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IMPACTS OF WASTEWATER IRRIGATION ON SOIL PROPERTIES

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ABSTRACT

Wastewater reuse in agriculture is a common practice in developing nations, particularly in urban areas where water scarcity leads farmers to utilize this resource. The aim of this study was to evaluate the impact of wastewater irrigation on soil properties. A survey was conducted in various *Peri-Urban* sites of Jabalpur district (Madhya Pradesh) to assess the sites where wastewater was used as an irrigation resource to study the impact of wastewater irrigation on soil properties. Wastewater and soil samples were collected and analyzed following standard procedures. Parameters like pH, electrical conductivity (EC), and total content of essential nutrients (Ca, Mg, Na, K, Zn, and B) were evaluated for both wastewater and soil. Results revealed that wastewater characteristics were generally favorable for irrigation, with optimum pH and EC values. The pH of irrigated soils was neutral to slightly alkaline and was classified as non-saline, which indicated effective soil buffering capacity. Total potassium, calcium and magnesium contents in soils remained at optimum levels, whereas sodium hazard remained low to medium as indicated by SAR calculations. Though the concentration of zinc and boron in irrigation water was very low, their total content in soil was maintained at optimal levels. The study highlights that wastewater irrigation not only serves as an alternative water source but also contributes to soil fertility without adversely affecting soil properties. These findings support wastewater irrigation as a sustainable agricultural practice, particularly beneficial in water-scarce regions while maintaining soil health.
***Keywords* :** Wastewater, Soil fertility, Chemical properties, Irrigation, *Peri-Urban* areas

Introduction

Increasing growth in population, urban expansion, excessive water usage, and climate change are important factors contributing to the depletion of water resources. Wastewater reuse is the fundamental necessity globally, considering the prevailing water scarcity crisis. Ninety-two percent of global water is supposedly allocated for agricultural use, with around seventy percent derived from freshwater sources, such as rivers and groundwater (Rout and Kattumuri, 2022; World Resources Institute, 2020; WWAP - UNESCO World Water Assessment Programme, 2019). The reutilization of treated sewage or wastewater is an effective strategy for mitigating water scarcity and is attracting global attention (Contreras *et al.*, 2017). Research indicates that 1.6–6.3% of the global treated sewage is employed for agricultural irrigation (Ungureanu *et al.*, 2018). The reutilization of treated wastewater can enhance agricultural growth, reduce water pollution, and alleviate pressure on freshwater resources. The increasing water scarcity and its effects on water and food security emphasize the need of wastewater reuse as a vital water resource for agricultural practices (Elgallal *et al.*, 2016).

Untreated wastewater serves as a substantial supply of organic and inorganic nutrients for plant growth, farming using wastewater is prevalent in urban regions throughout India. Al-Hamaiedeh and Bino (2010) suggested that wastewater is a significant source of plant nutrients. The irrigation using wastewater has numerous economic and environmental advantages, including decreased reliance on natural water resources, diminished use of chemical fertilisers, safeguarding aquatic habitats from pollution, and enhanced agricultural yields. In this context, numerous researches have demonstrated that the application of wastewater (both treated and untreated) for irrigation has substantially altered soil parameters (Yao *et al*., 2013). A wide range of studies has been undertaken to investigate the effects of wastewater irrigation on soil chemical properties, including salinity, sodicity, and pH. Salinity is assessed by Electrical Conductivity (EC) and Sodium Adsorption Ratio (SAR), which collectively indicate the degree of soil sodium saturation and infiltration issues. Wastewater irrigation may supply soils with organic matter and nutrients (Chojnacka *et al*. 2020), hence enhancing agricultural yield (Gu *et al*. 2019). Rusan *et al*. (2007) examined soil and plant quality metrics to assess the long-term impacts of wastewater irrigation. The scientists discovered that prolonged wastewater irrigation elevated soil salt concentrations, organic matter, and plant nutrients. Conversely, Singh *et al*. (2012) discovered that residential wastewater irrigation exerted no substantial impact on the characteristics of clay soil, other from minor alterations in salt solubility and alkalinity. Abegunrin *et al*. (2013) also noted that sandy loam soil conditions Untreated wastewater irrigation did not significantly affect Alfisol and plant development indices; nonetheless, the authors observed a decrease in soil pH and an increase in sodium adsorption ratio (SAR) few weeks post-application.

The application of wastewater significantly elevates soil salinity, organic carbon, and the concentrations of cations such as potassium, calcium, and magnesium. Soil functions as a biofilter that can diminish a significant portion of residential wastewater contaminants; however, this filtration process elevates the electrical conductivity (EC), sodium adsorption ratio (SAR), and concentrations of sodium (Na), calcium (Ca), and magnesium (Mg) in the soil.

The application of wastewater for irrigation can improve soil health when appropriate management methods are employed (Nicolás *et al*., 2016). In contrast to soils irrigated with freshwater, numerous researchers demonstrated a considerable increase in effective phosphorus, total nitrogen, and total potassium content in soils subjected to treated wastewater irrigation (Guo *et al*., 2017). According to Hafiz *et al*. (2001), soil irrigated with sewage effluent exhibited a greater availability of potassium compared to soil irrigated with Nile freshwater.

Continuous irrigation with wastewater significantly enhances the exchangeable ions (Ambika *et al*. 2010). In light of these facts, a survey was conducted on locations where irrigation was done using wastewater, and samples of wastewater, and soil, were collected and examined for mineral content and other parameters.

Materials and Methods

The study area, Jabalpur, is located in the Satpura hills and Kymore plateau within the agroclimatic zone at 23°10' North latitude and 79°59' East longitude, with an elevation of 411.78 meters above mean sea level (MSL). During the winter season, from November to February, temperatures fluctuate between 4 and 33°C, while relative humidity varies from 70 to 90 percent. Between March and June, the climate is often arid and temperate. In the summer, temperatures can ascend to 44°C.The mean annual precipitation is approximately 1,386 mm (54.6 in).

Location description : Ten experimental sites were selected for the collection of water samples from sewage channels used for irrigation, as well as from the soil irrigated with this water. Details are mentioned in Table 1.

Table 1 : Description of experimental survey site

Name of Site	Water samples		Soil samples	
	Latitude N	Longitude E	Latitude N	Longitude E
Pariyat	23.2509	79.9715	23.2515	79.9726
Ricchai	23.2263	79.9726	23.2245	79.9651
Regama	23.1992	79.8892	23.1995	79.8895
Moti	23.2344	79.9199	23.2176	79.9316
Urdhawa	23.2116	79.9591	23.2117	79.9593
Kumhi	23.055	80.0243	23.0508	79.0241
Karonda	23.0668	80.0269	23.067	79.0265
Khurji	23.1033	79.9924	23.1033	79.9923
Khandari	23.1050	79.9580	23.1278	79.9658
Dhobighat	23.1463	79.9625	23.1461	79.9618

Collection and preparation of wastewater samples

Water samples were collected during the summer season in plastic bottles that had been thoroughly rinsed with 5% nitric acid and subsequently washed multiple times with Milli Q ultrapure water. Water samples were analysed for parameters such as pH and electrical conductivity (EC), measured using a pH meter and an EC meter, respectively, following the method proposed by Jackson (1973). The mineral content of wastewater was analysed using ICP-MS, which includes the digestion of 10 ml of sample with 0.1 ml of nitric acid and 25 µl of HCl (Trace metal grade, JT Baker). Single-element standard solutions at a concentration of 1000 mg/L (Agilent) were utilized to prepare mixed-element reference solutions. Water samples were introduced into the plasma using a nebulizer.

Collection and preparation of soil samples

Soil samples were collected from the topsoil using a hand auger. They were initially air dried for 24 hours. The sample had undergone sieving with a 2-mm sieve, was dried at 105 °C for 24 hours, and subsequently crushed with a wooden pestle and mortar. Following this process, the samples were homogenized, labelled, and appropriately stored.

Soil samples were analysed for parameters such as pH and electrical conductivity (EC), measured using a pH meter and an EC meter, respectively, following the method proposed by Jackson (1973).

For evaluation of minerals and metals, Trace metal grade acid (JT Baker) was utilised for the digestion of samples. For the digestion process, 0.5 gm soil was treated with 6 ml of HNO_3 and 1.5 ml of HF.

Closed vessel microwave digestion with Anton Paar was employed for the digestion of plant and soil samples. The parameters employed in microwave digestion included a power setting of 1200 W, a ramp time of 15 minutes, a final temperature of 200ºC, a temperature hold duration of 20 minutes, and a cooldown period of approximately 15 to 20 minutes. Following digestion, the samples were filtered with Whatman filter paper no. 42, and a volume of 50 ml was adjusted using ultra-pure water. The samples are prepared for analysis using ICP-MS. Mixed-element reference solutions were formulated utilising 1000 mg/L single-element standard solutions from Agilent. Following digestion, the samples were subjected to ICP-MS analysis for analysis.

Result and Discussion

Chemical properties of wastewater

pH

The pH levels of wastewater varied from moderately alkaline to slightly alkaline or neutral. The Pariyat site exhibited the highest pH value of 8.3, followed by the Ricchai and Khandari sites with values of 8.1 and 8.15, respectively. Sites such as Moti, Khurji, and Dhobighat exhibited pH levels ranging from 8.0 to 8.07, signifying somewhat alkaline conditions. Kumhi possessed a pH value of 7.98, indicating it is almost neutral yet slightly alkaline. Regama, Urdhawa, and Karonda exhibit the lowest pH readings, ranging from 7.65 to 7.72, indicating that these soils are almost neutral to slightly alkaline. Irrigation water with severe pH levels influences the bioavailability of nutrients, including phosphates. Phosphate precipitation transpires at elevated pH levels, whereas fixing occurs at reduced pH levels (Gorfie *et al*., 2022). The FAO states that the appropriate pH range for irrigation water is between 6.5 and 8.5; any pH value beyond this range signifies inadequate water quality (Habibi 2019). All wastewater samples complied with to the pH range established by the FAO for irrigation purposes.

EC

The Environmental Protection Administration suggests that EC quantifies the quantity of dissolved ions in water. A high EC indicates a greater concentration of salts, which may adversely affect plant growth. Excessive salt can hinder the absorption of essential nutrients, leading to nutritional imbalances that negatively affect crop quality and production. It serves as an effective indicator of salinity and is crucial in assessing irrigation water suitability (Shakir *et al*., 2017). Wilcox (1995) classified irrigation water into four categories based on EC values: C1 (0.1-0.25 dSm^{-1}), C2 (0.25-0.75 dSm^{-1}), C3 (0.75-2.25 dSm^{-1}), and C4 ($\geq$2.25 dSm^{-1}). Water categorised as C1 is acceptable for use, C2 enables limited leaching, and C3 can be exploited for irrigation with particular management strategies; however, C4 is inappropriate for irrigation applications.

The electrical conductivity levels in the surveyed locations varied from C2 to C3 classification. The maximum value of 1.25 dS/m was recorded at the Khandari site, followed by the Moti, Urdhawa, and Pariyat sites with values of 0.90 dS/m, 0.81 dS/m, and 0.75 dS/m, respectively, all classified as C3. The sites of Regama, Dhobighat, Ricchai, Karonda, Kumhi, and Khurji were classified as C2, with corresponding salinity values of 0.71 dS/m, 0.58 dS/m, 0.47 dS/m, 0.42 dS/m, 0.40 dS/m, and 0.35 dS/m. C2 classification is often suitable for irrigation with mild leaching requirements. Sites classified as C2 can be utilised for irrigation with caution, without yield loss, provided that moderately salt-tolerant crops are cultivated. Crops that exhibit sensitivity to salt may experience stress (Ayers and Westcot, 1985; Sharma *et al*., 2020). The C3 class indicates elevated salinity, necessitating thorough management measures and is applicable to well-drained soils suitable for crops with high salt tolerance (Hoffman *et al*. 1990; Munns & Tester, 2008). The utilisation of C3 water without proper management may lead to considerable yield reductions and soil deterioration over time.

Potassium (K)

The highest K values was obtained under Pariyat site (42.44 mg/L), whereas Kumhi site exbited the least value of K (2.54 mg/L). There is no specified limit of K content in irrigation water, although a suggestive limit of 100 mg/L is specified by Bres *et al*. 2010, whereas according to FAO, usual range lies between 0 to 78 mg/L. All the samples were within the range given. The potassium level in irrigation water influences soil potassium release and plant absorption (Ruan *et al*., 2014). Grasses and legumes can accumulate significant levels of potassium, reaching up to 5% of dry weight, rendering them beneficial for sustainable wastewater disposal methods (Arienzo *et al*., 2009). Potassium in irrigation water is essential for soil-plant systems and requires careful management. Very high levels of potassium (>78 mg/L) may interfere with magnesium uptake in some crops (Lauchli and Epstein, 1970).

Calcium (Ca)

Khandari site showed the highest content of Ca (69.51 mg/L), followed by Pariyat (64.59 mg/L), Moti (59.34 mg/L), Urdhawa (55.34 mg/L), Regama (54.49 mg/L), while the least content was shown by Karonda (28.97 mg/L). FAO suggested a maximum of 200 mg/L of calcium in irrigation water. However, in soils with poor drainage, higher Ca levels may lead to sodicity (FAO, 1985) and causes imbalance with other nutrients and toxicity in sensitive crops (WHO, 2006). All the sites were within range. Study conducted by Montesano & Iersel, (2007) revealed that Ca content in irrigation water can mitigate disease occurance and induce crop growth. Ca content in wastewater irrigation is also useful in preventing infestation of Phytophthora parasitica zoospores in Vinca seedlings (von Broembsen & Deacon, 1997), thus it can be stated that Ca levels in irrigation water is essential in preventing diseases and improving crop quality.

Magnesium (Mg)

According to Will and Faust (1999), the desireable range of Mg in irrigation water is upto 50 mg/L. The samples were within this prescribed range with highest Mg content in Kandari site (49.94 mg/L), followed by Pariyat (22.16 mg/L), Karonda (17.92 mg/L), Moti and Kumhi with values of 14.51 and 14.41 mg/L respectively and least content in in Ricchai site (8.96 mg/L). Wastewater sites having low Mg content such as Ricchai and Khurji can be used for long term without any risk on soil or crops, however, sites like Khandari should habe regular soil analysis as according to irrigation water quality guidelines, Mg content above 30 mg/L might cause salinity and nutrient imbalance under prolonged use in poorly drained soil or low rainfall regions. Mg is a critical element causing salt accumulation in soil and increased EC due to continuous use of wastewater (Phogat *et al*. 2023).

Sodium (Na)

FAO has suggested that Na content in irrigation water below 900 mg/L can be used for irrigation purpose, whereas GSC online press (2019) has given a range of Na content at 100 mg/L to be used as irrigation source with no restriction. The highest Na content in wastewater was obtained at Khandari site (96.29 mg/L), followed by Moti (73.28 mg/L), Urdhawa (57.76 mg/L), and Regama (49.527 mg/L) showing high levels of sodium, whereas Dhobighat (37.70 mg/L), Pariyat (27.37 mg/L) and Ricchai (26.99 mg/L) show moderate sodium levels. The lowest Na content was shown by Karonda (20.43 mg/L), Kumhi (16.41 mg/L), and Khurji (13.35 mg/L). Many studies have revealed that crops vary in their salinity tolerance level which makes it critical to have effective management strategies for different species (Maas and Hoffman, 1977), studies suggests that irrigation water having Na levels of 70 mg/L should be used to irrigate sensitive crops, whereas water having content up to 200 mg/L should be used only to irrigate tolerant crops. Here sites showing higher levels of Na should be regularly analysed for salinity hazard.

Boron (B)

According to Ayers and Westcot (1985), the permissible levels of B in irrigation water relies upon the tolerance of plants towards B toxicity. They classified the permissible limits as shown in Table 2.

Table 2 : Permissible levels of B in irrigation water (mg/L) (Ayers and Westcot (1985)

B (mg/L)	Very Low Levels	Low Levels	Medium Levels	High Levels
Sensitive crops	<0.33	0.33-0.67	0.67-1.00	1.00-1.25
Semi-Tolerant crops	0.67	0.67-1.33	1.33-2.00	2.00-2.50
Tolerant crops	>1.00	1.00-2.00	2.00-3.00	3.00-3.75

According to Ayers and Westcot (1985), Very low-level class water is considered as safe and is used for all soil types, while low level class can be used for irrigation purpose but with certain caution, medium level class is unsuitable for irrigation without any special management practices, whereas High level class is unsuitable for irrigation. The samples of wastewater collected fell into the category of very low-level class thereby, can be used for irrigation safely.

Similar results were obtained by Hyánková *et al* (2021).

Zinc (Zn)

As suggested by FAO, the permissible limit of Zn content in irrigation water is upto 2 mg/L. Only Urdhawa site showed some amount of Zn (0.09 mg/L), followed by Kumhi (0.05 mg/L), Dhobighat (0.04 mg/L), rest all the sites showed 0 to nil content of Zn in wastewater used for irrigation. Similar results were reported by Balkhair and Ashraf (2016). Zn is an essential micronutrient and its presence in wastewater at such levels is not a concern of accumulating in soil even for long term irrigation using wastewater (Yadav *et al.*, 2002). At such a low concentration plant can efficiently assimilate zinc at these concentrations, enhancing crop nutrition (Alloway, 2008).

Selected Chemical Properties of Soil irrigated with wastewater

pH

The pH of the soils varied from 6.82 to 7.85. The optimal soil pH for crop production is neutral, ranging from 6.5 to 7.5. The pH range of the selected sites was neutral to slightly alkaline, with the highest pH value of 7.85 recorded at Dhobighat and Khurji, followed by Regama (7.73), Moti (7.70), Khandari (7.45), and Urdhawa (7.42). The lowest pH value was observed at Ricchai (6.82), followed by Kumhi and Pariyat with values of 7.10 and 7.12, respectively. This pH range is ideal, as the majority of nutrients are available within it (Singh *et al*. 2012).

Wastewater utilised for irrigation might affect soil pH due to the presence of cations such as Na, Ca, and Mg. Wastewater abundant in ions helps sustain a neutral to slightly alkaline pH in soil (Jahan *et al.* 2019). The pH of wastewater was seen to be more alkaline than that of the soil, likely due to the soil's buffering ability, which restricts significant pH fluctuations despite the addition of acidic or alkaline agents (Abdel, 2015).

EC

The FAO (Landon, 1991; Agricultural Compendium, 1989) classifies soil salinity as non-saline when the EC value ranges from 0 to 2 dS/m. The highest EC value of 0.78 dS/m was recorded under Pariyat site, followed by Urdhawa (0.67 dS/m), Khurji (0.57 dS/m), Dhobighat (0.53 dS/m), Khandari (0.51 dS/m), Moti (0.49 dS/m), Karonda (0.48 dS/m), whereas least EC value was shown by Ricchai (0.23 dS/m), followed by Kumhi (0.25 dS/m). All the sites were classified as non-saline soils, which are considered as normal soils and will not hamper yield of crops grown on it.

The wastewater utilised for irrigation displayed EC classifications of C2 and C3; however, the soil did not experience salinity issues. This phenomenon may be attributed to the high cation exchange capacity (CEC) of the soil, which can adsorb cations and demonstrate effective buffering capacity against salinity increases, thus sustaining the soil's EC (USDA, 2022). The high-water retention capacity of clayey soils facilitates the leaching of salts beyond the root zone, thereby reducing salinity over time. The presence of basic cations in wastewater can temporarily elevate salinity; however, if their concentration remains low, they are counterbalanced by other soil properties, potentially preventing long-term salinity (Aref and Zare, 2014).

Total Potassium (K)

According to Potash development association (2019), the usual range of K in mineral soil ranges from 0.04% to 3% which depends upon soil characteristics and land use. The sites showed variations within the range of 0.03 to 0.51% with highest content of 0.51% observed at Moti followed by Khandari (0.29%), Ricchai (0.29%). The lowest K level was shown by Kumhi (0.03%), followed by Khurji and Dhobighat with values of 0.06% and 0.09% respectively. The variation among sites for K% might be attributed to difference in composition of wastewater and soil characteristics. On comparing the total K% in soil with that of wastewater it was found that there was inconsistent correlation between the two as Pariyat showed the highest wastewater K (42.43 mg/L) but moderate soil K (0.14%), whereas, Moti exhibited the highest soil K (0.51%) with moderate wastewater K content (17.11 mg/L). This revealed that soil K content is influenced by multiple factors beyond irrigation water composition. Similar findings were shown by Kasno *et al.* (2021). Although there is no direct relationship between soil and wastewater potassium contents, irrigation water is a substantial source of potassium input to the agricultural system. Lal *et al.* (2015) indicate that wastewater irrigation can yield 50-150 kg K/ha/year, supporting our findings. Irrigation by wastewater has proven to increase the potassium content of soil and improve soil nutrient profile (Sdiri *et al.* 2023; Rezapour *et al.* 2021). Freihat *et al.* (2021) suggested that use of wastewater for irrigation improves the nutrient profile of soil which may reduce the cost of expensive chemical fertilizers.

Total Calcium (Ca)

According to Metson (1961), Ca content in soil is classified into five categories of Very low (<0.20%), Low (0.20-0.40%), Medium (0.40-1.00%), High (1.00-2.00%), and very high (>2.00%). The highest Ca content was reported in Urdhawa (1.05%) which belonged to high category, followed by Khurji (0.54%), and Regama (0.46%), with medium category, Kumhi (0.39%), Pariyat (0.33%), Karonda (0.27%), Moti, Khandari and Dhobight (0.23%) with low category and Ricchai (0.18%) at very low category of Ca in soil. The results showed that the content of Ca in wastewater and soil do not match with each other, as sites with high Ca content in wastewater such as Pariyat and Khandari did not result in Ca accumulation in soil. The findings were consistant with the research conducted by Rusan *et al.* (2007), which concluded that the calcium concentration in soil does not necessarily correlate directly with the calcium concentration present in irrigation water. Also, sites like Urdhawa showed high content of Ca despite the fact that it had moderate Ca content in wastewater, which suggests that other properties of soil and management practices affect Ca accumulation in soil (Xu *et al.*, 2010; Mohammad and Mazahreh, 2003; Yadav *et al.*, 2002).

Despite the lack of correlation between the calcium levels in soil and wastewater, the irrigation process adds calcium to the soil profile. Wastewater contains an adequate amount of Ca, which improves soil fertility. For instance, sites like Pariyat and Karonda exhibited elevated calcium in wastewater, which might cause Ca accumulation in the soil over time. Irrigation using wastewater raises calcium levels in soils, enhancing nutrient availability (Rusanescu *et al.*, 2022; Mojid & Wyseure, 2013). The frequent use of wastewater can yield cumulative advantages, including enhanced nutrient retention, vital for soil health (Balengayabo *et al.*, 2022).

Total Magnesium (Mg)

According to Metson (1961), the classification of Mg in soil is done under five categories *i.e.* Very low (<0.04%), Low (0.04-0.10%), Medium (0.10-0.30%), High (0.30-0.60%) and Very high (>0.60%). All the samples were classified under low and very low categories with Urdhawa (0.09%) under low category and rest all the samples under very low category. Most of the sites showed Mg deficiency in soil, despite of varying wastewater Mg content. The trend of Mg is quite similar to Ca that despite of having higher content in wastewater, soil is low in Mg content. According to Singh *et al.* (2012), this deficiency of Mg might be due to leaching losses or competition with other cations. Sites that shoe low Mg content, though the wastewater content in high in Mg indicates that when nutrient content is high in wastewater it might cause leaching or imbalance in nutrient chemistry which affects its retention in soil (Shahalam *et al.* 1998).

Total Sodium (Na)

According to FAO, the permissible level of Na in soil should be less than 0.1%. All the sites showed Na content within the permissible range, the highest Na content was shown by Pariyat (0.09%), followed by Ricchai, Regama, Moti, Kumhi, Karonda,Khurji and Khandari with similar value of 0.08%, while Urdhawa and Dhobighat showed 0.07% of Sodium percentage. All the sites showed normal range of sodium content as typical sodium content in non-saline soil ranges up to 0.1% (Kabata-Pendias, 2011).

Since the values of Na% is almost similar in all sites, to get a better understanding of salinity or sodicity of soil, Sodium adsorption ratio (SAR) was calculated as it gives a precise assessment of sodium and other cations. While the Na% readings were similar, SAR values varied based on the concentrations of sodium, calcium, and magnesium, so providing a representation of salinity risk in contrast to total sodium percentages, which only indicate the sodium quantity without relevance to the context. According to Richards (1954), based on SAR soils are classified into four classes for sodium hazard which are mentioned in Table 3.

Table 3 : Classification of soil based on Sodium hazard (Richards, 1954)

SAR	Class	Interpretation
<10	Low	Generally, no Sodium hazard
10-18	Medium	Moderate sodium hazard
18-26	High	High sodium hazard
>26	Very high	Very high sodium hazard

Based on this classification, Regama, Urdhawa, Kumhi, Khurji, and Dhobighat showed no sodium hazard, whereas Pariyat, Richhai, Moti, Karonda, and Khandari sites were classified as medium class, showing moderate sodium hazard. Sites with low sodium hazards exhibit no stress in soil physical properties such as soil structure (Brady and Weil, 2017), exhibit normal to high water infiltration rates (Hanson *et al.*, 1999), and maintain balanced soil chemical properties like pH and electrical conductivity (EC), which are crucial for optimal soil functionality and plant development (Sarani *et al.*, 2016; Nabiollahi *et al.*, 2017). This class does not require a special amendment, but regular monitoring is necessary. Sites that show medium sodium hazards might suffer from moderate deterioration of soil structure (Qadir and Schubert, 2002). Managing soil properties requires leaching (Ayers and Westcot, 1985), and cultivating deep-rooted crops can enhance soil structure (Maas and Hoffman, 1977; Mohanavelu *et al.*, 2021).

Total Boron (B)

The data revealed a wide range of total boron concentrations in the soils, with highest B content at Khandari site (26.14 mg/kg), followed by Pariyat (25.33 mg/kg), Regama and Moti with values of 23.33 mg/kg and 23.78 mg/kg respectively, Richhai site (22.49 mg/kg), while sites like Kumhi (10.08 mg/kg), Karonda (19.74 mg/kg) and Dhobighat (13.91 mg/kg) showed medium B content. Sites like Urdhawa and Khurji showed least B content with values of 6.17 mg/kg and 2.11 mg/kg respectively. Sun *et al.* (1998) in his studies found that the total B content ranged between 19 to 76 mg/kg. Kumar *et al.* (2020) revealed that the total B content in Indian soils ranges from as low as 3.80 mg/kg to as high as 630 mg/kg. The total boron content in soil consists of various fractions such as freely soluble, particularly adsorbed, oxide-bound, organically bound, and residual boron, which collectively affects its overall availability (Ajayan *et al.* 2021). Average total B in soil reported by Singh and Randhawa (1977) was 28.40 mg/kg. Arora and Chahal (2014) also reported the total B concentrations between 10.25 and 25.42 mg/kg in alkaline alluvial soils, with significant correlations observed between various extractable forms and soil properties.

A weak correlation has been observed between boron concentrations in wastewater and its accumulation in soil at the research sites. Khurji, exhibiting the greatest wastewater boron concentration (0.08 mg/L), exhibits the lowest boron accumulation in the soil. In contrast, Khandari and Pariyat exhibit elevated soil boron levels despite minimal boron additions from wastewater. This suggests that the concentration of boron in wastewater is not the only factor influencing boron levels in soil; rather, site-specific elements such as soil properties, water usage patterns, and local environmental conditions significantly affect boron dynamics (Singh and Somashekar, 2015). Nearly all of the locations reveal optimal soil boron concentrations for plant growth. Shorrocks (1997) and Das *et al.* (2017) revealed that the ideal soil boron levels for the majority of crops range from 10 to 30 mg/kg, which includes most of our survey locations.

Total Zinc (Zn)

According to Lindsay (1972), typical Zn concentration in soil is reported in the range of 10-300 mg/kg. The concentration of Zn in surveyed soil ranged from 27.59 mg/kg to 279.65 mg/kg, with highest content of 279.65 mg/kg in Regama site followed by Dhobighat (96.44 mg/kg) and Pariyat (65.93 mg/kg). Sites showing moderate Zn content were Karonda (54.20 mg/kg), Urdhawa (53.00 mg/kg), Kumhi, Khurji and Khandari with values of 50.85 mg/kg, 50.83 mg/kg and 51.25 mg/kg respectively. Least Zn content was shown by Ricchai site (27.59 mg/kg), followed by Moti site (27.59 mg/kg). Žunić & Sabadoš, (2023) reported that in agricultural lands Zn concentrations ranges from 26.76 mg/kg to 228.20 mg/kg, with average around 60-80 mg/kg in certain regions. The surveyed sites showed acceptable amount of total Zn content in soil needed for crop growth.

Zinc deficiency is widespread and far more common than its toxic effects, due to which stunted growth and affected crop yield is observed. Therefore, regulating zinc concentrations in soil is essential for sustainable agricultural practices (Kaur *et al.*, 2024). Increased Zn concentrations can alter the availability of other nutrients, therefore affecting soil fertility (Kaur *et al.*, 2024). A lower total Zn concentration in soil (27.59 ppm) may result in reduced Zn bioavailability, causing deficiency in plants, which negatively impacts growth and production, whereas an elevated concentration (279.65 ppm) facilitates optimal plant development (Camila 2020), enhancing labile Zn fractions.

The zinc concentration in soil exhibited variability across the locations, showing minimal correlation with the zinc levels in the irrigation water. This suggests that factors including soil composition, past agricultural practices, and local geology substantially affect zinc concentrations in soils. Monitoring zinc levels in both soil and water is crucial for maintaining soil health and guaranteeing sustainable agricultural productivity (Mossa *et al*., 2021; Suganya *et al*., 2020).

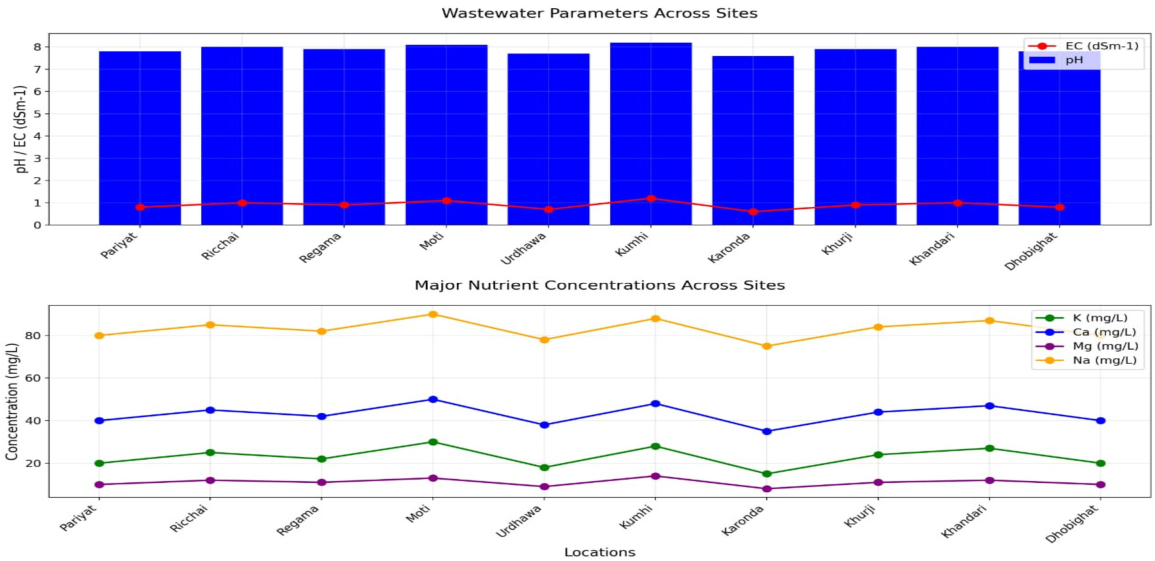

Fig. 1 : Chemical properties of Wastewater

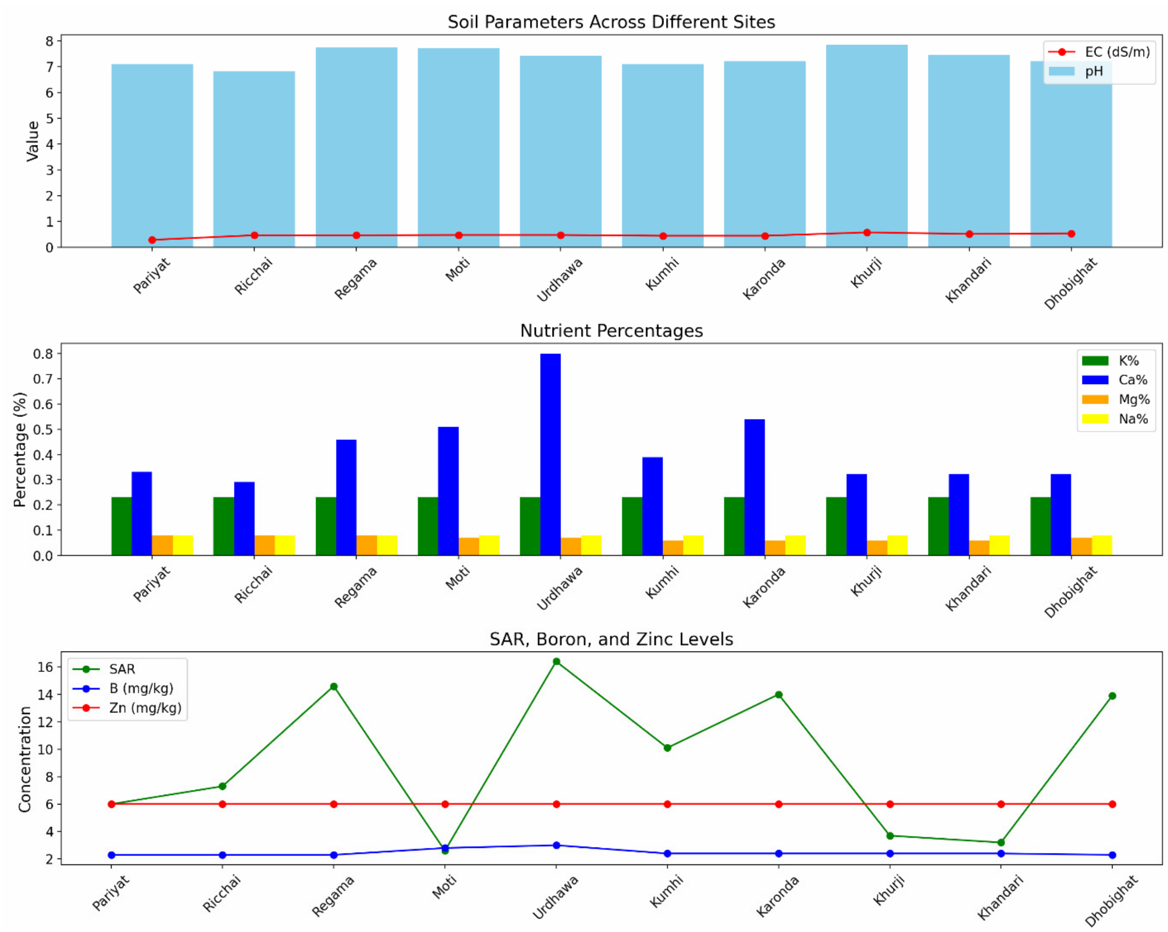

Fig. 2 : Chemical Properties of Soil

Table 4 : Chemical properties of wastewater

Name of site	pH	EC (dSm^{-1})	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	B (mg/L)	Zn (mg/L)
Pariyat	8.30	0.75	42.43	64.59	22.16	27.37	0.03	0.00
Ricchai	8.10	0.47	6.97	43.06	8.96	26.99	0.07	0.00
Regama	7.72	0.71	12.37	54.4	12.42	49.52	0.05	0.03
Moti	8.05	0.90	17.11	59.64	14.51	73.28	0.04	0.01
Urdhawa	7.68	0.81	14.04	55.34	12.99	57.76	0.04	0.09
Kumhi	7.98	0.40	2.54	35.06	14.41	16.41	0.02	0.05
Karonda	7.65	0.42	5.78	28.9	17.92	20.43	0.02	0.02
Khurji	8.01	0.35	4.49	33.02	9.93	13.35	0.08	0.03
Khandari	8.15	1.25	13.29	69.51	49.94	96.29	0.03	0.00
Dhobighat	8.07	0.58	8.65	53.18	12.15	37.70	0.03	0.04

Table 5 : Properties of soil irrigated by wastewater

Name of site	pH	EC (dS/m)	K%	Ca%	Mg%	Na%	SAR	B (mg/kg)	Zn (mg/kg)
Pariyat	7.12	0.78	0.14	0.33	0.03	0.09	10.49	25.33	65.93
Ricchai	6.82	0.23	0.29	0.18	0.01	0.08	14.64	22.49	27.59
Regama	7.73	0.46	0.11	0.46	0.03	0.08	8.66	23.33	279.65
Moti	7.7	0.49	0.51	0.23	0.01	0.08	15.41	23.78	47.20
Urdhawa	7.42	0.67	0.11	1.05	0.09	0.07	4.31	6.17	53.00
Kumhi	7.1	0.25	0.03	0.39	0.02	0.08	8.64	10.08	50.85
Karonda	7.2	0.48	0.13	0.27	0.01	0.08	14.01	19.74	54.20
Khurji	7.85	0.57	0.06	0.54	0.05	0.08	6.94	2.11	50.83
Khandari	7.45	0.51	0.32	0.23	0.01	0.08	14.24	26.14	51.25
DhobiGhat	7.85	0.53	0.09	0.23	0.02	0.07	9.57	13.91	96.44

Conclusion

The comprehensive examination of soils irrigated with wastewater indicated that prolonged wastewater irrigation did not negatively impact soil qualities. The wastewater displayed a moderately to slightly alkaline pH and moderate salinity (C2-C3 class), while the irrigated soils revealed considerable resistance. The soil pH was within the recommended range (neutral to slightly alkaline), and the EC readings classified the soils as non-saline, suggesting the soil's buffering capacity against potential salinisation. The mineral analysis showed that the Ca and Mg content was optimum in the soil, whereas, SAR values indicated a low to medium sodium hazard, thereby posing no to minimal risk to soil structure. Although the irrigation wastewater contained low concentrations of zinc and boron, their levels in the soil remained optimum, probably due to other soil and environmental attributes. This suggests that the inherent properties and buffering mechanisms of soil are essential for maintaining nutrient balance. Overall, these findings indicate that utilising wastewater for irrigation is sustainable, as it provides a valuable water resource and enhances soil nutrient content without negatively impacting soil health. The research indicated that effective monitoring and management may ultimately make wastewater irrigation a feasible approach for agricultural sustainability, especially in areas experiencing water scarcity.

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