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COMPARATIVE ASSESSMENT OF SOIL PHYSICOCHEMICAL PROPERTIES, NUTRIENT AVAILABILITY, AND SALINITY-ALKALINITY CONSTRAINTS IN AGRICULTURAL SOILS OF MASTUNG AND MUSAKHEL DISTRICTS, BALOCHISTAN

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Abstract

Assessment of soil physicochemical properties is fundamental for evaluating soil fertility and developing sustainable nutrient management strategies in arid and semi-arid agroecosystems. This study investigated the physicochemical characteristics of agricultural soils from the Mastung and Musakhel districts of Balochistan, Pakistan, to evaluate soil fertility status and identify major constraints limiting crop production. Soil samples were collected from three depths 0–10, 10–20, and 20–30 cm and analyzed for soil texture, pH, electrical conductivity, soil organic matter, soluble calcium and magnesium, carbonate, chloride, sodium, available potassium, and phosphorus.

The results revealed significant differences ($P < 0.05$) in soil physicochemical properties between the two districts and across soil depths. Mastung soils ranged from silt loam to sandy loam and exhibited significantly higher EC (2.13–2.36 dS m $^{-1}$) and alkaline pH (8.60–9.35), indicating greater salinity and alkalinity than Musakhel soils. Soil organic matter declined significantly with depth (0.55–0.42%), accompanied by decreases in available K (86.99–59.42 mg kg $^{-1}$), P (4.36–2.28 mg kg $^{-1}$), and Na (63.21–42.03 mg kg $^{-1}$), whereas CO_3^{2-} and Cl^- increased in the subsoil. In contrast, Musakhel soils were predominantly sandy loam with comparatively lower EC (0.74–1.27 dS m $^{-1}$) and pH (7.58–8.13), reflecting more favorable conditions for crop production. Potassium concentrations remained considerably higher (131.35–151.64 mg kg $^{-1}$), while phosphorus was consistently low (1.80–4.45 mg kg $^{-1}$), indicating phosphorus deficiency in both districts despite marked differences in salinity status.

Overall, Mastung soils are primarily constrained by alkalinity, moderate salinity, low organic matter, and nutrient depletion, whereas Musakhel soils exhibit

comparatively better physicochemical quality and greater potassium availability. These findings provide baseline information for site-specific soil fertility management and sustainable agricultural planning aimed at improving crop productivity in the arid and semi-arid regions of Balochistan.

INTRODUCTION

Soil is a fundamental natural resource that sustains agricultural productivity, food security, and ecosystem stability. Its physical and chemical properties govern water availability, nutrient cycling, root development, and microbial activity, thereby directly influencing crop growth and yield. Soil texture, pH, electrical conductivity (EC), organic matter (OM), and the availability of essential nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) are widely recognized as key indicators of soil fertility and land quality (Brady & Weil, 2017; Hazelton & Murphy, 2016). In arid and semi-arid environments, these properties are particularly important because limited rainfall, high evaporation rates, and poor organic matter accumulation often accelerate soil degradation, nutrient depletion, salinity development, and declines in agricultural productivity. Soil organic matter plays a central role in maintaining soil structure, water-holding capacity, cation exchange capacity, and biological activity, thereby enhancing nutrient availability and improving the resilience of agricultural systems under climatic stress (Lal, 2020; Lehmann & Kleber, 2015). Consequently, understanding the spatial variability of soil physicochemical properties is essential for designing sustainable soil management strategies and optimizing crop production in water-limited environments.

Soil quality is declining in most parts of the world, due to rising land degradation, climate variability and unsustainable agricultural practices, especially in dryland areas. It is estimated that about one third of soils in the world are moderately to highly degraded, mainly from processes of soil erosion, salinization, nutrient depletion and loss of organic matter, and that these processes threaten food security and environmental sustainability (FAO & ITPS, 2021). Soil physicochemical conditions are very important in arid and semi-arid areas since they are very vulnerable to salinity, alkalinity, moisture stress and less nutrient cycling. Soil property assessment is essential to identify fertility constraints, to support precision nutrient management, and to provide information for sustainable land-use planning and climate-resilient agriculture (Bünemann et al., 2018; Lal, 2020; Minasny et al., 2017; Hill, 2004; Hinsinger, 2001). Hence, there is an increasing need of soil systematic evaluation of physicochemical properties worldwide which serves as an essential part of sustainable agricultural development and natural resource management.

Balochistan is the biggest of all the provinces of Pakistan with land area of around 347,190 km2 or 44% of the total land area of the country. The land resources are huge, but only a small percentage is cultivated due to the severity of climatic conditions, inadequate water availability, salinity, and soil infertility (Government of Pakistan, 2024; Pakistan Bureau of Statistics, 2023; Mengal et al., 2024). Sustainable soil management is crucial for increasing food production and improving rural livelihood in the province as agriculture still plays an important role in the livelihood of people.

In the present study, the two districts – Mastung and Musakhel – are selected with extreme difference in climate, topography and soil properties. Mastung District is located in the middle part of Balochistan, with an area of 5896 km² at an altitude of 1700–1800 m asl. The district has an arid climate with minimal (150-250 mm) annual rainfall and high evapotranspiration which often leads to soil salinity, sodicity and nutrient deficiency (Government of Balochistan, 2023; Rasheed et al., 2025). The Musakhel District, in the northeast of the province, on the other hand, has a relatively high annual rainfall of 250 to 400 mm and a comparatively good crop production environment as it covers an area of about 5728 km². (Pakistan Meteorological Department [PMD] 2023).

Maintaining balanced physicochemical properties of agricultural soils is a major determinant of their

productivity in these districts. Salinity and alkalinity of the soils may affect the uptake of water, nutrient availability and crop growth, whereas the low level of soil organic matter may affect soil structure, microbial activity and nutrient retention (Rengasamy, 2010; Brady & Weil, 2017; Sparks, 2003; USDA-NRCS, 2014). Likewise, the availability of phosphorus changes depending on the soil pH and availability of the soil may differ due to soil mineralogy and management in Pakistan (Havlin et al., 2017). Furthermore, the interactions between soil pH, soluble salts and availability of nutrients is important in determining nutrient-use efficiency and fertilizer response, which is why soil assessment is an essential practice for sustainable crop production systems in arid agroecosystems (Six et al., 2002; Munns & Tester, 2008; Fageria, Baligar, & Jones, 2011; Singh et al., 2025).

Soil physicochemical properties should be assessed regularly to generate information that will help detect fertility constraints, develop site-specific nutrient management strategies and encourage sustainable farming practices. Some studies have been conducted on soils of various parts of Pakistan but complete information about agricultural soils of Mastung/Musakhel is still scanty. For this reason, this study was carried out to determine some selected physicochemical properties of the soils in the agriculture of these two districts such as soil texture, pH, EC, OM, soluble ions, and plant essential nutrients. The results will help in better management of soil fertility, help to have baseline data for the sustainable agricultural planning in Balochistan, and help in evidence based decision making for the enhancement of agricultural productivity in arid and semi-arid conditions.

2. Materials and Methods

2.1 Description of Study Area

The study was carried out in agricultural soil samples of Mastung and Musakhel districts of Balochistan Pakistan during internship study. These districts are extremes of two opposing agro-climatic environments having different climatic and edaphic conditions. Mastung is situated in a central part of Balochistan and has an arid climate with low annual rainfall, high estimate of evapotranspiration and salinity as well as alkalinity issues (Rasheed et al., 2025). Musakhel is in the north-eastern region of the province where the climatic conditions are comparatively moderate and the soils are more productive. The sites selected for sampling were the cultivated agricultural lands which are more frequently used for cereal and vegetable production.

2.2 Soil Sampling

Representative surface soil samples (0-10, 10-20 and 20-30 cm depth) were taken in selected agriculture fields in both districts according to soil sampling procedures. Random subsampling using a stainless-steel auger was used at each location to obtain several subsamples and thoroughly mixing them to get a single composite sample. The samples were inserted into clean polyethylene bags, labeled properly, carried to Soil Science Laboratory and air dried at room temperature. Plant residues, stones and other debris were first removed and the samples were gently crushed and passed through a 2 mm sieve prior to laboratory analysis.

2.3 Sample Processing and Analysis

Each soil sample was dried in the air, lightly crushed and sifted through a 2 mm sieve for analysis in the laboratory. Soil texture was determined by Bouyoucos (1962) method, and the soil was classified on USDA textural classification system. The pH and electrical conductivity (EC) of the soils were determined in soil: water suspension of 1:2.5 by using soil pH and EC meters following the method described by Richards (1954). Soil Organic Matter (OM) was calculated according to Walkley and Black wet oxidation procedure (Walkley and Black, 1934). The soluble calcium plus magnesium (Ca^{2+} + Mg^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^{-}), chloride (Cl^{-}) and sodium (Na^{+}) were measured from the saturated soil paste extract according to the standard method described by Richards (1954). Sodium bicarbonate extraction method, as suggested by Olsen et al. (1954) was used for available phosphorus (P), and neutral ammonium acetate extraction and subsequent use of a flame

photometer for available potassium (K). The standard analytical procedures were followed for all soils to assess their physicochemical characteristics and fertility in the two study districts.

3. Results

3.1 Soil physicochemical characteristics

Physicochemical properties of agriculture soils showed diverse results in terms of soil types between Mastung and Musakhail district and within different soil depths (Table 1). Soil texture varied from silt loam to sandy loam; while Mastung soil was mostly silt loam to sandy loam in the whole soil profile, Musakhail soil was sandy loam in entire profile. In both districts soil pH was alkaline, with differing trends of depth. Electrical conductivity (EC) also showed significant differences with depth in Mastung, increasing from 0.74 dS m^{-1} to 1.27 dS m^{-1}, which reveals a progressive increase in soluble salts with depth in soil.

Table 1: physicochemical characteristics of agricultural soils in the Mastung and Musakhel districts

Soil Depth	Soil textural Class	Soil EC (dS/m)	Soil pH
Districts Mastung			
0-10 cm	Sandy Loam	0.74+0.02c	7.58+0.14b
10-20 cm	Sandy Loam	0.91+0.01b	7.67+0.12b
20-30 cm	Sandy Loam	1.27+0.09a	8.13+0.02a
Districts Musakhail			
0-10 cm	Silt loam	2.2+0.06a	8.6+0.06b
10-20 cm	Sandy loam	2.13+0.12a	9.35+0.13a
20-30 cm	Sandy loam	2.36+0.15a	8.72+0.52b

Note: Data are expressed as mean ± SE (n = 3). Means followed by different lowercase letters within each district differ significantly among soil depths according to Tukey's HSD test ($P < 0.05$). Soil texture was classified according to the USDA textural classification system. EC = electrical conductivity (dS m^{-1}).

The pH and EC values were higher in case of Musakhail soils as compared to Mastung soils. The soil pH was 8.60 to 9.35 and the EC was 2.13 to 2.36 dS m^{-1}, which showed higher levels of alkalinity or salinity all the way up the soil profile. The pH was not significantly different between depths, while maximum at 10-20 cm.

3.2 Distribution of soil organic matter and plant nutrients

The amount of soil organic matter (SOM), potassium (K) and available phosphorus (P) also dropped significantly as depth increased in both districts. In Mastung, SOM declined from 0.55% at 0–10 cm to 0.42% at 20–30 cm (Figure 1). Likewise, potassium decreased from 86.98 mg kg^{-1} to 59.42 mg kg^{-1}, while available phosphorus declined from 4.35 mg kg^{-1} to 2.28 mg kg^{-1}.

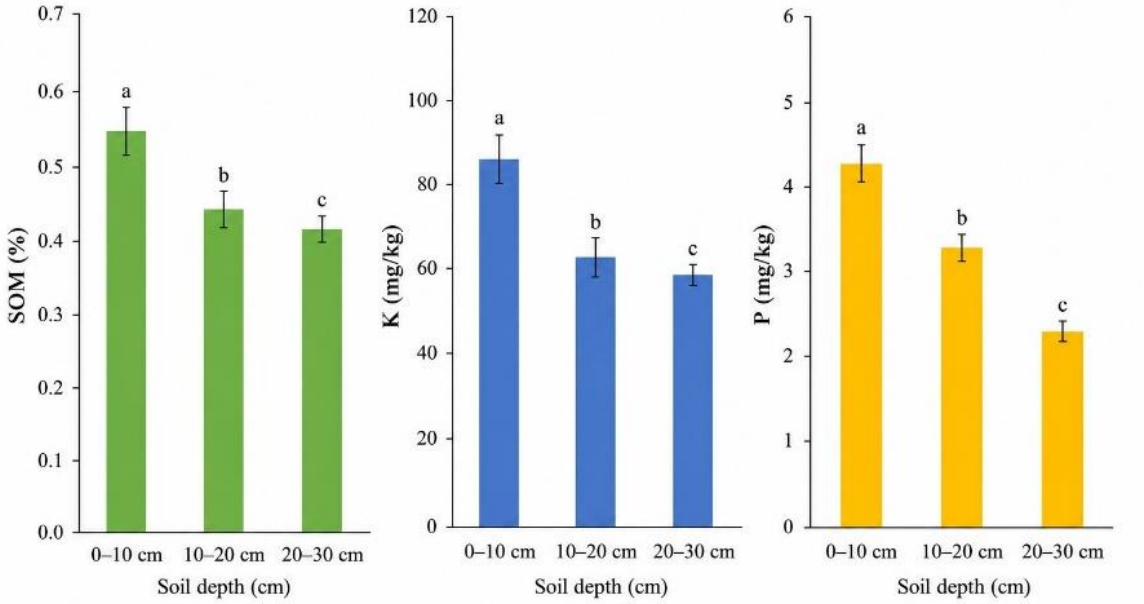

Figure 1: Variation in soil organic matter (SOM), available potassium (K), and available phosphorus (P) at different soil depths (0–10, 10–20, and 20–30 cm) in the agricultural soils of Mastung district. Bars represent the mean ± standard error (n = 3). Different lowercase letters above the bars indicate significant differences among soil depths according to Tukey's HSD test at $P < 0.05$.

The patterns of changes were also found to be similar in Musakhail with the SOM being generally higher than in Mastung, especially in the uppermost soil layer (Figure 2). The concentrations of potassium in Musakhail were significantly higher than that of Mastung, while concentrations of phosphate also decreased with depth in the soil.

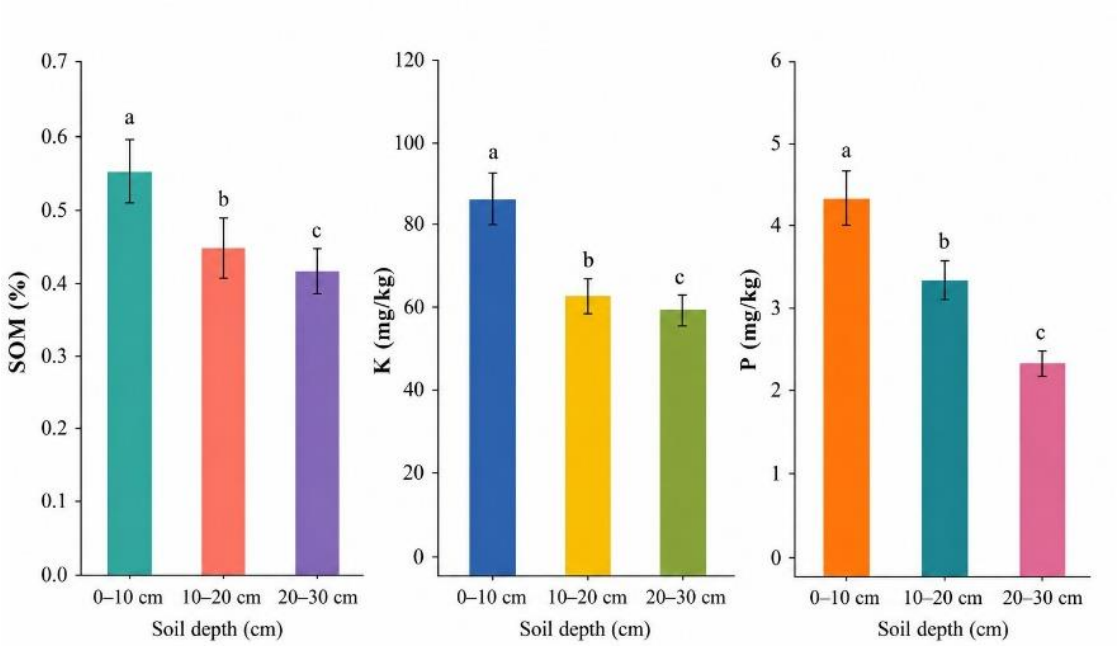

Figure 2: Variation in soil organic matter (SOM), available potassium (K), and available phosphorus (P) at different soil depths (0–10, 10–20, and 20–30 cm) in the agricultural soils of Musakhail district. Bars represent the mean ± standard error (n = 3). Different lowercase letters above the bars indicate significant differences among soil depths according to Tukey's HSD test at $P < 0.05$.

3.3 Distribution of soluble cations and anions

There was a significant difference in soluble ion concentrations between the soil depths. In Mastung, exchangeable sodium (Na) declined markedly from 63.21 mg kg^{-1} at 0–10 cm to 42.03 mg kg^{-1} at 20–30 cm. Carbonate (CO_3^{2-}) and chloride (Cl^-) concentrations tended to increase with depth while calcium plus magnesium (Ca+Mg) peaked at the middle layer (10–20 cm) Figure 3.

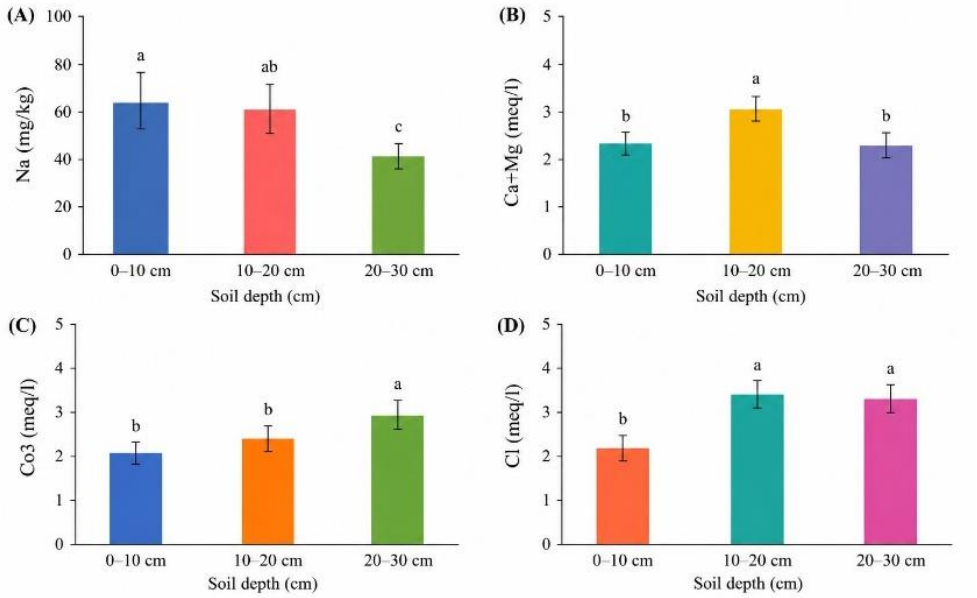

Figure 3: Variation in (A) exchangeable sodium (Na), (B) calcium plus magnesium (Ca + Mg), (C) carbonate (CO_3^{2-}), and (D) chloride (Cl^-) concentrations at different soil depths (0–10, 10–20, and 20–30 cm) in the agricultural soils of Mastung District. Bars represent the mean ± standard error (SE; n = 3). Different lowercase letters above the bars indicate statistically significant differences among soil depths according to Tukey's honestly significant difference (HSD) test at $P < 0.05$.

The same trend was noted on Musakhail while the concentration of Ca+Mg, CO_3^{2-} and Cl^- was higher than in Mastung. On the other hand, the concentrations of sodium were relatively lower across the soil profile of the Musakhail soil (Figure 4).

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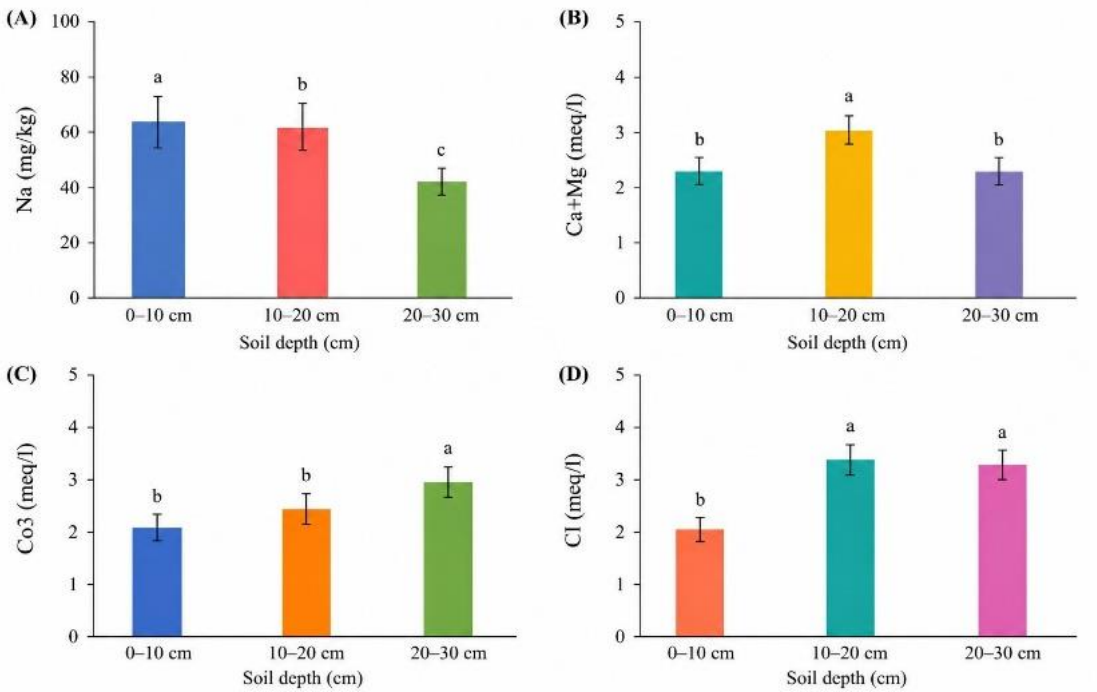

Figure 4: Variation in (A) exchangeable sodium (Na), (B) calcium plus magnesium (Ca + Mg), (C) carbonate (CO_3^{2-}), and (D) chloride (Cl^-) concentrations at different soil depths (0–10, 10–20, and 20–30 cm) in the agricultural soils of Musakhail District. Bars represent the mean ± standard error (SE; n = 3). Different lowercase letters above the bars indicate statistically significant differences among soil depths according to Tukey's honestly significant difference (HSD) test at $P < 0.05$.

3.4 Multivariate analysis of soil properties

The results of the PCA showed that the soil physicochemical properties were well summarized by the district and soil depth (Figure 5). The first two principal components accounted for 88.3% of the total variation, 54.9% by PC1 and 33.4% by PC2. Confirmed by the PCA biplot, the soil sample from Mastung differed from that of Musakhail and the differences were marked in terms of physicochemical properties between the two districts. Electrical conductivity, pH and sodium were found to be positive and related to one side of PC1 while soil organic matter, potassium, phosphorous, calcium plus magnesium, carbonate and chloride were negative and related to the other side of PC1, showing the contrasting gradients of nutrient and salinity levels between sampling locations.

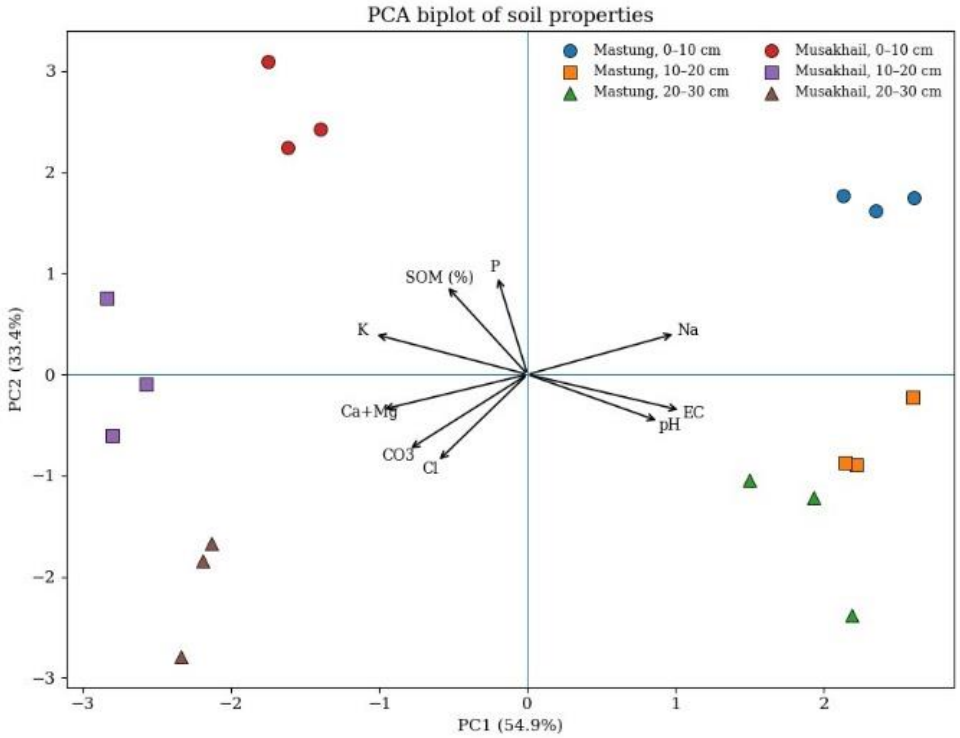

Figure 5. Principal component analysis biplot showing the distribution of soil samples from Mastung and Musakhail districts at three soil depths and the contributions of soil physicochemical properties. Different symbols represent soil depths, while colors distinguish the two districts.

3.5 Correlation among soil properties

The Pearson correlation analysis showed that there were high correlations between soil physicochemical properties (Figure 6). Correlation of electrical conductivity with other soil constituents were strong positive with pH (r = 0.82) and sodium (r = 0.69) and strong negative with potassium (r = −0.96) and calcium plus magnesium (r = −0.72). Positive relationships (r = 0.71, 0.69) were obtained between Soil Organic Matter and Potassium and Phosphorus respectively, indicating close relationship between Organic Matter accumulation and nutrient availability. Carbonate had strong positive correlations with chloride (r = 0.87) and calcium plus magnesium (r = 0.81) and a significant negative correlation with sodium (r = −0.88). Overall, the correlation heat map showed clearly that there were interactions between salinity indicators, nutrients and soil fertility parameters.

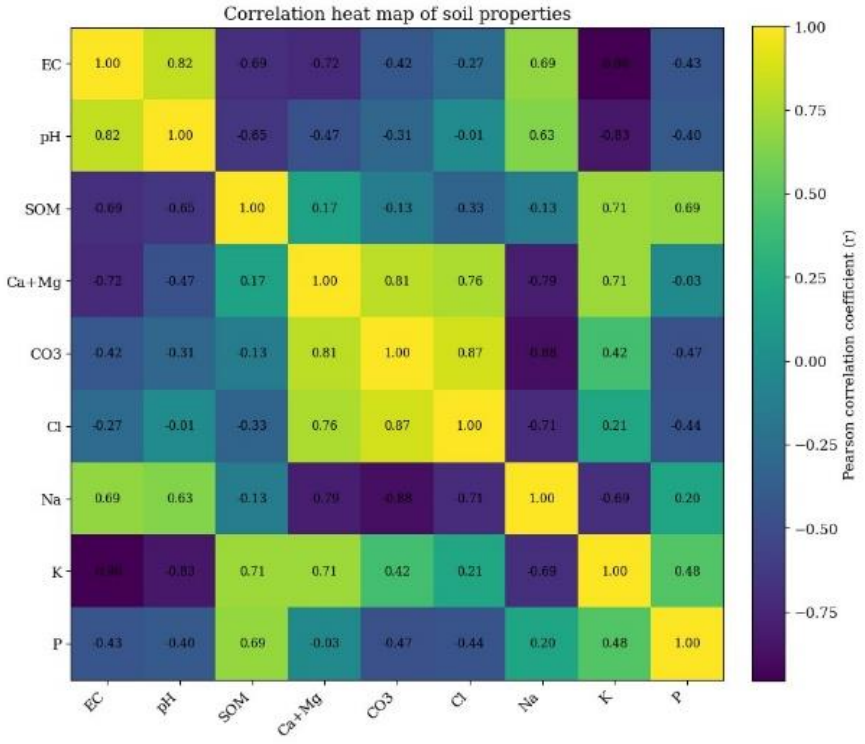

Figure 6. Pearson correlation heat map showing relationships among soil electrical conductivity, pH, soil organic matter, Ca+Mg, CO_3, Cl, Na, K, and P across the two districts and three soil depths. Values within cells represent Pearson correlation coefficients.

4. Discussion

Results of the present study showed that the soil physicochemical properties differed significantly between agricultural soils of Mastung and Musakhail, which indicated that different depth, texture and environmental conditions of the soils affected soil quality. The soils of both districts were coarse textured ranging from sandy loam to silt loam but the electrical conductivity (EC) and pH of Musakhail were consistently higher than that of Mastung, showing higher degree of soil salinity and alkalinity. The differences may be related to climatic conditions, lack of rainfall in arid and semi-arid areas, high evapotranspiration, and upward movement of soluble salts, which is common in arid and semi-arid climates (Qadir et al., 2014; Rengasamy, 2010; Daba, 2025). Recent reviews also point to the fact that poor drainage and the constant evaporation cause salts to build up in the soil of agriculture and lead to chemical degradation and loss of productivity.

The depth of soil showed an increase in electrical conductivity in Mastung, while in Musakhail the EC values remained relatively high in the soil profile indicating variations in the salt redistribution and leaching process. The alkaline pH for both districts is due to the buildup of carbonate rich salts and exchangeable bases in calcareous soils that are formed under water limited environments. There are numerous reports which describe the increasing salinity and alkalinity of the soil with depth in semi-arid agriculture, where the lack of leaching leads to the accumulation of soluble salts in the subsoil horizons (Rengasamy, 2010; Daba, 2025; Sathish & Patel, 2024; Qadir et al., 2007).

There was a significant decrease in soil organic matter (SOM), available phosphorus and exchangeable potassium with soil depth and the districts. This is the result of increased concentration of crop residues, root biomass, microbial activity and organic carbon in the top soil layer relative to lower soil horizons. Organic

matter is the main source of plant nutrients because it increases the cation exchange capacity, facilitates nutrient mineralization and improves nutrient retention. Therefore, the available phosphorus and potassium also declined with depth, in parallel with the decline in SOM. The vertical distribution of nutrients has been found to be similar in dryland agricultural ecosystems and in conservation agriculture trials, where nutrients have been found to be more concentrated in the upper soil layers due to biological activity and decomposition of residues (Lal, 2020; Six et al., 2004; Fageria & Baligar, 2008; Laghari et al., 2025). The work of Laghari et al. (2025) also showed that an increase in OM by incorporation of straw significantly enhanced aggregate stability, nutrient availability and biological activity in saline-sodic soils.

Contrasting soil chemical environments in the two districts were also further demonstrated by the distribution of the soluble cations and anions. The concentrations of sodium decreased with depth of soil while the concentration of carbonate increased in the deeper layers and that of chloride generally increased with depth of soil. Such patterns are evidence of increasingly re-distributed soluble salts in the soils and reflect continued salinity development. The carbonate mineral content is relatively higher in Musakhail as shown by the relatively high concentrations of Ca+Mg, thus helping to maintain alkaline soil condition. These ionic interactions have significant effects on the availability of nutrients, aggregate stability, hydraulic conductivity and root development. Meta-analysis studies have recently demonstrated that organic amendments and gypsum among other integrated soil amendments are effective in lowering the exchangeable sodium content and increasing calcium availability, aggregate stability and crop productivity of salt-affected soils.

Principal component analysis (PCA) was able to extract the multivariate variability of soil properties and the first two principal components accounted for 88.3% of the total variance. Clearly Mastung and Musakhail samples are separated each other, suggesting that salinity related variables (EC, pH and Na) and fertility related variables (SOM, P and K) are major factors affecting soil variability. Past use of PCA has shown its usefulness to select important soil quality parameters and to differentiate soils grown under different environmental and management conditions (Andrews et al., 2002; Lal, 2020). The high loading of EC and sodium on one side of the PCA axis, and SOM and nutrients on the other side of the axis highlights the opposing effect of salinity and soil fertility on overall soil quality.

The Pearson correlation analysis confirmed the PCA findings and showed high interactions between soil physicochemical properties. The positive correlation between EC and pH suggests that higher salinity is accompanied by higher alkalinity and strong negative correlation between EC and potassium indicates that excessive salt buildup results in lower nutrient availability due to ionic competition and lower nutrient uptake. However, the positive relationships between SOM, phosphorus and potassium highlight the importance of organic matter in soil nutrient cycling and fertility. Similar effects have been observed in saline and semi-arid soils where organic matter increased microbial activity, nutrient retention, aggregate formation and reduced the salinity effects (Bronick & Lal, 2005; Lal, 2020; Badrari et al., 2024; Laghari et al., 2025).

Overall, the combination of traditional soil statistical analysis with PCA and Pearson correlation gave a complete evaluation of the soil quality in the two districts. The findings show that soil salinity and alkalinity are the major factors that reduce soil fertility, while soil organic matter is the key factor to ensure soil nutrient availability and soil productivity. Hence, sustainable practices like residue retention, integrated nutrient management, use of organic amendments, when suitable, use of gypsum, and conservation tillage should be encouraged to promote sustainable soil management in semi-arid areas of Balochistan, which will improve soil structure and nutrient cycling, alleviate salinity stress and enhance the long-term agricultural soil resilience. These integrated strategies to restore salt-affected soils and enhance agricultural sustainability are supported by recent global evidence.

5. Conclusion

The present study provides a comparative assessment of the physicochemical properties of agricultural soils from Mastung and Musakhel districts of Balochistan and highlights marked differences in their soil quality and fertility status. The soils in Mastung were characterized by high electrical conductivity, strongly alkaline pH, higher concentrations of soluble salts and higher sodium accumulation, which suggested high salinity and sodicity problems that can negatively impact nutrient availability, soil structure and crop productivity. Musakhel soils, in contrast, had low salinity, near neutral to slightly alkaline pH, low sodium concentrations, and relatively high potassium concentrations, which are more favorable for sustainable agriculture production. Although there were differences between the two districts, both had low levels of organic matter and available phosphorus, indicating a high prevalence of nutrient deficiencies that need to be addressed. The results highlight the importance of site-specific strategies for soil management to improve soil fertility and sustainability for agriculture. Adequate irrigation management, proper use of gypsum (if feasible), proper drainage, and the use of organic amendments should be promoted for salinity and sodicity reclamation in Mastung. Applying farmyard manure, compost, crop residue and green manure, and applying a balanced phosphorus fertilizer will be crucial to enhancing the soil health and productivity for both districts. This study presents useful baseline data for farmers, extension and policy makers, to make informed decisions of soil management and sustainable agricultural production in arid and semi-arid regions of Balochistan.

Author Contributions: Ejaz Ahmed designed the study, performed field experiment, laboratory analyses, data collection, and wrote the initial draft of the manuscript. Shahmir Ali Kalhoro designed and monitored the research, interpreted the results, critically revised the manuscript and finalized the manuscript for publication. Khalid Hussain Talpur did statistical analyses and helped in the interpretation of the data. Mehar-un-Nisa Narejo and Saima Raza helped conduct laboratory analyses, data validation, and manuscript revision. Rabia Raza and Abdul Hafeez Mastoi were involved in collecting data, literature review and editing the manuscript. Fateh Muhammad and Asad Hafeez Aliani contributed to the experimental implementation, data interpretation and critical review of the manuscript. All authors read and approved the final manuscript and will take responsibility for all aspects of the work.

Availability of the data and materials: The data available at the reasonable request of the corresponding author.

Conflict of interest: The authors declare that they have no potential conflict of interest to disclose.

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