

Linking Sewage Effluent Quality with Salinity-Sodicity Dynamics and Cation Imbalance in Greywater-Irrigated Soils of an Arid Coastal Environment

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ABSTRACT

The increasing reuse of greywater for irrigation necessitates a comprehensive understanding of its effects on soil quality and chemical dynamics. This study evaluated the efficiency of a greywater treatment system and its subsequent impact on soil physicochemical properties across multiple urban green spaces. Significant reductions in biochemical oxygen demand, chemical oxygen demand, and total dissolved solids showed limited reduction, indicating the persistence of dissolved salts during treatment.

Soil analyses revealed moderately alkaline conditions (pH 7.43-8.33) and elevated electrical conductivity (0.86-1.27 dS/m), suggesting progressive salinity buildup under greywater irrigation. Nutrient parameters, including soil organic matter (0.49-0.82%), nitrogen, phosphorus, and potassium, exhibited positive interrelationships, reflecting enhanced nutrient retention. In contrast, higher sodium concentrations (130-165 mg/kg), sodium adsorption ratio (10.54-13.33), and magnesium hazard (35.1-44%) indicated increasing sodicity risks. The Ca:Mg ratio (1.27-1.85) showed an inverse relationship with sodicity indicators, highlighting the stabilizing role of calcium in soil structure.

Correlation analysis demonstrated strong positive associations among salinity-related parameters (EC, Na, SAR, MH, and cation balance), while nutrient variables showed negative relationships with salinity indicators, indicating a trade-off between fertility and salinization. Principal component analysis further distinguished salinity-driven processes from nutrient-driven dynamics, with clear clustering of study areas based on soil chemical characteristics.

Overall, the findings suggest that while greywater irrigation enhances soil nutrient status, it simultaneously contributes to salinity and sodicity development. Sustainable management strategies, including controlled irrigation practices and calcium-based amendments, are essential to mitigate long-term soil degradation and ensure the safe reuse of greywater in urban landscapes.

Keywords: Salinity-Sodicity Interactions, Sodium Adsorption Ratio, Calcium-Magnesium Ratio, Treated Grey-Water Reuse, Sewage Treatment Plant Efficiency, Sustainable Irrigation Management

Introduction

Water scarcity has become one of the most critical environmental issues of the 21st century, especially in arid and semi-arid areas where the high rate of urbanization, population increase, and climate changes have put a strain on the scarce freshwater availability [1]. The coastal areas are especially vulnerable due to high evaporation rates, salt waters intrusion and water scarcity. Gwadar, Pakistan is an example of this vulnerability because the increasing urbanization, as part of strategic development plans, has led to a significant increase in the water demand but the natural supply of fresh water is limited. The imbalance causes the necessity to investigate alternative and environmental water sources in order to secure long-term urbanization and

ecological sustainability.

Treated wastewater and greywater have been considered as promising options to provide alternative water sources to irrigate lands and manage urban landscapes among non-conventional water resources. The processes introducing the generation of greywater in the household include bathing, laundry, and kitchen use (but not toilet waste), and comprise of approximately 50-75 percent of total household wastes [2, 3]. The latest developments in decentralized wastewater treatment systems [4] Zhang et al., 2024. It is comparatively less polluted as compared to the black water, therefore, it can be reused with proper treatment. The latest developments in the field of decentralized wastewater treatment systems have increased the viability of greywater reuse in urban settings with a lack of water even more [5, 6].

The reuse of treated greywater on urban forest and establishment of green infrastructure presents a number of benefits both environmentally and economically. Besides decreasing freshwater reliance, treated greywater includes vital nutrients to plants, including nitrogen (N), phosphorus (P), and potassium (K), which can be essential to growth and improvement of soil fertility [7, 8]. These improvements are strongly linked to increased soil organic carbon and nutrient availability under wastewater irrigation [9, 10]. Recent results show that the irrigation of wastewater can boost soil organic matter, microbial activity, and the establishment of vegetation, especially in arid and nutrient-depleted soils [11, 12]. The mentioned advantages, in particular, can be applied to the urban greening activities to improve the quality of the environment and the ecosystem functions.

Nevertheless, regardless of these benefits, there are possible environmental hazards associated with the long-term use of treated greywater. The main issues related to wastewater reuse are the high salinity levels, sodium deposition, and the disproportions of physicochemical properties of soils [13]. Such conditions significantly affect soil structure, permeability, and long-term productivity [14, 15]. Continuous irrigation with sodium-enriched water can lead to the dispersion of soils, ready to reduce the rate of infiltration, and the reduction of soil structure that eventually affects the growth of plants and their sustainability [16]. The recent study, in turn, highlights the need to monitor such parameters as electrical conductivity (EC), sodium adsorption ratio (SAR), and nutrient dynamics more frequently as the tool of a safe and sustainable areas of reuse [6, 17].

Wastewater treatment and its use in Pakistan is an issue that is slowly starting to be considered as a strategic approach to the shortage of urban water, and to promote the emergence of green areas in the nation. As a developing city with an increasing number of people live in the coastal region, Gwadar as a city under the Gwadar development authority (GDA) has been working on several urban afforestation and landscaping as park areas, road and recreational areas. These lowlands have sandy to loamy soils, low natural fertility, and low organic matter are susceptible to foreign nutrient input, yet prone to the salinity and sodicity threats. The success of these greening programs then is not just because water is available, but because of the water availability, and the health of the soil and nutrient balance with the irrigation using treated greywater.

Urban forestation can play a crucial role in creating urban resilience by enhancing air quality, reducing urban heat islands, enhancing carbon sequestration, and protecting

biodiversity [18, 19]. Afforestation programs using treated wastewater is a feasible approach to ensuring a sustainable future in arid coastal regions like Gwadar where providing the environment with treated wastewater will have a positive impact on the environment, the society, and the economy. The success of these measures, however, will rest on location-specific measurements of soil reaction and nutrient cycles in response to greywater irrigation.

Although there is an increasing interest in reuse of wastewater territory among the world, only a small number of researches are carried out on the application of the same in arid urban forestry arid-coastal system. The literature found is mostly about agricultural sites, the urban environment, especially in the growing cities such as Gwadar are not researched thoroughly. Such lack of knowledge justifies the necessity to conduct empirical, field-based researches that will help to assess the advantages and disadvantages of treated grey water reuse in the field setting.

Other than soil tests, the efficiency of the sewage treatment plants should be checked to show whether or not the treated grey water can be reused. Performance of treatment and quality of effluent is measured using the most common physicochemical parameters (pH) and the following [6, 20]: chemical oxygen demand (COD), biological oxygen demand (BOD5), total suspended solids (TSS), and total dissolved solids (TDS). These parameters provide us with an idea of the disappearance of organic loads, removal of the particles and dynamics of dissolved contaminants. In addition, it is important to monitor heavy metals like lead (Pb), chromium (Cr), and nickel (Ni) to protect the environment and avoid the contamination of soils in the long term [7]. Therefore, considering the STP performance measurement and soil quality measurement, a holistic approach to evaluate sustainability of greywater reuse in urban afforestation systems can be achieved. This is why the objective of the current investigation is to define the physicochemical characteristics, and the nutrient composition of the soils in the cities of the area of interest that are under the jurisdiction of the Gwadar Development Authority and irrigated using the treated grey water sources. Particularly, it measures the soil texture, pH, electrical conductivity, organic matter and all the significant macronutrients (N, P, K, Ca, and Na) and describes their significance to urban afforestation system soil sustainability and plant growth. The given study will add to the sustainable reuse of water as it will offer site-specific evidence that would help to develop sustainable urban ecosystems in the arid coastal areas. Green infrastructure approaches are increasingly recognized as effective climate adaptation strategies in urban environments [21].

Material and Methods

Study Area Description and Soil Sampling Strategy

The present study was carried out in Gwadar located in Balochistan, Pakistan, under the Gwadar Development Authority (GDA), which is an arid coastal city. The area is typified by scarce supply of fresh water, high levels of evaporation, and growing urban water pressure, which requires utilization of treated grey-water to irrigate and afforest urban areas. Seven representative urban sites irrigated with treated grey-water were sampled (Marine Drive Road, Airport Road, Gwadar Cricket stadium, Football stadium, GDA Padizer Park, Beach Model Park and Central park). Sampling was done in systematic random manner with a collection of surface soil samples (0-20

cm). Several subsamples were sieved together at each location to get representative samples. The samples were dried in the air, sieved (less than 2 mm) and kept to be analyzed in the laboratory.

Soil Physicochemical Characterization

Soil analyses were conducted using standard analytical procedures. Soil texture was determined using the hydrometer method. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil–water suspension following established protocols [22, 23]. Soil organic matter (SOM) content was determined using the Walkley–Black wet oxidation method [24] (Walkley & Black, 1934). Total nitrogen (N) was analyzed by the Kjeldahl digestion method, available phosphorus (P) was determined using the Olsen extraction method, and exchangeable potassium (K) was measured by flame photometry, following standardized procedures [25, 26]. Exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) and sodium (Na^+) were determined by using flame photometer [27]. All the analysis was carried followed by an international methods followed by [28]. Derived soil indices were calculated to assess structural stability and sodicity risk. The calcium–magnesium ratio (Ca:Mg) was computed as:

$$\text{Calcium } (\text{Ca}^{2+}) \text{ and Magnesium } (\text{Mg}^{2+}) \text{ ratio } Ca : Mg = \frac{Ca^{2+}}{Mg^{2+}} \quad (1)$$

MH = Magnesium hazard

$$MH (\%) = \frac{Mg^{2+}}{Ca^{2+} + Mg^{2+}} \times 100 \quad (2)$$

$$SAR = Na^+ \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (3)$$

SAR = Sodium Adsorption ratio, where all ionic concentration are expressed in milliequivalent per liter [27]

Sewage Treatment Plant (STP) Performance Evaluation

The effluents and influent samples of sewage treatment plants (STP) were sampled to measure the efficacy of treatment. Interesting parameters such as pH, biological oxygen demand (BOD_5), chemical oxygen demand (COD), and total dissolved solids (TDS) were determined by conventional procedure BOD_5 was calculated through the 5-day incubation technique, COD through dichromate oxidation, TDS through the use of conductivity measurement, and heavy metal lead (Pb), chromium (Cr) and nickel (Ni), cadmium (Cd), Mercury (Hg) and oil and grease were analysis by using atomic absorption spectrophotometer determined to maintain environmental safety followed by international methods [28].

Statistical analysis

Descriptive statistics (triplicate mean, standard deviation, minimum, and maximum) were used to represent soil physicochemical properties' variability. Correlation coefficients (Pearson's r) were calculated to assess the interrelation between soil properties (pH, electrical conductivity (EC), soil organic matter (SOM), macronutrients (N, P, K), exchangeable cations (Ca, Mg, Na) and calculated indices (Ca: Mg, MH, SAR, and cation balance). A heat-map was used to display the correlation matrix. Principal Component Analysis (PCA) was carried out using z-

score transformed data to determine the major factors controlling soil variability. PCA is widely used to identify dominant factors influencing soil systems under wastewater irrigation [29]. The first two principal components (PC1 and PC2) were selected based on the variance contribution and a PCA biplot was created; plot loadings represent the main drivers of soil property. STP efficacy was assessed from influent and effluent levels of BOD₅, COD, and TDS and reduction was calculated as percentage. The data were analysed and plotted using statistical software.

Results

Removal Efficiency of Organic and Suspended Pollutants

Organic and suspended pollutants were removed to a large extent in the treatment system at the two sampling points. Biochemical oxygen demand (BOD) was markedly reduced, from 141 to 70 mg/l and from 118 to 66 mg/l and chemical oxygen demand (COD) was reduced from 202 to 120 mg/l and from 163 to 100 mg/l respectively. By contrast, total dissolved solids (TDS) exhibited mixed trends, with them decreasing in one system (4600 to 3200 mg/l) but they increased in the other (1900 to 2400 mg/l), suggesting that dissolved salts remained present through the treatment process (Figure 1A). Additionally; metal analysis revealed that the concentrations of Pb (0.042-0.107 ppm), Cr (0.60-1.15 ppm) and Ni (0.11-0.80 ppm) were below internationally acceptable levels for irrigation water (Figure 1B). The absence of Cd and Hg in the treated effluent indicates minimal risk of contamination by these highly toxic metals. This suggests that the treated grey-water is safe from the perspective of trace metal toxicity and can be safely used for urban irrigation. Lack of toxic metal accumulation minimizes environmental and health risks, suggesting a low risk of wastewater reuse from a toxicological point of view.

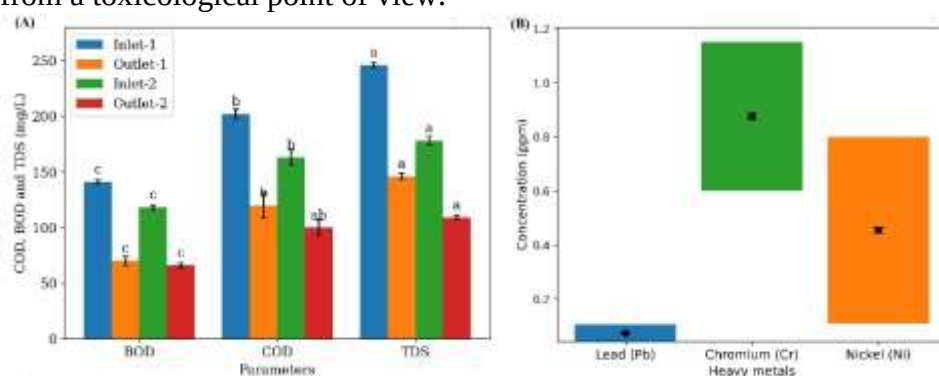


Figure 1 Organic and suspended pollutants removal by the grey-water treatment system. Plots (A) showing the changes in biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS) levels between the influent and effluent conditions of the treatment. Plot (B) showing the concentration of heavy metal lead (Pb), chromium (Cr) and Nickel (Ni) presents in the inlet and outlet of grey-water treatment units. Values are presented as mean $\pm$ standard error of three replicates, different letters (a, b, c) indicate statistically significant differences among land-use systems at $p < 0.05$.

Soil Physicochemical Properties under Grey water Irrigation

The study sites had variable soil physic-chemical properties. The pH ranged between 7.43 - 8.33 (slightly alkaline) and the electrical conductivity (EC) between 0.86 - 1.27 dS/m, respectively, with moderate salinity levels. EC values were higher at Beach Model Park and Airport Road, indicating potential salt build-up from grey-water use. In general, the soils were suitable for cultivation; however, salinity was beginning to increase (Figure 2A). Further; Textural analysis of the soils showed considerable variation in the sand, silt and clay content. Sand percentages varied between 41.94% and 64.40%, the greatest at Gwadar Cricket Stadium and the least at Marine Drive Road. Silt content varied between 13.09% and 30.97%, while clay content ranged from 20.71% to 30.12%. According to USDA classification, soils are mostly of the loam to sandy clay loam texture (particular size of soil with a balanced mix of clay and sand). Soils at locations like Gwadar Cricket Stadium, GDA Padizer Park and Beach Model Park had higher sand percentages while Marine Drive Road and Central Park had higher clay percentages (Figure 2B). The standard errors are relatively low, suggesting precision in the replicates.

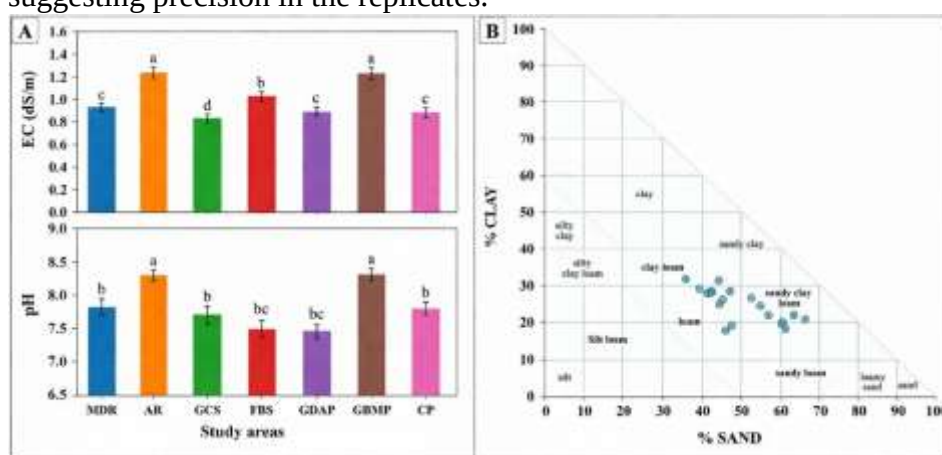


Figure 2 Panel (A) present Electrical conductivity (dSm^{-1}) of soils across different study areas. Bars represent mean $\pm$ SE ($n = 3$). Different letters above bars indicated significant difference among study areas at $p < 0.05$ (Tukey's HSD test). Panel (B) showing soil textural class triangle (USDA classification) showing the distribution of soil sample based on sand, silt and clay percentage.

Soil Nutrient Dynamics and Exchangeable Cation Chemistry

Soil organic matter (SOM) varied between 0.49% and 0.82% with increased content at GDA Padizer Park and Central Park (Figure 3A). The SOM was positively correlated with nutrients, such as nitrogen (N), phosphorus (P) and potassium (K) and improved their retention. Exchangeable cations showed variability in their concentrations, with calcium (Ca) ranging 210-240 mg/kg and magnesium (Mg) 128-163 mg/kg. Sodium (Na) ranged from 130 to 165 mg/kg (Figure 3B). Sodium adsorption ratio (SAR) varied from 10.54 to 13.33, while magnesium hazard (MH) ranged from 35.1% to 44%. Calcium-magnesium (Ca:Mg) ratios (1.27-1.85) and cation balances (599-629.33) also reflected variations in ion balances (Figure 3C).

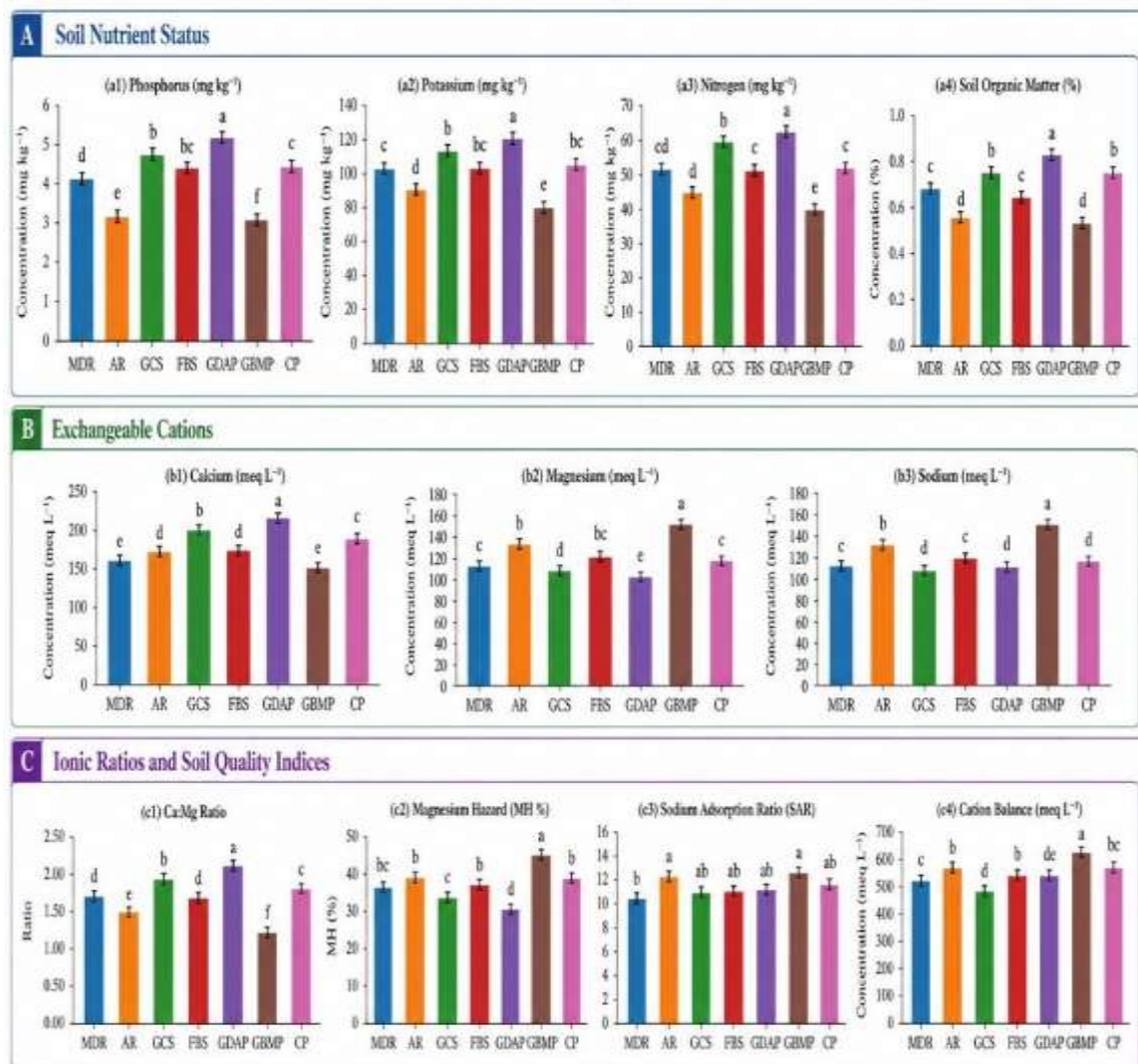


Figure 3 Soil chemical properties under greywater irrigation across different sites. Panel (A) soil nutrient status including available phosphorous (mg kg^{-1}), available potassium (mg kg^{-1}), total nitrogen (mg kg^{-1}), and soil organic matter (%). Panel (B) include exchangeable cations (calcium, Magnesium, and sodium meq L^{-1}). Panel (C) ionic ratios and soil quality indices: Ca: Mg ratio, magnesium hazard (MH %), sodium adsorption ratio (SAR), and cation balance mean $\pm$ SE ($n=3$). Different letters above bars indicate significant differences among treatment at $p<0.05$.

Correlation Analysis and Key Soil Chemical Interactions

Correlation analysis showed a positive association between salinity-related variables (EC, Na, SAR, MH, and cation balance), suggesting a shared source of salt accumulation. Fertility values (SOM, N, P, and K) were positively related to each other but negatively to salinity indicators. Calcium: Magnesium ratio was negatively related to MH and SAR, suggesting that increased calcium relative to magnesium decreased MH and SAR (Figure 4). This suggests intricate relationships between soil fertility and salinity in greywater irrigation systems.

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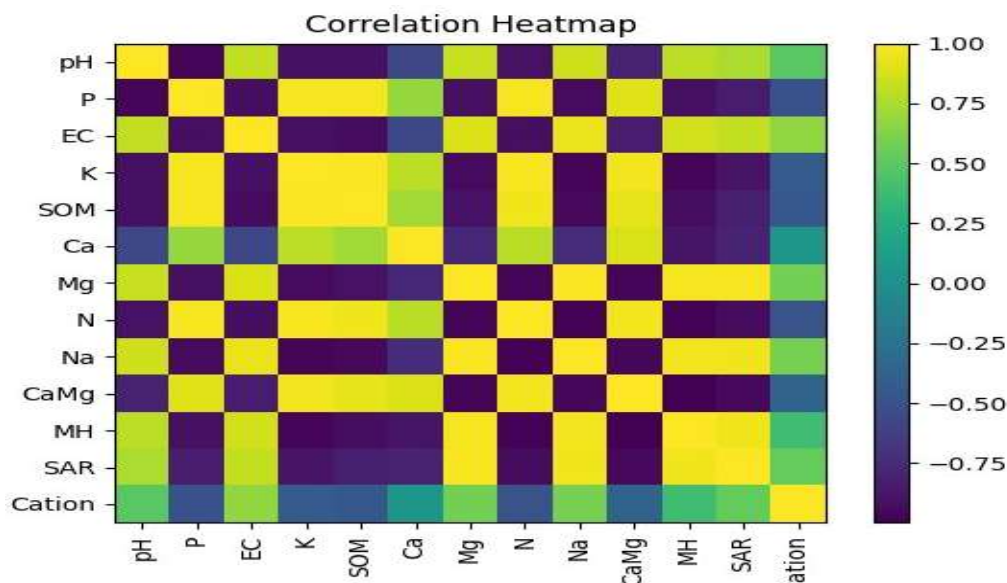
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Figure 4 Correlation heat-map showing the relationships among key soil physicochemical properties, including pH, phosphorus (P), electrical conductivity (EC), potassium (K), soil organic matter (SOM), calcium (Ca), magnesium (Mg), nitrogen (N), sodium (Na), Ca: Mg ratio, magnesium hazard (MH), sodium adsorption ratio (SAR), and total cations. Color intensity represents the strength and direction of the correlation, with yellow indicating strong positive correlations and dark purple indicating strong negative correlations. Strong positive associations were observed among nutrients such as P, K, SOM, and N, suggesting their interdependence in soil fertility dynamics. In contrast, parameters such as SAR and MH showed distinct relationships with cation composition, reflecting their role in assessing soil sodicity and irrigation suitability.

Multivariate Analysis of Soil Chemical Properties (PCA)

Salinity indicators (EC, Na, SAR, MH and cation balance) accounted for the largest portion of soil variability in principal component 1 (PC1), while fertility parameters (SOM, N, P and K) were related to PC2 (Figure 5).

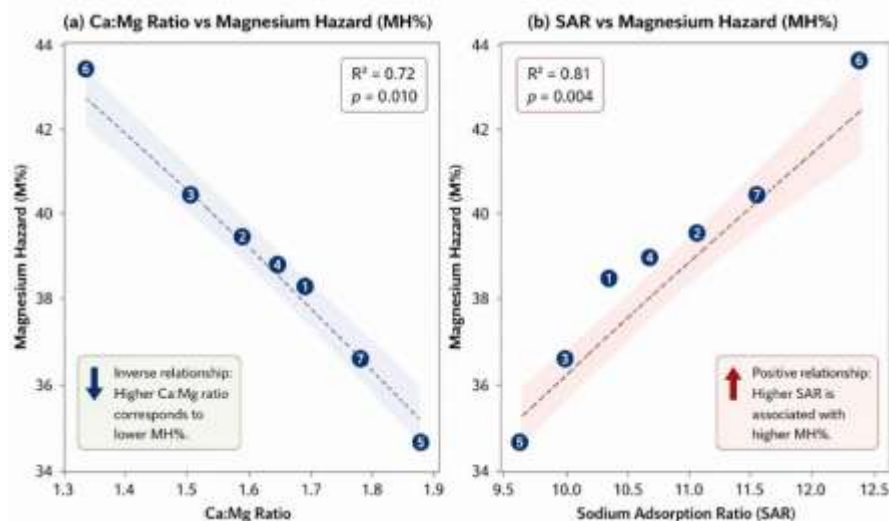


Figure 5

Relationship between Ca: Mg ratio, sodium adsorption ratio (SAR), and magnesium hazard (MH %). (A) Negative relationship between Ca: Mg ratio and magnesium hazard (MH %), indicating that higher Ca: Mg ratios are associated with lower magnesium hazard levels.

(B) Positive relationship between SAR and MH%, showing that increasing sodium adsorption ratio corresponds to higher magnesium hazard. Regression lines are shown with confidence intervals, and statistical significance is indicated by the coefficient of determination (R^2) and p-values.

The biplot of PCA showed distinct groupings of the study areas based on their chemical properties, confirming the contrasting effects of salinity and nutrition in the study sites (Figure 6).

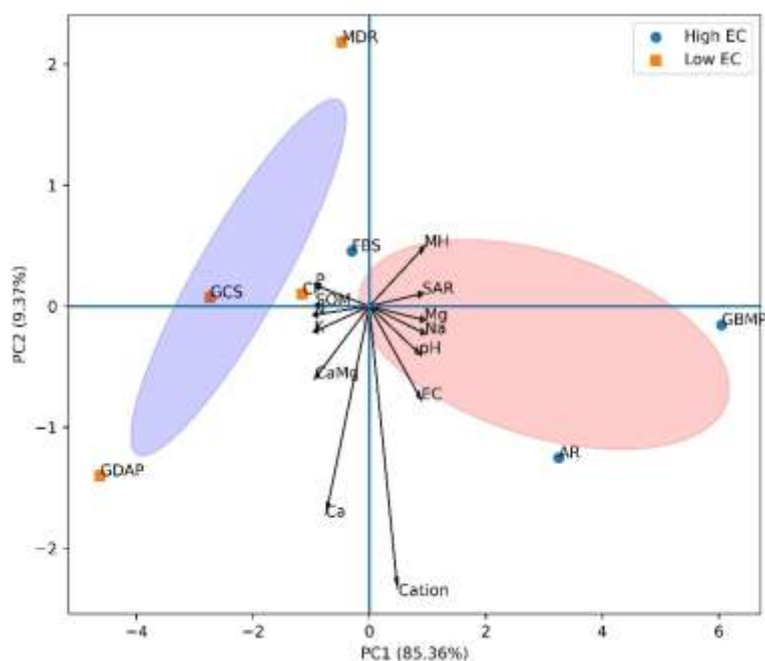


Figure 6 Principal component analysis (PCA) biplot showing the distribution of sampling sites and the relationships among soil physicochemical properties. The first two principal components (PC1: 85.36%, PC2: 9.37%) explain the majority of the total variance. Arrows represent the contribution and direction of variables, including pH, EC, SAR, Ca, Mg, Na, Ca: Mg ratio, magnesium hazard (MH), and total cations. Sampling sites are grouped into high EC and low EC clusters, with ellipses indicating group dispersion. The spatial separation of sites reflects differences in salinity, sodicity, and nutrient dynamics.

Discussion

The decrease in BOD, COD and TSS confirms the satisfactory performance of the treatment system in eliminating organic and particulate pollutants, as reported in recent studies on the effectiveness of grey-water treatment systems in enhancing effluent quality [30, 31]. But, the constant and even increasing values of TDS suggest that soluble salts are not efficiently removed and could present risks for soil salinization under long-term irrigation [4, 10, and 32]. Soil physicochemical data

show moderately alkaline conditions and growing salinity, characteristic of greywater irrigation. EC measurements indicate low salinity, especially in the continuously irrigated areas. This is consistent with findings in arid areas, where wastewater irrigation leads to increasing soil salinity [33].

Soil texture is a regulating factor in the study region is predominately covered with loam to sandy clay loam textures, providing good support for plant growth due to a good balance between water retention and pore space. The more sand, the better water drains and the more salt can potentially be leached; the more clay, the more water and ions are retained and the greater salinity and/or sodicity become. This is evident in the spatial distribution of salinity indicators in study areas. Similar research found clay-textured soils are more susceptible to salinity and soil structure and health degradation when irrigated with water containing excess sodium [14, 31].

The relationships between nutrients and exchangeable cations also highlight the adverse and favorable effects of greywater irrigation. The increases in SOM with increasing nutrients (N, P, K) may reflect increased soil fertility with the addition of organic matter. Similar findings have been reported where wastewater irrigation enhances soil fertility while simultaneously increasing salinity risks [9, 10]. Consistent with previous studies showing organic matter increases nutrient retention and soil structure [10, 15]. However, the increasing Na and SAR and MH, indicate that there is a risk that the soil may be becoming sodic, affecting soil structure and water infiltration. These changes are known to disrupt soil aggregation and hydraulic conductivity under prolonged exposure [14].

Correlation analysis and PCA support these findings by showing salinity and sodicity as the main factors affecting soils. Multivariate approaches have been widely applied to distinguish salinity and fertility drivers in irrigated soils [29]. Positive correlations between EC, Na, SAR, and MH confirm that salt build-up is largely due to greywater. In contrast, the inverse relationship between salinity indicators and fertility highlights a negative balance between soil quality and salinity. A negative association between the Ca:Mg ratio and sodicity indices highlights the role of calcium in preserving soil structure. These multivariate relationships have been recently noted, where salinity indicators and nutrient concentrations interactively affect soil quality under grey and black water irrigation [21, 32, and 33]. Although trace metal concentrations remained within safe limits and pose minimal environmental risk, the accumulation of salts and sodium presents a more critical challenge for sustainable reuse [34, 35]. Overall, the results demonstrate that greywater treatment systems are efficient in reducing organic pollution but less effective in controlling dissolved salts, which subsequently drive soil salinity and sodicity dynamics. This highlights the need for integrated management strategies that not only optimize treatment performance but also mitigate downstream soil impacts, particularly through controlling SAR, maintaining cation balance, and managing long-term salt accumulation.

In summary, the results show that although grey-water applications improve nutrient levels, they also pose salinity and sodicity hazards. The interactive effects of soil texture and fertility highlight the importance of multifaceted approaches such as controlled irrigation, leaching and calcium amendments to maintain soil health and productivity.

Conclusion

The research indicates that grey water treatment is effective in removing organic and particulate pollutants as indicated by the reduction in BOD, COD and TSS, thereby enhancing the quality of the effluent. The study also shows that the treatment was insufficient in removing dissolved solids, which poses a significant limitation; residual amounts of salt remain and accumulate in the soil subjects to irrigation. Soils at the study sites were moderately alkaline and had increasing electrical conductivity, suggesting that salinity is emerging and is at levels tolerated for agricultural use.

Importantly, grey water irrigation increased soil fertility indices through increase in soil organic carbon (SOC) and major nutrients (N, P, K) content suggesting enhanced nutrient recycling and retention. This is however, offset by the increase in the sodium (Na⁺) ion, the increasing value of the sodium adsorption ratio (SAR) and magnesium hazard (MH) which all point to the risks of sodicity. The inverse relation between the soil Ca:Mg ratio and sodium indices shows that Ca plays an important role in eliminating negative impacts of sodicity.

Texture was also found to be a significant control factor with loam to sandy clay loam textures being suitable for plant growth and salt transport and storage. Coarse textured soils facilitated drainage, and potential leaching of salt, while fine textured soils aided ion retention, aggravating salinity problems. Multivariate (principal components analysis or "PCA") and correlation analyses showed that salinity indices were major components of variability of the soil profile and clearly filtered the changes resulted from a fertility-improving treatment, thus revealing the negative-positive trade-offs of the treatment.

To conclude, the results highlight that irrigation with grey-water has a beneficial impact on soil fertility, but a detrimental impact on salinity and sodicity. Thus, identifying an overall approach, including irrigation amount management, leaching and calcium treatments, is essential for safe reuse. The results will aid in safe grey-water reuse in arid regions, as well as development of scientifically based techniques that could be used for irrigation in urban environments.

Author Contribution: Mir Sheyhak conducted the field experiment, laboratory analyses, and data collection. Shahmir Ali Kalhoro conceived and supervised the study, interpreted the results, and prepared the original manuscript. Abdul Rahim, Muneer Ahmed, Kashif Ali Kubar, Mehar-un-Nisa Narejo, Muhammad Abuzar Jaffar, Saima Kalsoom Babar, Saima Raza, and Rabia Raza contributed to data interpretation and critically reviewed the manuscript. Iftakhar Ahmed performed the statistical analyses and assisted with data interpretation. All authors read, revised, and approved the final version of the manuscript.

Data and material availability: This article contains all the soil and plant analysis data generated during the course of this research study. The analysis and the resulting data presented herein may be obtained at the reasonable request of the corresponding author.

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