation on chili plants did not exhibit any significant incidence of wilt disease or the Murda complex (Table 5).

MANOVA results (Table 9) indicated that irrigation, soil amendments, and year significantly affected growth, quality, and yield of green chili ($p < 0.001$). The irrigation × soil amendment interaction was not significant ($p > 0.05$). Effect size analysis showed strong main effects, with soil amendments ($\eta^2 = 0.89$) and year ($\eta^2 = 0.68$) exerting greater influence than irrigation ($\eta^2 = 0.61$), while interaction effects were comparatively weaker.

Multivariate analysis was done to gain a comprehensive understanding of the interaction between a multitude of growth characteristics, quality, and disease incidence on the yield of green chilies (Figures 6, 7). It was observed that barring root dry weight (RDW), wilt incidence (WI), Murda complex (MC), and all eight metrics exhibited positive connections with one another. However, a

significant negative association was observed between MC and WI (Figure 6). The PCA showed that the soil parameters, viz., N, P, K, and SOC, were closely affected by I₃ and SA₂ application, whereas the pH of the soil was not significantly influenced by the irrigation sources and soil amendments. Furthermore, the dimension reduction in the dataset through PCA affirmed that the combination of I₁SA₁ (normal water irrigation and FYM 25 t ha⁻¹) had no predominant influence on soil parameters under study compared to I₃SA₂ (untreated sewage water + sewage sludge at 25 t ha⁻¹) (Figure 8).

4 Discussion

4.1 Environmental safety concerns

The use of SW and S raised concerns about the potential accumulation of heavy metals, pathogens, and other contaminants in plants, which could pose risks to human health and the environment (Nahar and Shahadat, 2020; Jahan et al., 2023; Nahar and Shahadat, 2020). Likewise, domestic wastewater irrigation also contaminates groundwater with nitrate contamination, and a study reveals significant fluctuations in nitrate concentration, which affect the quality of drinking water

TABLE 8 Influence of irrigation sources and soil amendments on growth, yield, quality, and root parameters of green chili.

Treatments	Plant height (cm)		Branches plant ⁻¹		Dry weight plant ⁻¹ (g)		Yield (t ha ⁻¹)		Ascorbic acid (mg 100 g ⁻¹)	
	2018	2019	2018	2019	2018	2019	2018	2019	2018	2019
Sources of irrigation (I)										
I ₁	53.6 ^b	63.3 ^b	16.8 ^b	18.9 ^b	78.3 ^c	72.5 ^c	11.1 ^b	8.9 ^{bc}	89.3 ^{bc}	107.0 ^b
I ₂	58.6 ^{ab}	71.6 ^a	21.5 ^a	23.0 ^a	88.1 ^b	89.7 ^b	14.3 ^a	9.2 ^b	96.6 ^b	112.3 ^a
I ₃	60.6 ^a	74.8 ^a	23.5 ^a	23.5 ^a	91.6 ^a	97.0 ^a	15.4 ^a	10.0 ^a	114.9 ^a	118.2 ^a
Soil amendments (SA)										
SA ₁	52.9 ^{bc}	67.0 ^{bc}	17.0 ^{bc}	19.2 ^{bc}	80.1 ^{bc}	75.1 ^{bc}	12.3 ^{bc}	8.3 ^{bc}	68.5 ^c	93.3 ^c
SA ₂	64.0 ^a	73.1 ^a	24.7 ^a	24.5 ^a	93.3 ^a	99.8 ^a	15.0 ^a	10.4 ^a	126.8 ^a	128.4 ^a
SA ₃	55.9 ^b	69.7 ^b	20.1 ^b	21.7 ^b	84.7 ^b	84.4 ^b	13.5 ^b	9.3 ^b	105.5 ^b	115.8 ^b

I₁, normal water; I₂, treated sewage water; I₃, untreated sewage water; SA₁, FYM 25 t ha⁻¹; SA₂, sewage sludge at 25 t ha⁻¹; SA₃, sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹. Values with different superscript letters in a column are significantly ($p < 0.05$) different as determined by Tukey's honest significant difference test.



FIGURE 4
 Root attributes of chili plants as influenced by different irrigation and soil amendments sources {I₁SA₁—normal water + farmyard manure at 25 t ha⁻¹; I₂SA₂—treated sewage water + SA₂—sewage sludge at 25 t ha⁻¹; I₃SA₂—untreated sewage water + sewage sludge at 25 t ha⁻¹.

(Iqbal et al., 2025). Another study conducted using irrigation with unconfined aquifers also shows that high levels of fluoride and nitrate concentrations above the permissible limits posed high risks in infants, followed by children and adults. Similar findings were observed in spatial distribution analyses, which confirmed heightened aquifer vulnerability due to industrial activities and agricultural practices (Mishra et al., 2023; Lamma, 2021; Nyashanu et al., 2023; Tytła and Widziejewicz-Rzońca, 2023; Baloch et al., 2025b). Additionally, Ilic Ilić et al. (2024) also reviewed that sewage water contamination posed a serious risk of heavy metal total daily exposure dose in both adults and children, exhibiting possible hazards to human health.

Various alternative sewage sludge sources can be utilized for crop production with minimal environmental risk after appropriate treatment. Among them, aerobic granulated sludge shows great potential for future application, as it effectively mitigates environmental impacts through biotechnological approaches (Hussain et al., 2024). The release of emerging pollutants, such as

antibiotics and microplastics, through the use of industrial wastewater for irrigation poses serious ecological threats. Zafar et al. (2024) conducted a study aimed at removing antibiotics from industrial water, demonstrating that selected adsorbents hold strong potential for real-world applications, as lab-scale experiments successfully simulated actual environmental conditions.

The assessment of normal water (I₁) revealed that it contained adequate amounts of essential plant nutrients and was devoid of pathogens and harmful substances, which are necessary for their application in crop production (Figure 3; Tables 1, 2). The sewage employed in this study was of domestic origin and did not contain any chemical constituents exceeding acceptable limits, therefore rendering it suitable for agricultural application (Figures 3A, B). Additionally, a microbiological analysis revealed the lack of hazardous pathogens such as *E. coli* and *Salmonella* in sludge samples or treated sewage water (I₂) and untreated sewage water (I₃) (Table 1). Biological nutrient removal activities (nitrification, denitrification, and enhanced biological phosphorus removal) may

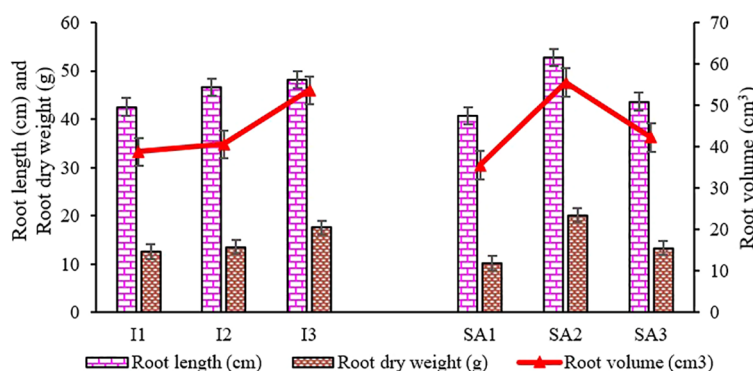


FIGURE 5
 Root trait (root dry weight, root length, and root volume) system of green chili as influenced by irrigation and soil amendment sources. Any treatment difference that exceeds the range of the bar is significantly different, as indicated by the LSD 0.05 bar above each column.

TABLE 9 MANOVA statistical analysis for assessing the relative significance between growth (plant height, branches, dry matter, and root characteristics), quality (ascorbic acid), and yield as influenced by irrigation and soil amendment sources.

Source of variance	df	Wilks' lambda	Approx. F	Num df	Den df	Pr (>F)	μ^2 (partial)	95% CI
Irrigation	2	0.04383	16.522	16	70.00	<2.2e ⁻¹⁶ ***	0.68	0.54, 1.00
Soil amendments	2	0.03774	18.145	16	70.00	<2.2e ⁻¹⁶ ***	0.61	0.44, 1.00
Year	1	0.10468	37.418	8	35.00	6.351e ⁻¹⁵ ***	0.89	0.82, 1.00
Irrigation × soil amendments	17	0.39113	1.184	32	130.67	0.25176.	0.20	0.00, 1.00
Residuals	42							

df, degrees of freedom; Approx. F, approximate F statistic; Num df, numerator degrees of freedom; Den df, denominator degrees of freedom; μ^2 , partial eta square; CI, confidence interval; one-sided CI, upper bound fixed at 1.00. Significance codes: 0; "****" 0.001; "." 0.1; 1.

account for reduced nutrient content of sewage post-treatment (Dutta and Sarkar, 2015).

4.2 Soil properties (chemical and microbiological)

Our study investigated the effects of different irrigation water sources (I₁, I₂, and I₃) on soil properties and their potential to enhance chemical and biological qualities. The sewage water was found to be alkaline (Figure 3), likely contributing to increased soil pH and EC due to high salt concentrations in the effluents. These findings align with those of Iqbal et al. (2014), who observed high salt content in sewage water from Aligarh University. Additionally, Kesari et al. (2021) reported that the addition of organic matter with

higher N, P, and K through I₃ irrigation likely resulted in the highest levels of SOC (2.5%), available N (10.5%), P (14.7%), and K (13.3%) in I₃-irrigated plots. The successive application of I₃ significantly influenced microbial communities in soil, which followed the trend I₃ > I₂ > I₁ in both study years (Table 6). The elevated microbial population under I₃ is likely due to its higher organic matter content, which serves as a microbial growth substrate (Nascimento et al., 2018).

In contrast, the soil pH in SS-treated plots declined by 10%–12% due to the production of organic acid during the decomposition and mineralization of organic matter. Over the course of the study, soil pH increased by approximately one unit across all treatments, possibly due to the accumulation of residual salts from previous and subsequent applications, which contain substantial amounts of soluble and neutral salts (Figures 3A, B). However, the SS-treated plots showed an increase

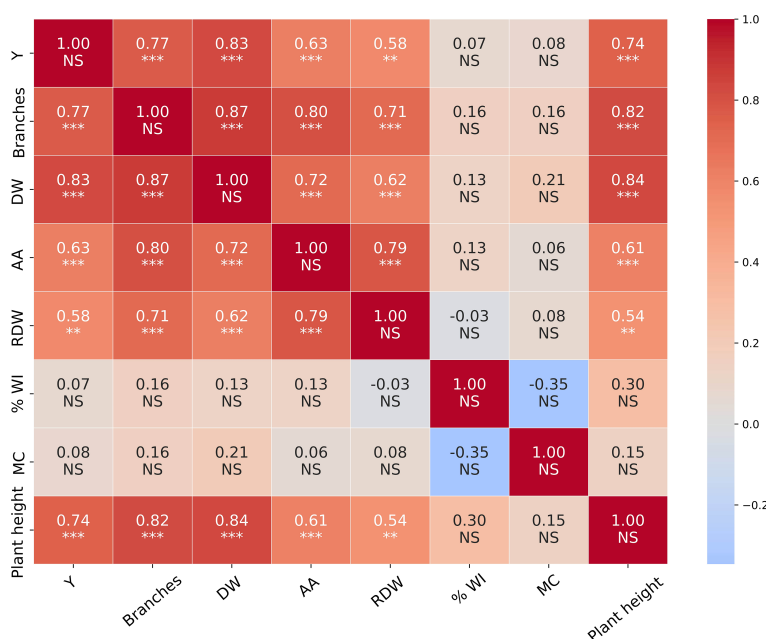


FIGURE 6 Multivariate analysis showing correlation between various crop growth parameters, viz., plant height, branches, dry weight (DW), root dry weight (RDW), ascorbic acid (AA) at maximum vegetative stage, and disease incidence, viz., % wilt incidence (WI), Murda complex (MC), and green chili yield (Y), with correlation coefficient ($p = 0.05$) (2-year pooled data).

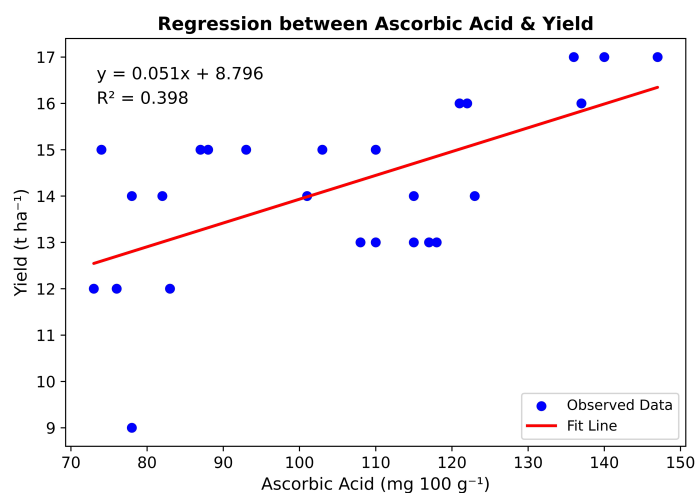


FIGURE 7

Regression plot showing the positive association between green chili yield and ascorbic acid content.

in soil EC up to 33.3%–38.4%, contrasting with the reduced soil pH (Table 4). This was possibly due to the addition of anions and cations through the SS and the release of salt-containing compounds during sludge mineralization. Similarly, the SS-treated plots showed significantly higher levels of N, P, and K (Table 4). The direct addition of N via mineralization and organic P might explain the rise in available nutrient status (Supplementary Table 1). Comparable effects on soil-available nutrients were reported in several studies (Dhanker et al., 2021; Ma and Rosen, 2021).

The principal component analysis revealed that the combination of I₁SA₁ (normal water and FYM at 25 t ha⁻¹) was less effective in improving soil-available nutrient status and SOC content compared to other treatments (Figure 8). The increased microbial populations

observed under SW and SS treatments could be attributed to the enhanced availability of organic substrates and nutrients that stimulate microbial growth and activity. Sewage water provides a continuous input of dissolved organic carbon, nitrogen, and other micronutrients, which serve as energy sources for soil microorganisms, thereby promoting microbial biomass carbon and enzymatic activities involved in nutrient cycling (Wang et al., 2021; Kumar et al., 2021; Zhao et al., 2025). Moreover, the organic matter and labile carbon fractions from sewage sludge act as substrates for heterotrophic microorganisms, leading to accelerated mineralization and nutrient turnover. The higher bacterial population compared to fungi and actinomycetes in SW-treated soils suggests that bacteria, being more adaptable to nutrient-rich and moist environments, respond rapidly to

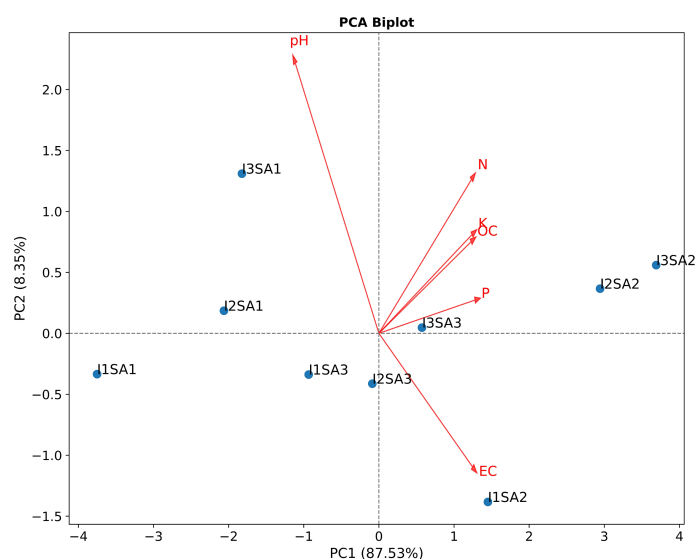


FIGURE 8

PCA biplots on the effect of irrigation sources [I₁ (normal water), I₂ (treated sewage water), and I₃ (untreated sewage water)] and soil amendments [SA₁ (FYM at 25 t ha⁻¹), SA₂ (sewage sludge at 25 t ha⁻¹), and SA₃ (sewage sludge at 12.5 t ha⁻¹ + FYM at 12.5 t ha⁻¹)] on soil properties, viz., pH, EC, SOC, N, P, and K, from the pooled data of 2018 and 2019. Triangles indicate treatment combinations of irrigation sources (I) and soil amendments (S).

the influx of easily decomposable organic compounds (Suhadolc et al., 2010). In addition, beneficial microbial communities present in SS, as reported by Frac et al. (2014), may have contributed to improved enzymatic activity and enhanced soil fertility through the mineralization of organic matter and the transformation of nutrients into plant-available forms. Collectively, these mechanisms explain the observed stimulation of microbial activity and improved soil biological health under SW and SS amendments.

4.3 Performance of green chili (growth, yield, quality, and disease incidence)

The concomitant application of SW and S affected the growth of chili plants (Table 8). The significantly elevated nutrient content in sewage water augmented the biological activities of chili plants (Supplementary Table 1). Furthermore, field experiments revealed that I₃-treated plots exhibited greater assimilatory pigments like chlorophyll, thereby facilitating the growth of chilies by increasing their height, promoting the development of new branches, and augmenting dry weight (Hoogendijk et al., 2023; Mishra et al., 2023). The present study also demonstrated that higher organic matter content in SW and S helps improve the microbial load in soil, improving soil fertility and increasing nutrient accessibility for plants (Table 6). Zhao et al. (2016) found analogous findings, observing that enhanced bacterial and fungal populations augmented soil fertility in plots treated with SS. The aforementioned addendum enhanced the transfer of photosynthates to the sink, resulting in a markedly increased production of green chilies under I₃ and SA₃. The increment in yield was approximately 30.6% over I₁ irrigation. The use of soil amendments resulted in a yield increase of approximately 23.7% for green chili in SA₂ (Table 8). A significant positive association was noted across all growth indices, contributing to an increase in green chili production (Figure 6). The yield improvement observed in the present study could partly be attributed to short-term nutrient enrichment following the application of SW and S, as both amendments provided readily available macro- and micronutrients. However, the consistent increase in yield over both study years, along with improvements in soil organic carbon and available nutrient status (Table 4), suggests that the benefits extended beyond immediate nutrient supply. These results indicate a gradual enhancement of soil physical and chemical properties, implying that SW and S applications may promote sustainable soil fertility improvement rather than solely a transient nutrient effect (Krishna et al., 2022; Kacprzak et al., 2023; Okebalama and Marschner, 2023).

Irrigation with I₃ and SA₃ enhanced the AA content of green chili fruit by 19.5%–63.5% relative to I₁ and SA₁ application throughout both years (Table 8). Additionally, a strong correlation between green chili yield and AA ($r = 0.63$) was established during the study period (Figures 7, 8). Given that AA functions as an antioxidant, its synthesis may be enhanced in the treatment with SW and S, as it plays a vital role in scavenging the free radicals produced from the heavy metals, which are accumulated by the plants grown on SW- and S-treated plots

(Hafshajani et al., 2022; Jamil et al., 2023). Sinha et al. (2007) indicated an increased production of AA in fenugreek cultivated in soil enriched with sludge to mitigate the detrimental impact of heavy metals.

Correlation and heat maps indicated that, as expected, root dry weight exhibited a strong positive correlation with all assessed growth parameters of chili (Figure 6), emphasizing the integral role of root traits in overall plant performance. The incorporation of organic matter through SW and S likely improved soil aggregation, porosity, and moisture retention capacity, thereby maintaining a more stable rhizosphere environment during the crop growth phase (Delibacak et al., 2020). This favorable soil physical condition facilitated greater root penetration and elongation, allowing the plants to explore a larger soil volume for nutrients and water uptake.

Furthermore, the application of SW and S enriched the rhizosphere with macro- and micronutrients (N, P, Fe, Zn, Cu), which may have stimulated root branching and proliferation of lateral roots in the upper soil layers where nutrient concentration was the highest. Enhanced nutrient availability in this zone encourages the production of auxins and cytokinins, phytohormones known to promote lateral root initiation and elongation (Awasthi and Laxmi, 2021; Krishna et al., 2022). Additionally, the increased organic carbon and microbial activity associated with SW and S application could have further enhanced enzymatic mineralization and rhizosphere biological processes, leading to improved root growth and higher root biomass accumulation (Figure 4), thus leading to an increase in root volume and accumulation of root biomass (Figure 5).

Wilt disease incidence might be due to a higher rainfall in the later stage of the crop (Thoyajakshi Bai et al., 2018). A positive change in weather conditions, which is favored by a high RH during the crop period, supported the vector multiplication (thrips, mites, and viruses) that might have caused the Murda complex (Rai et al., 2014).

4.4 MANOVA statistical evaluation

The Wilks' lambda statistics from MANOVA indicated that both irrigation ($p < 0.001$) and soil amendments ($p < 0.001$) exerted significant influences on soil chemical and microbial properties (Tables 6, 7). Effect size analysis further clarified the practical relevance of these findings. The very large partial η^2 for year ($\eta^2 = 0.99$), followed by soil amendments ($\eta^2 = 0.46$), indicates that temporal accumulation and repeated application of amendments play a dominant role in improving soil fertility, rather than short-term or single-season management interventions. In agronomic terms, this suggests that sustained wastewater irrigation and sludge application are more effective for enhancing soil nutrient status (N, P, K) and SOC than isolated inputs.

The stronger year effect can be attributed to the gradual nutrient release and stabilization capacity of sewage sludge, combined with repeated inputs of nutrient-rich irrigation water (I₂ and I₃), which collectively improved soil fertility over time. This interpretation is consistent with the findings of Arif et al. (2018), who reported

progressive improvements in soil physicochemical properties, nutrient availability, SOC, and microbial abundance under long-term sewage sludge application. Similarly, earlier studies have emphasized that the availability of organic substrates from amendments is critical for sustaining soil microbial growth (Proietti et al., 2015; Poulsen et al., 2013). Accordingly, the large η^2 values for year and soil amendments in the present study reflect their high practical significance for long-term soil health and microbial enhancement, particularly under wastewater reuse systems.

The interaction between irrigation and soil amendments was significant only for soil microbial parameters, but with comparatively lower effect sizes, indicating a moderate and context-dependent synergy rather than a strong interactive control. From a management perspective, this suggests that while a combined application can stimulate microbial activity likely through enhanced labile carbon availability from wastewater and substrate supply from sludge, the benefits are incremental rather than transformative within a short experimental period. The weaker interaction effects are plausibly due to the 2-year duration of the experiment, as synergistic effects of organic inputs often intensify over longer time frames through cumulative carbon buildup and microbial adaptation. Similar delayed interaction effects have been reported by Liang et al. (2023), where combined organic inputs enhanced soil C pool activity primarily under extended application periods.

For crop growth, yield, and quality parameters, MANOVA results showed highly significant main effects of irrigation and soil amendments (Table 9), with large partial η^2 values indicating strong agronomic relevance. Nutrient-rich wastewater irrigation directly supports physiological processes such as chlorophyll synthesis, photosynthesis, and nutrient uptake, leading to improved crop performance (Asirifi et al., 2023). Likewise, soil amendments significantly improved soil fertility, structure, and microbial activity, which translated into enhanced plant growth and yield attributes (Pretty et al., 2006). Importantly, the effect size analysis and confidence intervals demonstrate that cumulative management practices across years have greater practical importance than individual factors applied in isolation.

Overall, large η^2 values in this study signify management practices with high potential for real-world applications, particularly sustained sewage sludge amendment and wastewater irrigation for improving soil fertility and microbial health. Moderate or weaker η^2 values for interaction effects suggest that while combined inputs are beneficial, their full agronomic impact is likely to emerge over longer periods, emphasizing the importance of long-term planning in wastewater reuse and soil fertility management strategies.

4.5 Limitations of the study

The current study was limited in time and resources to continue for an extended period of time; however, it suggests that future research should prioritize careful monitoring and management of

potential contaminants, such as heavy metals and harmful microbial communities in SW and S, to prevent long-term negative effects on soil health and crop productivity in the near future for sustainable waste management. Furthermore, the absence of data on heavy metal uptake in plant tissues was a major limitation of the study.

5 Conclusion

In southern India, the chemical and biological characteristics of Typic Haplustalf soil were significantly improved by the simultaneous application of SW and S. As a result, a notable increase in organic matter, nutrient levels (N, P, and K), and microbial activity was observed, suggesting a significant improvement in soil fertility, which in turn enhanced green chili performance in terms of growth, yield (25%), and quality. Agronomically, the study supports the inclusion of SW and S co-application within integrated nutrient management (INM) frameworks, particularly in resource-constrained regions such as Karnataka's southern transition zone. Adoption of these practices could reduce dependency on synthetic fertilizers, improve water-use efficiency, and foster circular bioeconomy principles in agriculture. Overall, this research provides a scientific foundation for developing evidence-based policies that promote safe waste reuse, strengthen soil–water–crop management strategies, and advance the short- to medium-term sustainability of peri-urban farming systems. Additionally, this study provides possible policies to promote the controlled and monitored application of SW and S based on their nutrient composition and contaminant thresholds, ensuring safe and short- to medium-term soil health. Establishing standardized quality criteria, periodic monitoring of heavy metals, and microbial safety parameters will be essential to minimize environmental and public health risks.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

KS: Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Investigation, Methodology, Resources. HV: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Project administration, Supervision. AD: Writing – original draft, Writing – review & editing, Formal analysis, Visualization. MH: Formal analysis, Software, Writing – original draft. IB: Formal analysis, Writing – original draft, Writing – review & editing. GR: Writing – review & editing, Visualization. MS: Formal Analysis, Writing – original draft, Writing – review & editing. KN: Software, Writing – original draft, Writing – review & editing. VP: Formal analysis, Writing – review & editing, Writing – original draft. BN: Writing – review & editing. GK: Writing – review & editing. AY:

Writing – review & editing. BP: Writing – review & editing. RH: Formal analysis, Writing – review & editing, Writing – original draft. KK: Writing – original draft. DA: Writing – review & editing. AS: Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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