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Original Research

Effect of Long-Term Application of Sewer Water on Soil Properties and Plant Nutrient Contents in the Drainage Basin Area across Different Crop Seasons

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Abstract

With increasing water scarcity and the need for sustainable agricultural practices, the reuse of treated wastewater for irrigation has gained attention. Although there are studies on the short-term effects of wastewater irrigation, limited research focuses on the long-term implications across various crop seasons in drainage basin regions. Hence, this study examines how the crop season has influenced changes in soil characteristics and plant nutrient levels of sorghum and soybean crops after 40 years of continuous sewage water application. The research employs a longitudinal field study where soil samples are collected regularly from plots irrigated with sewer water. Plant samples were also analyzed for nutrient concentrations to evaluate the impact on crop growth. Various analytical techniques, such as soil testing, plant tissue analysis, and statistical methods, are utilized to interpret the data. The study showed that 40 years of continuous application of sewage water significantly impacted the crops' different soil qualities and plant nutrients, specifically soybeans and sorghum. Similarly, the other soil characteristics and nutrient levels of both crops were equally impacted by the agricultural season

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(*rabi* and *kharif*). While the values of bulk density, exchangeable K, and sulfur were greater in the *kharif* season, higher levels of pH, EC, organic carbon, calcium carbonate, CEC, N, and P were discovered in the *rabi* season. The grains of sorghum and soybean crops included higher levels of N, P, and S, but the straws of the same crops contained higher levels of K. The study emphasizes the importance of monitoring soil health and plant nutrition when using sewer water for irrigation in drainage basin areas. Long-term wastewater application can positively and negatively impact soil fertility and crop productivity, emphasizing the need for sustainable management practices. Future research could explore the mechanisms underlying these changes and investigate potential remediation strategies to mitigate adverse effects.

Keywords: sewer water, sorghum, soybean, irrigation, soil properties, plant nutrient content

Introduction

Applying sewer water can introduce various beneficial and potentially harmful elements to the soil, altering its physical, chemical, and biological properties over time [1, 2]. However, understanding these changes is essential for optimizing the benefits of sewer water application while minimizing potential risks. Physical properties of soil, such as texture, structure, and porosity, can be affected by long-term sewer water application, affecting water retention capacity and aeration and ultimately affecting crop growth and yield [3-5]. Increased sodium content from sewer water may lead to soil dispersion and reduced aggregate stability. Increased organic carbon, nitrogen, phosphorus, potassium, and magnesium contents in the soil can result from using sewage water for agricultural soil irrigation instead of pure groundwater irrigation [6]. When soil microorganisms are irrigated with sewage effluent, their metabolic activity also increases [7-9]. However, as wastewater irrigation continues, the organic carbon, total nitrogen, microbial biomass (C and N), and microbial activity also increase. This is because soil microorganisms exhibit higher metabolic activity when exposed to sewage effluent irrigation. Thus, it is important to take into account the possible advantages of applying sewage water for agricultural land irrigation [8].

The chemical properties encompass nutrient content, pH levels, and potential contaminants introduced by sewer water application, where excessive concentrations may lead to detrimental effects such as nutrient leaching and eutrophication in nearby water bodies [10]. However, the biological properties include soil microorganisms that play a significant role in maintaining ecosystem functions. Research suggests that the long-term application of sewer water may alter soil microbial communities due to changes in nutrient availability or potential contaminant exposure, as sewage water contains significant quantities of nutrients like nitrogen, phosphorus, and potassium, which reduce dependence on chemical fertilizers and enhance soil productivity [11, 12]. Continuous sewage irrigation can yield better crops such as soybean, maize, cotton, and sorghum due to the additional nutrient inputs, especially in nutrient-deficient soils. Also, the increased availability of organic matter contributes to plant growth factors such as biomass production, shoot elongation, and leaf expansion. Studies have shown that the effects of long-term sewer water application on plant nutrient content vary across different crop seasons due to temperature fluctuations, evapotranspiration rates, and nutrient demands. Understanding these variations helps in informed crop selection and irrigation management strategies.

When water is recycled for irrigation, it is possible that nutrients in recycled water can be used as fertilizer sources. Therefore, sewage water is an important source of plant nutrients and organic substances required to maintain soil fertility and productivity [13]. The results of several researchers showed that the length of the shoot, the number of leaves and plants, the total area of the leaves and plants, and the dry weight of the shoot and root increased significantly [14, 15]. Crops like soybean, maize, cotton, *rabi* sorghum, tomato, and wheat recorded a higher yield under sewer water application than normal irrigation water [16]. Furthermore, applying wastewater increases both the macronutrients and micronutrients in the soil, which are essential to plant growth and photosynthesis pigments. Prolonged application of sewage water can enhance organic carbon content, leading to improved soil structure, water-holding capacity, and microbial activity. These changes collectively promote healthier soil ecosystems [17, 18]. As a result, the level of nutrients in soils is expected to improve considerably with continuous water treatment with wastewater [19-21].

Also, the accumulation of heavy metals is one of the main disadvantages of irrigation wastewater [10]. In sewage water, trace elements such as zinc (Zn) and copper [22] can provide micronutrient benefits. However, their accumulation beyond critical thresholds poses toxicity risks to both plants and soil microorganisms. Heavy metals such as lead (Pb), cadmium [23], and chromium (Cr) often accumulate in soils due to untreated or poorly treated sewage water. These metals may enter the food chain, posing long-term health risks, and have been found to inhibit root elongation and crop productivity. The total concentrations of Mg, Hg, Mo, Ca, Cu, and Cr and the available Pb, Cd, and Cu concentrations increase significantly under drainage water irrigation [24]. Also, excessive sodium in wastewater can lead to soil dispersion, which reduces aggregate stability, compromising soil texture and permeability. Most studies confirm that heavy metal content and its accumulation in soil depend on the source and nature of sewer water. However, some harmful effects, such as inhibition of root and shoot growth and reduction in yield, are due to the accumulation of heavy metals in plants grown in sewer water-irrigated fields [2, 25, 26]. Variability in sewage water quality and seasonal fluctuations can result in inconsistent impacts on soil properties, including salinity and pH, such as higher salinity levels, which may occur during summer due to concentrated effluents. Nutrient leaching from sewage-irrigated fields into nearby water bodies contributes to eutrophication and subsequent ecological damage, such as algal blooms and oxygen depletion in aquatic systems [27].

Although sewage water enriches the soil with macronutrients like nitrogen and phosphorus, the seasonal variability in their availability remains a challenge. For example, nitrogen availability is higher during the *rabi* season due to favorable biological nitrogen fixation, while phosphorus levels vary due to leaching during rainy seasons. Prolonged sewage irrigation modifies soil texture through changes in organic matter content and fine particle distribution. While increased organic matter can improve soil structure and water retention, high sodium content disrupts soil aggregates, leading to crust formation and reduced porosity. Sewage irrigation enhances microbial activity and soil biomass due to increased organic matter. However, long-term exposure to contaminants in sewage water alters microbial diversity and may lead to the proliferation of harmful pathogens or antibiotic-resistant bacteria.

Sewage irrigation presents a dual-edged sword in sustainable agriculture. While it offers significant benefits in terms of nutrient recycling and water conservation, the associated risks of soil contamination, heavy metal accumulation, and environmental pollution necessitate careful management. Addressing these challenges requires an integrated approach, combining advanced wastewater treatment technologies, soil remediation strategies, and informed irrigation practices. The present study was undertaken to evaluate the effect of sewer water application after 40 years of continuous application on soil properties and plant nutrient contents as affected by crop season. The study further aimed at addressing the following: (1) investigating the cumulative effects of sewage irrigation on soil health, crop productivity, and environmental sustainability, particularly in regions with continuous application spanning decades; (2) developing soil management practices to counteract salinity, heavy metal accumulation, and soil structural degradation caused by sewage irrigation; and (3) tailored studies on nutrient uptake, heavy metal accumulation, and yield variations across different crop species and seasons can help optimize sewage irrigation practices. Future research must identify optimal sewage water treatment methods to retain beneficial nutrients while mitigating harmful contaminants like heavy metals and pathogens. Sustainable sewage irrigation can be achieved by fostering collaboration among researchers, policymakers, and farmers, ensuring long-term soil health, crop productivity, and environmental protection.

Materials and Methods

Study Location and Experimental Design

The experiment was conducted at MPKV, Parbhani, during the 2022-2023 agricultural year to assess the impact of 40 years of continuous sewage water application on soil properties and plant nutrient levels of sorghum and soybean across crop seasons (*rabi* and *kharif*). The experimental plots had been receiving treated sewage water from the MPKV Parbhani sewage treatment plant for the past 40 years (Fig. 1). The soils in the study area, derived from basaltic "Deccan trap" rocks, are rich in iron, copper, and magnesium (Table 1). Predominantly black in color due to montmorillonite clay, the soils exhibit a high coefficient of expansion and

Fig. 1. Map showing the GPS soil sampling of the study location.

shrinkage, resulting in deep cracking during summer. These soils vary in texture from light to heavy and range in depth from very shallow to extremely deep. Based on the USDA soil taxonomy, they are classified as Typic Halplusterts (Parbhani series).

Soil Sampling and Preparation

Soil samples were collected from the research field near the Sorghum Research Station, MPKV, Parbhani, after harvesting the sorghum (*rabi*) and soybean (*kharif*) crops. Fifty representative GPS-based soil samples were taken during both seasons, with a 0-30 cm sampling depth. Samples were air-dried, crushed, and sieved through a 2-mm sieve. Physicochemical analyses were conducted using standard laboratory procedures:

pH Measurement: The pH was measured using a 1:2 soil-to-water suspension. A soil sample of 10 g was mixed with 20 ml of distilled water and stirred intermittently for 30 min to allow equilibrium between the soil and water phases [28]. The pH meter was calibrated with standard buffer solutions before use.

Electrical Conductivity (EC): EC was determined using a conductivity meter in a 1:2 soil-to-water solution [29]. The soil-water suspension was prepared similarly to the pH test, and the EC meter measured the soil solution's ability to conduct electrical current. EC reflects the salinity levels of the soil, with higher values indicating potential salinization risks.

$$EC = \frac{1}{R}\ (dSm^{-1}) \tag{1}$$

Where R is the resistance of the soil solution.

Organic Carbon**:** OC was analyzed using the Walkley–Black wet digestion method, where soil organic matter was oxidized with potassium dichromate

Table 1. Soil sample site with GPS location of study area.

Sample site	GPS location
SRS* 1	19° 15' 09.9" N 76° 46' 28.6" E
SRS 2	19° 15' 10.0" N 76° 46' 26.8" E
SRS 3	19° 15' 12.6" N 76° 46' 26.8" E
SRS 4	19° 15' 15.0" N 76° 46' 26.9" E
SRS 5	19° 15' 17.6" N 76° 46' 26.9" E
SRS 6	19° 15' 07.2" N 76° 46' 25.7" E
SRS 7	19° 15' 09.5" N 76° 46' 25.7" E
SRS 8	19° 15' 11.3" N 76° 46' 25.6" E
SRS 9	19° 15' 13.5" N 76° 46' 25.5" E
SRS 10	19° 15' 16.7" N 76° 46' 25.6" E
SRS 11	19° 15' 08.1" N 76° 46' 24.5" E
SRS 12	19° 15' 09.4" N 76° 46' 24.6" E
SRS 13	19° 15' 11.4" N 76° 46' 24.6" E
SRS 14	19° 15' 14.2" N 76° 46' 24.5" E
SRS 15	19° 15' 16.9" N 76° 46' 24.6" E
SRS 16	19° 15' 08.0" N 76° 46' 23.2" E
SRS 17	19° 15' 09.9" N 76° 46' 23.2" E
SRS 18	19° 15' 12.6" N 76° 46' 23.3" E
SRS 19	19° 15' 15.2" N 76° 46' 23.2" E
SRS 20	19° 15' 17.8" N 76° 46' 23.3" E
SRS 21	19°15' 07.4" N 76°46' 22.3"E
SRS 22	19° 15' 10.0" N 76° 46' 22.2" E
SRS 23	19° 15' 12.5" N 76° 46' 22.3" E
SRS 24	19° 15' 15.1" N 76° 46' 22.2" E
SRS 25	19° 15' 18.2" N 76° 46' 22.2" E
SRS 26	19° 15' 08.0" N 76° 46' 29.7" E
SRS 27	19° 15' 09.7" N 76° 46' 29.8" E
SRS 28	19° 15' 11.3" N 76° 46' 29.8" E
SRS 29	19° 15' 12.8" N 76° 46' 29.8" E
SRS 30	19° 15' 15.0" N 76° 46' 29.9' E
SRS 31	19° 15' 08.0" N 76° 46' 30.9" E
SRS 32	19° 15' 09.4" N 76° 46' 30.9" E
SRS 33	19° 15' 10.7" N 76° 46' 31.1" E
SRS 34	19° 15' 12.1" N 76° 46' 31.1" E
SRS 35	19° 15' 13.7" N 76° 46' 31.3" E
SRS 36	19° 15' 08.2" N 76° 46' 15.3" E
SRS 37	19° 15' 08.7" N 76° 46' 15.4" E
SRS 38	19° 15' 09.4" N 76° 46' 15.4" E
SRS 39	19° 15' 10.1" N 76° 46' 15.4" E
SRS 40	19° 15' 11.1" N 76° 46' 15.4" E
SRS 41	19° 15' 08.1" N 76° 46' 15.9" E
SRS 42	19° 15' 08.7" N 76° 46' 15.9" E
SRS 43	19° 15' 09.7" N 76° 46' 15.9" E
SRS 44	19° 15' 10.4" N 76° 46' 16.0" E
SRS 45	19° 15' 11.2" N 76° 46' 16.0" E
SRS 46	19° 15' 08.3" N 76° 46' 16.7" E
SRS 47	19° 15' 09.1" N 76° 46' 16.6" E
SRS 48	19° 15' 09.8" N 76° 46' 16.6" E
SRS 49	19° 15' 10.4" N 76° 46' 16.7" E
SRS 50	19° 15' 11.2" N 76° 46' 16.7" E

*SRS = Sorghum Research Station.

($K_2Cr_2O_7$) and sulfuric acid (H_2SO_4) [30, 31]. The residual dichromate was titrated with ferrous ammonium sulfate to estimate the carbon content.

$$OC\ (\%) = \frac{(V_b - V_t) \times 0.003 \times 1.3}{W} \tag{2}$$

where: V_b: Volume of ferrous ammonium sulfate for blank titration, V_t: Volume for sample titration, and W: Weight of the soil sample.

Available Nitrogen (N): The alkaline-$KMnO_4$ method was used. Soil nitrogen was oxidized by alkaline potassium permanganate under heating, releasing ammonia gas, which was trapped in boric acid and titrated with HCl [32]. This is crucial for assessing the soil's potential to support plant growth.

Available Phosphorus (P): Extracted using 0.5 M sodium bicarbonate solution (pH 8.5) and quantified with Barton's reagent, which reacts with phosphorus to produce a yellow-colored complex measurable by a UV-VIS spectrophotometer at 420 nm [33].

Available Potassium (K): Soil potassium was extracted using a neutral ammonium acetate solution and measured using an inductively coupled plasma spectrophotometer (ICP-OES, GBC, Australian Model) [34, 35].

Exchangeable Calcium (Ca) and Magnesium (Mg): Extracted using a 1 N ammonium acetate solution and analyzed using an atomic absorption spectrophotometer (GBC 906, Australian Model) [36, 37].

Bulk Density: Measured using the soil core method by determining the soil mass in a given volume [38]. This indicates soil compaction, which influences water infiltration and root penetration.

$$Bulk\ Density = \frac{\text{Mass of soil (g)}}{\text{Volume of soil } (cm^3)} \tag{3}$$

Calcium Carbonate ($CaCO_3$): Estimated using acid neutralization and calcimeter methods. The soil was treated with dilute acetic acid, and the released CO_2 volume was measured. This indicates the soil buffering capacity and the potential for lime-induced alkalinity. The Cation Exchange Capacity (CEC) was measured following the procedure described by [39].

Plant Sampling and Analysis

Sample Preparation

Fifteen whole-plant sorghum (*rabi*) and soybean (*kharif*) samples were collected from the field post-harvest. Both grain and straw samples were collected and analyzed for nutrient content. Samples were air-dried for 2-3 days on clean, dust-free surfaces at ambient temperature. This step prevented contamination and retained the integrity of the samples. Dried samples were placed in an oven at 65ºC to remove residual moisture. This ensured consistent and accurate weight measurements for subsequent analysis.

Nutrient Analysis

Nitrogen (N): Measured using the micro-Kjeldahl distillation method after digestion, as digested with concentrated sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2), breaking down the organic bonds and releasing nitrogen as ammonium ions (NH_4^+) [40]. Ammonia was distilled and trapped in a boric acid solution, then titrated with standard HCl to determine nitrogen content.

$$N\ (\%) = \frac{(S - B) \times N \times 1.4}{W} \tag{4}$$

Where S: Sample titration volume, B: Blank titration volume, N: Normality of HCl, and W: Weight of the sample in grams.

Phosphorus (P): Estimated by digesting plant samples in a di-acid mixture (HNO_3: $HClO_4$ in a 3:1 ratio). The digested solution was reacted with Barton's reagent, forming a yellow-colored complex proportional to phosphorus concentration. Absorbance was measured at 420 nm using a UV-VIS spectrophotometer [39]. Phosphorus availability is critical for energy transfer and metabolic processes in plants.

Potassium (K): Potassium in the di-acid digest was analyzed using a flame photometer (Systronic manufacture). The intensity of the emitted light (at a specific wavelength) indicated potassium concentration. This method is highly sensitive and specific for detecting potassium in plant tissues and regulates water use, enzyme activation, and photosynthesis in plants.

Statistical Analysis

Data were statistically analyzed using standard methods to evaluate the impact of long-term sewage water application on soil and plant characteristics across seasons. Results were compared for significant differences between the *rabi* and *kharif* seasons.

Results and Discussion

Effect of Sewer Water Application on Soil Physicochemical Properties

Table 2 shows information regarding the soil's pH, EC, organic carbon, calcium carbonate, cation exchange capacity, and bulk density. The findings showed that during the *kharif* season, the soil's pH ranged from 7.05 to 8.09 with a mean value of 7.67, while during the *rabi* season, it ranged from 7.39 to 8.25 with a mean value of 7.92. In the same way, the soil EC varied from 0.25 dS m^{-1} to 0.52 dS m^{-1} with a mean value of 0.39 dS m^{-1} during the *kharif* season and from

Table 2. Physicochemical properties of the study area after 40 years of continuous application of the sewer water.

Sample site	pH		EC (dSm^{-1})		Organic carbon ($g\ kg^{-1}$)		Calcium carbonate ($g\ kg^{-1}$)		Bulk density ($g\ cm^{-3}$)		CEC [cmol (P^+) kg^{-1}]	
	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi
SRS 1	7.75	7.97	0.36	0.54	9.20	10.40	65.22	64.81	1.20	1.18	54.26	54.12
SRS 2	8.00	8.14	0.38	0.56	9.90	10.70	70.78	69.84	1.21	1.19	51.43	51.47
SRS 3	8.09	8.25	0.48	0.64	6.90	8.10	60.65	59.17	1.32	1.30	50.36	49.61
SRS 4	7.86	8.00	0.47	0.61	6.60	8.70	60.20	58.84	1.35	1.32	53.02	52.94
SRS 5	7.89	8.03	0.45	0.57	8.10	9.80	65.01	63.48	1.26	1.25	54.37	54.00
SRS 6	7.67	7.79	0.39	0.43	6.40	7.70	56.23	55.12	1.37	1.35	52.01	52.12
SRS 7	7.74	7.99	0.37	0.48	6.90	6.10	43.89	42.78	1.31	1.29	50.23	49.98
SRS 8	7.68	7.89	0.33	0.42	6.70	7.40	61.02	60.95	1.39	1.38	56.25	56.34
SRS 9	7.63	7.86	0.35	0.53	5.10	6.70	52.78	51.84	1.20	1.18	51.78	52.01
SRS 10	7.71	8.01	0.36	0.57	4.20	5.10	65.01	64.85	1.30	1.29	54.36	53.89
SRS 11	7.05	7.39	0.39	0.57	4.80	5.30	55.96	54.20	1.45	1.43	52.46	52.06
SRS 12	7.64	7.91	0.29	0.43	3.90	4.10	58.12	55.42	1.32	1.30	58.45	58.26
SRS 13	7.69	8.07	0.30	0.51	4.10	5.30	61.56	60.80	1.43	1.41	57.36	57.30
SRS 14	7.84	8.08	0.37	0.58	3.10	4.70	56.89	55.95	1.35	1.33	51.25	51.22
SRS 15	7.56	7.82	0.36	0.47	4.30	5.60	30.25	29.84	1.34	1.32	53.26	52.79
SRS 16	7.95	8.03	0.28	0.49	3.20	4.00	55.78	53.80	1.32	1.31	51.25	51.23
SRS 17	7.81	7.93	0.29	0.58	6.90	7.60	30.52	29.00	1.20	1.18	56.20	56.35
SRS 18	8.00	8.20	0.35	0.64	3.60	4.70	70.86	69.52	1.46	1.45	50.23	50.00
SRS 19	7.89	8.10	0.31	0.68	3.70	4.90	69.54	67.20	1.31	1.29	51.23	51.42
SRS 20	7.58	7.73	0.52	0.74	9.20	10.10	60.21	58.96	1.35	1.34	50.36	50.21
SRS 21	7.45	7.97	0.25	0.48	3.60	4.90	60.89	59.30	1.23	1.20	53.36	53.30
SRS 22	7.88	8.01	0.34	0.53	4.60	6.20	61.45	59.51	1.46	1.45	52.56	52.68
SRS 23	7.98	8.11	0.30	0.50	7.50	8.40	70.13	69.40	1.43	1.42	51.36	51.46
SRS 24	7.99	8.20	0.39	0.54	3.70	4.20	47.36	45.80	1.25	1.23	50.69	50.90
SRS 25	7.50	7.82	0.39	0.59	7.60	8.60	30.47	29.84	1.37	1.35	50.12	49.80
SRS 26	7.80	8.00	0.40	0.64	5.36	6.90	70.26	69.78	1.38	1.37	54.36	54.00
SRS 27	7.56	7.81	0.36	0.65	7.50	8.60	35.02	34.10	1.26	1.24	52.36	52.30
SRS 28	7.48	7.76	0.39	0.57	7.10	8.40	68.56	67.82	1.29	1.28	56.74	56.45
SRS 29	7.43	7.86	0.33	0.57	7.60	8.90	69.47	67.32	1.33	1.31	57.43	57.34
SRS 30	7.55	7.82	0.45	0.67	5.80	6.10	55.63	54.10	1.36	1.34	54.34	54.10
SRS 31	7.59	7.86	0.39	0.48	6.70	7.80	70.25	69.42	1.43	1.41	56.54	56.24
SRS 32	7.46	7.87	0.37	0.50	3.30	4.50	70.13	68.48	1.29	1.28	54.10	53.86
SRS 33	7.51	7.72	0.44	0.61	7.60	8.60	64.23	63.89	1.34	1.32	52.76	52.65
SRS 34	7.80	7.84	0.38	0.53	6.90	8.00	30.12	29.75	1.36	1.34	53.92	54.00
SRS 35	7.36	7.58	0.42	0.61	9.20	10.80	67.01	65.30	1.35	1.34	52.74	52.86
MSRS 36	7.59	7.87	0.29	0.46	3.10	4.50	56.23	55.40	1.32	1.30	54.61	54.78
SRS 37	7.37	7.80	0.32	0.54	9.60	10.10	62.98	60.80	1.34	1.32	52.32	52.65
SRS 38	8.05	8.21	0.43	0.60	8.40	9.70	46.92	45.34	1.34	1.33	50.23	50.40

SRS 39	7.91	8.09	0.39	0.58	6.10	7.50	70.95	69.50	1.46	1.44	51.02	50.86
SRS 40	7.46	7.86	0.39	0.54	5.70	7.30	53.05	51.70	1.31	1.29	53.61	53.19
SRS 41	7.73	8.05	0.32	0.49	6.90	7.60	70.11	69.60	1.32	1.3	54.23	54.24
SRS 42	7.57	7.85	0.36	0.48	6.00	8.10	63.87	62.58	1.43	1.42	53.25	53.00
SRS 43	7.51	7.75	0.43	0.52	6.10	7.50	55.96	54.90	1.39	1.38	51.25	51.28
SRS 44	7.41	7.81	0.42	0.57	7.10	8.40	30.18	28.91	1.41	1.39	50.12	50.02
SRS 45	7.56	7.94	0.34	0.54	6.90	8.00	70.00	69.40	1.42	1.40	51.84	52.00
SRS 46	7.61	7.97	0.47	0.56	8.40	9.60	68.19	67.18	1.29	1.27	52.96	53.12
SRS 47	7.68	7.93	0.48	0.51	7.70	8.70	61.64	59.67	1.23	1.21	50.14	50.31
SRS 48	7.99	8.05	0.39	0.57	7.50	8.10	56.93	55.93	1.28	1.27	51.54	51.68
SRS 49	7.23	7.93	0.46	0.59	9.00	10.20	51.36	50.10	1.34	1.32	53.25	53.28
SRS 50	7.54	7.73	0.43	0.51	9.10	10.40	68.12	67.71	1.26	1.24	50.24	50.04
Mean	7.67	7.92	0.39	0.55	6.37	7.47	58.16	56.98	1.33	1.32	52.88	52.80

0.42 dS m^{-1} to 0.74 dS m^{-1} with a mean value of 0.55 dS m^{-1} during the *rabi* season.

The study area's soil organic carbon concentration varied from 3.1 g kg^{-1} to 9.9 g kg^{-1}, with a mean value of 6.37 g kg^{-1} during the *kharif* season, and from 4 g kg^{-1} to 10.8 g kg^{-1}, with a mean value of 7.47 g kg^{-1} during the *rabi* season. Similar to this, the calcium carbonate concentration in the soil in the examined area varied from 29.0 g kg^{-1} to 69.84 g kg^{-1} with a mean value of 56.98 g kg^{-1} in the *rabi* season and from 30.12 g kg^{-1} to 70.95 g kg^{-1} in the *kharif* season. The results also indicated that during the *kharif* season, the bulk density of the soil varied from 1.18 g cm^{-3} to 1.45 g cm^{-3}, with a mean value of 1.32 g cm^{-3}, while during the *rabi* season, it ranged from 1.2 to 1.46 mg m^{-3}. In the same way, during the *kharif* season, the soil's CEC varied from 50.12 cmol (P^+) kg^{-1} to 58.45 cmol (P^+) kg^{-1} with a mean value of 52.88 cmol (P^+) kg^{-1}, and during the *rabi* season, it varied from 49.61 cmol (P^+) kg^{-1} to 58.26 cmol (P^+) kg^{-1} with a mean value of 52.80 cmol (P^+) kg^{-1}.

The results revealed higher mean soil pH in *rabi* than in *kharif* season. This might be due to the leaching of the basic cations (e.g., Ca, Mg, K) from the top soil layer (0.30 cm) into the below soil horizons and leaving more stable minerals that are rich in Fe and Al oxides [41, 42]. The higher mean soil EC in the *kharif* season compared to *rabi* season might be due to more sewer water contamination in summer and may enhance the high build-up of the salts in the soil [43]. Organic carbon was present more during the *rabi* season than during the *kharif* season. The declining trend in soil organic carbon during the *kharif* season might be due to higher temperatures than the *rabi* season, as high temperatures enhance soil organic matter decomposition rates (microbial respiration) [44, 45]. No difference was observed in the mean values of soil bulk density and CEC in the *rabi* and *kharif* seasons.

Effect of Sewer Water Application on Soil Nutrient Contents

Table 3 presents the soil N, P, K, S, exchangeable Ca, and Mg information. During the *kharif* season, soil nitrogen content ranges from 100.4 kg ha^{-1} to 281.36 kg ha^{-1} with a mean value of 224.88 kg ha^{-1}, and during the *rabi* season, it ranges from 115.12 kg ha^{-1} to 294.45 kg ha^{-1} with a mean value of 236.56 kg ha^{-1}. According to further data, the available phosphorus level in the soil varies from 6.78 kg ha^{-1} to 14.96 kg ha^{-1}, with a mean value of 9.78 kg ha^{-1} during the *kharif* season and from 8.12 kg ha^{-1} to 17.85 kg ha^{-1} with a mean value of 12.71 kg ha^{-1} during the *rabi* season. With a mean value of 514.87 kg ha^{-1} in the *kharif* season, the potassium content ranges from 370.96 kg ha^{-1} to 796.34 kg ha^{-1}; in the *rabi* season, it ranges from 357.45 kg ha^{-1} to 784.69 kg ha^{-1} with a mean value of 503.96 kg ha^{-1}. In the *rabi* season, the soil exchangeable calcium concentration varies from 14.95 cmol (P^+) kg^{-1} to 31.7 cmol (P^+) kg^{-1} with a mean value of 23.51 cmol (P^+) kg^{-1}. The range of values is 18.45 cmol (P^+) kg^{-1} to 35.12 cmol (P^+) kg^{-1}.

The exchangeable magnesium concentration in the soil varies during the *kharif* season, with a mean value of 18.97 cmol (P^+) kg^{-1} and a range of 13.45 to 24.96 cmol (P^+) kg^{-1}. The mean value throughout the *rabi* season is 17.30 cmol (P^+) kg^{-1}, with a range of 10.7 to 23.7 cmol (P^+) kg^{-1}. During the *kharif* season, the accessible soil sulfur varies between 4.12 and 8.89 mg kg^{-1}, with an average of 5.72 mg kg^{-1}. It has a mean value of 5.45 mg kg^{-1} and varies from 4.0 mg kg^{-1} to 8.49 mg kg^{-1} during the *rabi* season.

The results of the soil nutrient analysis revealed that after 40 years of continuous application of sewer water, no build-up of the soil's available N and P was reported. However, a build-up of the soil's available K was observed after 40 years of continuous application

Table 3. Soil nutrient contents of the study area after 40 years of continuous application of the sewer water.

Sample site	Nitrogen (kg ha^{-1})		Phosphorus (kg ha^{-1})		Potassium (kg ha^{-1})		Exchangeable Calcium [cmol (P^+) kg^{-1}]		Exchangeable Magnesium [cmol (P^+) kg^{-1}]		Available Sulfur (mg kg^{-1})	
	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi
SRS 1	163.10	172.69	6.94	8.59	400.28	384.10	25.42	24.12	15.96	14.20	4.43	4.15
SRS 2	270.36	281.20	7.50	9.65	409.85	400.12	26.32	23.95	17.35	15.76	4.56	4.23
SRS 3	150.50	160.70	7.28	10.58	406.35	394.54	35.12	30.84	16.45	14.75	6.85	6.55
SRS 4	270.59	280.54	8.36	11.84	384.25	371.46	28.95	25.84	17.26	15.45	6.74	6.43
SRS 5	100.40	115.12	9.15	12.78	395.78	386.43	27.45	22.10	16.80	14.70	5.69	5.13
SRS 6	268.78	280.40	7.18	8.75	394.36	379.36	26.89	22.74	13.45	10.70	5.58	5.24
SRS 7	250.90	265.84	6.98	9.84	573.21	560.71	27.32	24.39	22.65	20.40	4.13	3.89
SRS 8	276.58	284.62	8.45	11.45	436.28	421.36	28.65	24.80	19.65	17.94	4.95	4.58
SRS 9	135.46	150.62	6.91	9.45	489.69	482.78	31.14	27.64	18.30	15.12	4.86	4.24
SRS 10	276.00	289.40	6.78	8.12	668.79	655.95	32.10	28.19	17.55	16.84	5.25	4.98
SRS 11	175.60	184.21	7.12	10.85	469.85	456.48	24.36	20.70	20.36	18.47	4.12	4.00
SRS 12	273.23	285.48	7.89	9.60	432.52	420.10	23.75	20.40	21.15	19.34	4.56	4.07
SRS 13	276.00	284.10	8.45	13.45	394.58	381.89	25.34	21.64	17.58	15.70	5.69	5.16
SRS 14	279.62	290.45	9.47	14.95	456.45	448.12	23.89	21.60	16.30	16.00	5.12	5.00
SRS 15	150.50	162.10	8.19	10.54	536.89	529.80	24.12	20.49	16.20	15.70	5.36	5.10
SRS 16	137.90	150.78	6.94	9.74	372.69	357.45	26.90	23.69	16.89	15.10	6.25	6.02
SRS 17	175.60	186.20	7.36	8.32	469.89	459.75	25.50	22.47	15.50	14.34	6.26	6.07
SRS 18	280.39	294.45	11.74	14.25	436.25	428.40	27.58	24.50	17.65	15.50	6.48	6.25
SRS 19	150.50	161.36	9.75	14.36	399.80	394.34	25.14	22.36	16.40	16.00	5.23	5.03
SRS 20	281.36	293.54	6.92	10.46	569.78	549.78	23.85	20.40	15.36	14.35	5.56	5.34
SRS 21	188.20	199.80	7.16	11.85	500.32	492.70	24.56	21.61	16.95	16.41	5.48	5.45
SRS 22	276.32	290.40	7.89	12.84	512.96	500.75	23.21	20.40	15.80	15.20	5.79	5.36
SRS 23	175.60	187.40	6.94	9.41	401.36	386.61	23.56	21.70	16.25	16.13	5.89	5.49
SRS 24	271.36	286.25	7.43	10.12	400.36	386.56	24.12	22.76	15.60	14.75	4.26	4.13
SRS 25	225.80	236.80	10.36	13.81	392.00	387.60	22.12	20.70	14.36	13.75	4.56	4.46
SRS 26	188.20	200.50	12.84	15.73	397.85	386.69	27.58	24.90	22.58	20.47	8.26	8.20
SRS 27	269.84	280.40	14.38	17.54	391.78	376.56	29.40	27.94	23.12	21.60	8.29	7.86
SRS 28	279.84	290.78	14.30	16.21	469.84	459.45	30.50	28.37	24.85	22.75	8.89	8.49
SRS 29	280.36	291.84	13.75	18.45	382.90	370.10	31.20	30.13	25.48	23.70	8.78	8.41
SRS 30	267.32	278.45	12.95	15.80	370.96	360.84	29.80	26.43	24.96	21.47	8.46	8.27
SRS 31	274.36	285.71	10.47	12.45	675.12	670.37	32.80	29.54	23.89	20.30	6.25	6.20
SRS 32	133.21	145.85	11.36	14.32	594.15	585.15	34.00	31.70	21.25	19.57	6.59	6.36
SRS 33	280.95	291.25	10.75	13.84	578.36	570.90	32.50	30.00	23.58	20.74	6.89	6.59
SRS 34	281.72	294.45	11.85	14.10	596.45	589.19	31.85	27.30	21.15	19.37	6.47	6.40
SRS 35	275.12	287.90	14.96	17.20	512.74	502.46	29.56	28.41	23.54	21.50	4.12	4.00
SRS 36	264.12	271.10	13.43	15.94	753.25	746.84	27.50	26.74	24.36	22.45	4.45	4.26
SRS 37	268.21	279.15	12.12	14.56	796.34	784.69	28.60	24.70	22.12	20.35	4.58	4.27
SRS 38	270.19	282.45	9.45	13.15	684.79	672.76	25.60	22.25	21.20	19.30	4.69	4.13

SRS 39	135.74	145.96	10.25	14.25	512.96	500.46	24.30	21.60	20.80	20.00	5.53	5.48
SRS 40	270.46	281.69	14.32	16.40	693.70	681.48	25.60	22.75	21.36	19.53	5.98	5.68
SRS 41	188.20	200.45	7.10	10.51	612.42	600.46	23.12	21.75	19.58	17.56	4.56	4.49
SRS 42	135.65	149.25	8.78	11.70	694.76	685.50	22.10	20.43	17.52	15.25	4.58	4.30
SRS 43	135.48	146.95	6.92	9.60	614.36	604.86	27.32	24.84	16.80	15.40	4.69	4.35
SRS 44	213.20	226.80	11.56	13.45	691.36	685.40	20.36	18.64	17.50	14.35	6.58	6.40
SRS 45	270.89	281.25	13.58	16.90	579.63	571.80	21.30	21.10	19.54	17.42	6.89	6.58
SRS 46	265.42	278.45	8.17	10.25	698.35	684.56	22.50	19.40	18.25	15.60	6.74	6.37
SRS 47	150.50	160.20	8.36	11.75	679.85	667.40	19.60	14.95	19.36	17.58	5.32	5.20
SRS 48	163.10	178.62	11.89	14.10	456.95	448.63	19.85	17.46	15.20	14.89	5.89	5.50
SRS 49	255.35	267.90	13.58	17.85	385.96	374.20	18.45	15.67	16.40	15.95	4.56	4.23
SRS 50	245.78	256.47	12.78	14.00	614.36	600.14	20.36	18.70	16.35	15.46	4.36	4.20
Mean	224.88	236.56	9.78	12.71	514.87	503.96	26.26	23.51	26.26	23.51	5.72	5.45

of sewer water. Results further indicate that the soils were deficient to sufficient in soil-available sulfur content after 40 years of continuous application of sewer water. The critical limit of soil-available sulfur is 10.7 mg kg^{-1} for soils in Maharashtra, as previously reported by [46].

Similarly, no build-up was observed for the soil exchangeable Ca and Mg in the study area. The activity of nitrogen-fixing bacteria may be the best explanation for the elevated nitrogen concentrations during the *rabi* season. Evidence shows that the *rabi* season is associated with higher rates of biological nitrogen fixation and mineralization, leading to an increase in the season's nitrogen content [47, 48]. The findings demonstrated little nutrient drainage from the soil throughout the *rabi* season with little to no rain, which caused an accumulation of high levels of nutrients during this time. It is well known that phosphorus levels in soil with maximum leaching are lower than in soil with minimum leaching. This was consistent with the study of [49] and [22]. Additionally, it was noted that the *rabi* season had higher potassium levels than the *kharif* season. This difference can be attributed to the *rabi* season's tendency to experience elevated potassium levels as a result of soil equilibrium changes from freezing and thawing, which release fixed potassium from non-exchangeable forms [22, 23]. The increased levels of exchangeable calcium and magnesium during the *kharif* season may result from the sorghum crop's lower absorption than the soybean crop during the *rabi* season.

Effect of Sewer Water Application on Straw and Grain Nutrient Contents of Sorghum

Table 4 contains information related to examining plant nutrients in sorghum grain and straw. With a mean value of 0.61%, the nitrogen content of sorghum straw varies from 0.51% to 0.78%. On the other hand, it has a mean value of 0.91% and varies from 0.82% to 1.12% in sorghum grain. Straw contains 0.20% to 0.36% phosphorus, with a mean of 0.28%. With a mean value of 0.48%, it varies from 0.33% to 0.58% in grain. Additional data showed that straw had a mean potassium content of 3.36%, with a range of 3.09% to 3.98%. On the other hand, it varies with grain, from 2.38% to 3.08%, with a mean of 2.72%. Straw has a mean sulfur level of 0.37%, with a range of 0.21% to 0.52%. In contrast, the range for grain is 0.85% to 1.37%, with a mean of 1.07%. Effective water use in irrigation and maintaining sufficient N improved grain sorghum's biomass, nitrogen use, and nitrogen use efficiency [50]. Additionally, irrigation rates have been found to significantly affect infiltration rate and soil-saturated hydraulic conductivity, with higher moisture contents leading to a decrease in these parameters [51, 52].

Effect of Sewer Water Application on Straw and Grain Nutrient Contents of Soybean

Data pertaining to soybean nutrient contents are shown in Table 5. Results revealed that nitrogen in soybean straw ranges from 0.58% to 0.70%, with a mean value of 0.63%. While in soybean seeds, it ranges from 5.01% to 5.93%, with a mean value of 5.47%. The phosphorus in soybean straw ranges from 0.17% to 0.31%, with a mean value of 0.24%. Meanwhile, the P content in seed ranges from 0.34% to 0.58%, with a mean value of 0.47%. The potassium content in soybean straw ranges from 1.29% to 1.8%, with a mean value of 1.49%, and it ranges from 1.26% to 1.76%, with a mean value of 1.45% in the seed. Similarly, sulfur content in soybean straw ranges from 0.11% to 0.21%, with a mean value of 0.16%, while it ranges from 0.77% to 0.92%, with a mean value of 0.81% for seeds. Results further showed that the N, P, and S content was higher in sorghum grain, while K content was higher in sorghum

Table 4. Nutrient contents in sorghum straw and grain.

Sample site	Total Nitrogen (%)		Total Phosphorus (%)		Total Potassium (%)		Total Sulfur (%)	
	Straw	Grain	Straw	Grain	Straw	Grain	Straw	Grain
SRS 1	0.51	0.92	0.23	0.33	3.12	2.73	0.45	1.37
SRS 2	0.54	0.96	0.20	0.46	3.23	2.69	0.37	1.02
SRS 3	0.66	0.88	0.24	0.43	3.34	2.58	0.52	1.03
SRS 4	0.67	0.87	0.26	0.46	3.67	2.51	0.31	1.01
SRS 5	0.78	0.92	0.22	0.41	3.94	2.46	0.41	0.95
SRS 6	0.59	0.82	0.29	0.48	3.13	2.38	0.37	0.85
SRS 7	0.57	0.93	0.36	0.52	3.24	2.36	0.29	0.98
SRS 8	0.61	0.91	0.20	0.47	3.16	2.48	0.42	1.28
SRS 9	0.63	1.12	0.31	0.53	3.02	2.61	0.39	1.09
SRS 10	0.55	0.83	0.26	0.46	3.90	2.83	0.29	1.04
SRS 11	0.52	0.90	0.28	0.48	3.98	2.97	0.41	1.19
SRS 12	0.57	0.89	0.35	0.56	3.09	2.99	0.36	0.86
SRS 13	0.60	0.95	0.31	0.49	3.14	3.03	0.21	0.98
SRS 14	0.65	0.86	0.34	0.58	3.24	3.06	0.32	1.23
SRS 15	0.67	0.87	0.36	0.52	3.27	3.08	0.43	1.11
Mean	0.61	0.91	0.28	0.48	3.36	2.72	0.37	1.07

Table 5. Nutrient contents in soybean straw and seed.

Sample site	Total Nitrogen %		Total Phosphorus %		Total Potassium %		Total Sulfur %	
	Straw	Seed	Straw	Seed	Straw	Seed	Straw	Seed
SRS 1	0.68	5.20	0.27	0.43	1.31	1.28	0.13	0.87
SRS 2	0.62	5.72	0.29	0.49	1.34	1.32	0.16	0.77
SRS 3	0.64	5.16	0.22	0.46	1.37	1.34	0.12	0.78
SRS 4	0.64	5.61	0.19	0.51	1.30	1.26	0.14	0.80
SRS 5	0.61	5.01	0.17	0.57	1.35	1.34	0.11	0.75
SRS 6	0.66	5.50	0.23	0.47	1.43	1.41	0.14	0.76
SRS 7	0.63	5.42	0.21	0.58	1.29	1.26	0.18	0.82
SRS 8	0.59	5.65	0.20	0.52	1.47	1.44	0.15	0.77
SRS 9	0.58	5.31	0.27	0.49	1.50	1.48	0.12	0.81
SRS 10	0.60	5.48	0.29	0.50	1.60	1.53	0.13	0.83
SRS 11	0.61	5.81	0.26	0.46	1.63	1.59	0.19	0.92
SRS 12	0.70	5.93	0.31	0.40	1.80	1.76	0.21	0.86
SRS 13	0.62	5.69	0.25	0.34	1.72	1.67	0.18	0.89
SRS 14	0.63	5.42	0.21	0.36	1.58	1.52	0.20	0.79
SRS 15	0.64	5.12	0.22	0.40	1.69	1.60	0.19	0.80
Mean	0.63	5.47	0.24	0.47	1.49	1.45	0.16	0.81

crop straw [53]. Similarly, N, P, and S were greater in soybean seeds, while K content was higher in soybean straw.

Effect of Sewer Water Quality from Drainage and Wells near the Sorghum Field

The analysis of water quality parameters, as summarized in Table 6, reveals notable differences between morning and evening sewage water and well water. The electrical conductivity (EC) of morning sewage water was recorded at 1.18 dS m^{-1}, while evening sewage water showed a higher EC value of 1.33 dS m^{-1}. In comparison, well water had an EC range of 0.539 to 0.714 dS m^{-1}, with a mean value of 0.649 dS m^{-1}, indicating relatively low salinity levels [16, 31]. Carbonate content in morning sewage water was 12 meq L^{-1}, increasing to 14 meq L^{-1} in the evening, whereas well water exhibited a carbonate range of 0.4 to 1.6 meq L^{-1}, with a mean value of 0.96 meq L^{-1}. Bicarbonate levels showed the opposite trend: morning drainage water contained 1.2 meq L^{-1}, reducing to 0.8 meq L^{-1} in the evening. Well water displayed a bicarbonate range of 3.6 to 5.6 meq L^{-1}, with an average of 4.48 meq L^{-1}, indicating a more consistent bicarbonate concentration [16, 54]. Chloride levels in morning sewage water were measured at 8.0 meq L^{-1}, slightly decreasing to 7.6 meq L^{-1} in the evening. Well water, by contrast, showed a chloride range of 3.6 to 5.2 meq L^{-1}, with a mean value of 4.56 meq L^{-1}, indicating a relatively low salinity hazard from chloride ions [10, 55].

The calcium content in the morning sewage water was 4.2 meq L^{-1}, increasing marginally to 4.6 meq L^{-1} in the evening. Well water had calcium levels ranging from 1.6 to 3.2 meq L^{-1}, with a mean of 2.32 meq L^{-1}. Magnesium in morning sewage water was 4.8 meq L^{-1}, with evening values remaining consistent. By comparison, well water magnesium levels ranged from 1.6 to 3.2 meq L^{-1}, averaging 2.44 meq L^{-1} [8]. The sodium adsorption ratio (SAR), a key parameter in assessing water suitability for irrigation, was significantly higher in sewage water. Morning drainage water had a SAR of 5.4, which increased to 6.8 in the evening. In contrast, well water exhibited a much lower SAR range of 0.98 to 1.51, with a mean value of 1.25, indicating better suitability for irrigation purposes [19]. The residual sodium carbonate (RSC) values further highlighted the differences between water sources. Morning drainage water had an RSC of 4.0 meq L^{-1}, slightly decreasing to 3.8 meq L^{-1} in the evening. On the other hand, well water had an RSC range of 0.4 to 1.2 meq L^{-1}, with a mean of 0.68 meq L^{-1}. These findings suggest that prolonged use of untreated sewage water could lead to soil sodicity, necessitating appropriate management strategies [2].

Effect of Long-Term Application of Sewer Water on the Soil

Long-term sewage irrigation has been shown to enhance soil macronutrient content, including nitrogen (N), phosphorus (P), and potassium (K). The study revealed that soil nitrogen levels ranged from 100.4 kg ha^{-1} to 281.36 kg ha^{-1} during the *kharif* season, with a mean value of 224.88 kg ha^{-1}, and increased further during the *rabi* season to a range of 115.12 kg ha^{-1} to 294.45 kg ha^{-1} with a mean value of 236.56 kg ha^{-1}. Phosphorus levels also showed an upward trend, with mean values of 9.78 kg ha^{-1} and 12.71 kg ha^{-1} in the *kharif* and *rabi* seasons, respectively. The organic carbon content in the soil increased over time, with a mean value of 6.37 g kg^{-1} during the *kharif* season and 7.47 g kg^{-1} in the *rabi* season. This improvement positively impacted soil structure, water retention, and microbial activity, indicating that sewer water contains a variety of dissolved and suspended substances that significantly impact the soil's physical, chemical, and biological properties [15].

Sodium-rich sewer water caused soil dispersion and reduced aggregate stability, resulting in poor aeration and water infiltration. While cation exchange capacity (CEC) remained stable across seasons (mean values of 52.88 cmol kg^{-1} in *kharif* and 52.80 cmol kg^{-1} in *rabi*), this was likely due to the soil's buffering capacity.

Table 6. Water samples from drainage and wells near the sorghum research station of the Parbhani district of the Marathwada region.

Serial No.	Sample	pH	EC (dSm^{-1})	Carbonates ($meqL^{-1}$)	Bicarbonates ($meqL^{-1}$)	Chlorides ($meqL^{-1}$)	Calcium ($meqL^{-1}$)	Magnesium ($meqL^{-1}$)	SAR	RSC ($meqL^{-1}$)
1	Morning sewage	7.24	1.180	12.0	1.2	8.0	4.2	4.8	5.40	4.0
2	Evening sewage	7.24	1.330	14.0	0.8	7.6	4.6	5.4	6.80	3.8
3	Well 1	7.48	0.539	1.2	4.0	5.2	2.4	1.6	0.98	1.2
4	Well 2	7.11	0.714	1.6	3.6	4.4	1.6	3.2	1.51	0.4
5	Well 3	7.43	0.618	0.8	4.0	3.6	2.0	2.2	1.36	0.6
6	Well 4	7.20	0.710	0.4	5.2	4.4	2.4	2.8	1.18	0.8
7	Well 5	7.19	0.663	0.8	5.6	5.2	3.2	2.4	1.21	0.4

However, areas with high sodium levels experienced degradation over time. Using sewer water reduced the dependency on synthetic fertilizers by recycling nutrients, particularly in resource-constrained areas. This approach also addressed freshwater scarcity using an alternative water source [56, 57]. The application of sewer water for irrigation has been a subject of interest, as it can provide a reliable water source for agricultural production, particularly in regions with limited water resources [5, 54]. However, the long-term effects of this practice on soil properties and ecosystem health require careful consideration.

Conclusions

Utilizing wastewater can be beneficial because it reduces adverse impacts on the quality of downstream water resources, recycles minerals found in the wastewater, and closes the growing gap between water supply and demand, especially in semi-arid areas. The study found significant changes in soil properties, such as pH, organic matter content, and nutrient levels, due to continuous sewer water application and that plant nutrient contents are influenced by the type of crop grown and the specific nutrients present in the sewer water. Similarly, the positive influence of sewage water on available nutrients was found more during the *rabi s*eason than the *kharif s*eason, with the plant nutrient contents increasing the variables in grain and straw in both crops. Furthermore, the results suggest that the long-term use of sewer water for irrigation can both positively and negatively impact soil fertility and plant growth, offering valuable insights for agricultural practices in areas where sewer water is used for irrigation. Further studies are needed to explore the long-term effects of sewer water irrigation on soil health, crop productivity, and environmental sustainability.

Contribution Statements

Conceptualization- PHG, KY, MIA, SPZ, Validation- MIA, BDW, PHG, OOH; Resources-MIA, KY, PHG; Writing – original draft preparation- MIA, PHG, writing – review MIA; MFD, PHG, MFS; and Editing- MIA, MFD, PHG, OOH, MFS; Investigation – MIA, PHG, KY, BDW, SPZ; supervision, PHG, MIA, SPZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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