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Soil Spatial Variability Mapping of District Shaheed Benazirabad for Climate Resilient Sustainable Agriculture

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Abstract

Soil spatial variability mapping is essential for location-specific, economically optimized fertilizer management, and climate-resilient environment-friendly sustainable agriculture. We developed soil spatial variability maps of district Shaheed Benazirabad, Sindh, Pakistan using advanced geospatial interpolation techniques. Soil samples were collected from 115 locations across the study region, involving all the agriculturally important union councils of four talukas, viz. Daur, Kazi Ahmed, Nawabshah and Sakrand. Moreover, we involved all the important major crops grown in the district by giving due weight during the selection of various farms and their representative composite soil sampling. Our findings revealed that the district Shaheed Benazirabad is characterized by the contrasting presence of different types of soils textures ranging from heavy to light and the dominance of slightly to highly saline soils, with the presence of very high to extremely high saline pockets in taluka Kazi Ahmed and Daur. Moreover, slightly to medium alkaline soils dominated the whole district, with the exception of some strongly alkaline patches. Organic matter was deficient in taluka Sakrand and Daur, however, it was comparatively better in Kazi Ahmed and Nawabshah. Soil P was deficient in the whole district, except for a few areas of Taluka Kazi Ahmed and Daur, while soil K was found deficient to medium in many areas, despite it being adequate in most areas of the district. We recommend the use of these spatial variability maps for site- and/or zone-specific climate resilient practices for better environments and sustainable agriculture.

Keywords: GIS; Soil variability mapping; Shaheed Benazirabad District; Inverse distance weighted

Introduction

Soil fertility is a crucial natural resource that directly influences agricultural productivity and economic prosperity. Variability in soil properties significantly affects crop growth, nutrient uptake, and overall farm productivity. Understanding this variability at a spatial level is essential for the development of site-specific soil management practices, which can optimize fertilizer use, improve crop yields, and enhance sustainability. The integration of geospatial technologies, such as Geographic Information Systems (GIS), has revolutionized soil mapping, enabling the precise identification of areas with specific soil properties, facilitating targeted interventions (Acosta *et al.* 2018; Sharma *et al.* 2022). GIS maps are essential for site-specific variable rate fertilizer application and to examine toxicity or deficiency of specific plant nutrients in soil (Hussain *et al.* 2019; Khouni *et al.* 2021; Saraz *et al.* 2023). Kumar *et al.* (2024) developed soil spatial variability maps to delineate management zones for Suketi basin, Himachal Himalaya, India. Their findings also endorsed that such information helps generate baseline data for site-specific fertilizer management. Hence, it has been strongly advised to regularly evaluate soil physicochemical properties and fertility status to keep them productive and manage them wisely (Hou 2023).

Globally, geoscientists use geographic information systems (GIS) and advanced statistical analysis methods to identify factors influencing soil fertility that aim to develop strategies to improve the sustainability of agriculture practices (Megahed 2020; Sharma *et al.* 2021; Sharma *et al.* 2022). Sustainable management of agricultural resources is adopted through the mapping of physicochemical properties of soil, which account for instant and long-term effects on the environment, soil fertility, and crop productivity (Mujiyo *et*

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al. 2022). However, GIS are relatively new tools for managing environmental research. It can control challenging assets like soil fertility and improve awareness, real-life, and model-building skills (Feudis *et al*. 2021; Sharma *et al*. 2021). Recently, Gorasiya *et al.* (2024) developed thematic maps to depict spatial distribution of soil boron by employing GIS models. Soil fertility mapping investigates the soil fertility factors, nutrient-deficient zones, and management strategies (Priori *et al*. 2020). The researchers utilized various methods to predict soil physiochemical properties through spatial variability, such as Ordinary kriging (OK), inverse distance weighted (IDW), etc. (Shit *et al*. 2016; Tang *et al*. 2017). The kriging method was also used to evaluate soil fertility through unsampled areas from data of known sample locations and generate prediction maps (Rajesh *et al*. 2023).

According to Waqar *et al*. (2017), Shaheed Benazirabad district is considered one of the important agricultural districts of Sindh, which is situated on the left bank of the Indus River, with overall a hot climate, dry summer, and mild winter. It plays a crucial role in shaping both the provincial and national economic landscape due to its variety of crops for the climates of variable extremes, such as cotton, wheat, sugarcane, banana, vegetables, and orchards, etc. The soil parent material of district Shaheed Benazirabad is composed of mixed calcareous alluvial deposits and exhibits diverse and varied properties, with dominant soil series including Jarwar, Miani, Nabipur, Pacca, and Shahdara which generally exhibit variations in their properties. The district is spread over 380,293 hectares with almost (43%) cultivated area. However, the net sown cultivated area is about 176,718 hectares, while the leftover (212,575 hectares) area includes fallow lands (GoP 2022). Despite it being the agricultural point of view most important district of Sindh, the farmers of Shaheed Benazirabad district unexpectedly have little awareness of getting the soils of their farms analyzed and it has been reported that only 19% of the farmers take advantage of soil testing services. Thereby for extremely worrying as a result of the instant decline in soil condition of Pakistan soils are deficient in nitrogen, phosphorus, potassium, zinc, and boron up to varying levels (35 ~100%) (Memon 1996; Zia-ul-hassan *et al*. 2008, Jamali *et al*. 2023). Recently it has been reported that district Tando Allahyar soils more than half (55%) low in P and adequate K (Jamali *et al*. 2023). However, Saraz *et al*. (2023) found that most of the soils of district Mirpurkhas were categorized as low in available P.

In addition, a recent study conducted by Sabir (2017) and Sudheer (2018), who mapped and analyzed soils of the rice growing areas of taluka Dokri, and guava orchards of Larkana district and they found soil ABDTPA-P was low and soil ABDTPA-K were adequate. In a while, another study by Talpur (2016) reported that the soils of taluka Khairpur and Kotdiji orchards of date palm were deficient in P content and adequate in K. Such variability highlights the importance of regular soil assessments to ensure appropriate fertilizer recommendations and sustainable farming practices.

Therefore, the present study aimed to address the gap in evaluating the spatial variability of soil physicochemical properties in Shaheed Benazirabad district for optimizing climate-smart plant nutrition management in regard to soil quality. The specific objective of this study was to assess and quantify the spatial variability of key soil properties, including texture, salinity, pH, organic matter, phosphorus, and potassium, in Shaheed Benazirabad District, Sindh, and to develop GIS-based spatial variability maps to guide effective and site-specific soil management and nutrient optimization.

Materials and Methods

Study area

The research study was conducted in Shaheed Benazirabad District, Sindh, Pakistan (Fig. 1), situated at 26.2483°N latitude and 68.3925°E longitude, with an elevation of 15 meters above sea level, cover approximately 380,293 hectares. The district comprises the four administrative talukas: Daur, Nawab Shah, Sakrand and Kazi Ahmed. The areas cover diverse agricultural lands under a semi-arid climate with maximum temperatures reaching up to 50°C, and average annual rainfall of 150 mm. This area is dominated by alluvial soils, which support a variety of crops, including wheat, cotton, sugarcane, mustard, rice, and other significant local crops.

Selection of farms based on crop diversity

The percentage distribution of farms selected for this study, with major crops grown, in district Shaheed Benazirabad is presented in Fig. 2. As reported by Waqar *et al*. (2017), through the survey during this study, it was found that in district Shaheed Benazirabad banana and wheat were the dominant major crops, followed by cotton and wheat. Accordingly, 43% farms with banana as a major crop, 29% farms with wheat as major crop, followed by 17, 7 and 2.6% farms with sugarcane, cotton and mustard crops were selected for this study.

The Taluka-wise percentage distribution of farms involved in this study, with major crops grown, in Shaheed Benazirabad is given in Table 1. It is evident that most farms of Taluka Sakrand and Nawabshah selected for this study had banana as a major crop, while majority of farms of Taluka Daur and Kazi Ahmed had wheat and sugarcane as major crops. At the time of soil sampling, wheat and mustard crops were both already harvested, while sugarcane was 4 to 5 months old. Moreover, the cotton crop was two months old and banana crop was 12 to 24 months old (Table 1).

Soil sampling philosophy

Soil samples were collected across the different agricultural land types and crop species of all Talukas of district Shaheed Benazirabad, involving all agriculturally important union councils, except the desert area of Taluka Daur, as depicted in Fig. 1. The number of samples obtained from various farms

Table 1: Taluka wise percent distribution of farms involved in this study, with major crops grown, in district Shaheed Benazirabad

Taluka	Wheat	Sugar cane	Banana	Cotton	Mustard
Daur	44	17	14	19	6
Nawabshah	30	10	60	0	0
Sakrand	17	2	79	0	2
Kazi Ahmed	26	44	26	4	0

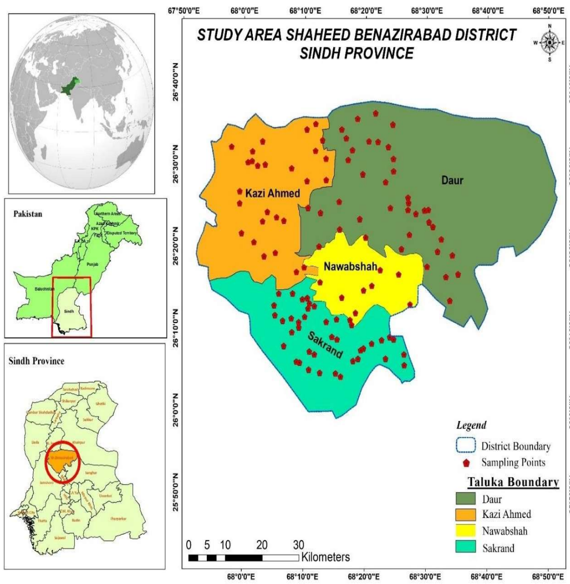

Fig. 1: Location map of district Shaheed Benazirabad, Sindh

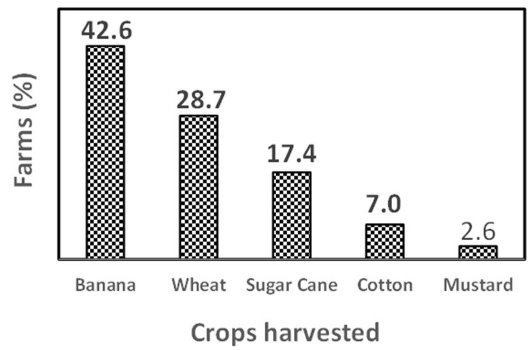

Fig. 2: Percent distribution of farms involved in this study, with major crops grown, in district Shaheed Benazirabad

representing various major crops were in line with the percentage of area covered by these crops in a Taluka, as suggested earlier (Saraz *et al.* 2023).

Soil sampling technique

Survey of agricultural farms and their soil sampling was done from April 13 to May 25, 2023. Surface soil samples (0–20 cm depth) were obtained from selected 115 farms of various union councils of four Talukas of Shaheed Benazirabad district, involving different major crops/cropping systems. At each farm, eight core samples were collected from five evenly distributed, homogeneous sections within one-acre plots, following the composite sampling method outlined by Ryan *et al.* (2001). These cores were combined to create a representative composite soil sample for each site, aiming to accurately analyze soil variability (Saraz *et al.* 2023). Each sampling point was georeferenced using Magellan® Triton™ 200 GPS device, recording latitude, longitude, and elevation.

Analysis of soil samples

In the present study, the collected soil samples were processed for detailed laboratory analyses to assess physicochemical properties at the Plant Nutrition Laboratory; Department of Soil Science, Sindh Agriculture University, Tandojam. Soil texture was determined using the Bouyoucos hydrometer method (Bouyoucos, 1936), which classifies particles into sand, silt, and clay fractions, providing an essential foundation for understanding soil composition. Electrical conductivity (EC) and pH were measured in a 1:2 soil-to-water suspension using an EC meter and pH meter, respectively, to evaluate the soil's salinity and alkalinity levels. However, soil organic matter (SOM) content, an indicator of soil fertility, was analyzed using the Walkley-Black method, which quantifies organic carbon as a percentage. Nutrient analysis focused on phosphorus and potassium, critical for plant growth, utilizing the Ammonium Bicarbonate-Diethylene Triamine Penta Acetic Acid (AB-DTPA) extraction method, a standard approach for alkaline soils (Ryan *et al.* 2001). Each soil property was subsequently categorized following classification guidelines provided by Ryan *et al.* (2001) and Zia-ul-hassan *et al.* (2008), ensuring consistency in data interpretation across soil samples. This comprehensive analysis provided insights into the spatial distribution of essential soil nutrients and properties, enabling targeted soil management practices in the study region.

Soil spatial variability mapping and interpolation method

The spatial variability of soil physicochemical properties was analyzed using advanced geostatistical methods integrated within the Inverse Distance Weighted (IDW) method, by using ArcGIS® ver. 10.6. (Environmental Systems Research Institute (ESRI), 380 New York Street, Redlands, CA, USA). The Inverse Distance Weighting (IDW) is a relatively quick, simple, flexible, exact and convex interpolation model. It utilizes the values of certain traits acquired from the known spots to predict the values of some other spots of interest, by assuming that the neighboring values are more alike one another. Hence, IDW efficiently creates continuous surfaces from discrete spatial data (Khouni *et al.* 2021; Saraz *et al.* 2023). Spatial prediction maps were generated using this interpolation model for key soil parameters, including texture, EC, pH, SOM, ABDTPA-P and ABDTPA-K, and these maps serve as critical tools for visualizing the heterogeneity of soil properties and guiding region-specific soil fertility management practices.

Descriptive statistics

Descriptive statistics for each soil property was performed to highlight details of soil variability across the study area and aided in understanding the distribution and extent of nutrient deficiencies or toxicities across different agricultural regions, aiming to enhance region-specific soil fertility management and support sustainable agricultural practices.

Results

Soil type and texture

The distribution of soil texture among different soil types in the district of Shaheed Benazirabad, Sindh is illustrated in Table 2 and Fig. 3. Predominantly, most of the soils were loamy slightly medium-textured types (76.4%) including (28.6%) loam, (4.3%) silt, and (43.5%) silt loam, while the sandy, coarse-textured light types were (20%), including sandy loam (19.1%) and sand (0.9%). Soils with loamy moderately medium-textured (2.6%) including sandy clay loam (1.7%) and silty clay loam (0.9%). However, Spatial variability maps were developed using IDW interpolation techniques demonstrated eight soil textures distributed across the study area, with dominated by sandy loam (coarse texture) and silt loam (slightly medium texture), while negligible coverage of moderately medium textures. This spatial mapping highlights the heterogeneity and dominance of specific soil textures within the district, with implications for agricultural practices and land management strategies.

Soil EC

Soil electrical conductivity (EC_e) ranged from 0.15 to 6.54 dS m^{-1}, with an average value of 1.45dS m^{-1}, and a mode vale of EC of 0.87 dS m^{-1} (Table 3), which reflected significant spatial variability as evidenced by a high coefficient of variability (78%). The EC of sampling points were utilized classification criteria by Sonon *et al*. (2015) and categorized that the majority (57%) of soils having low (17%) to medium (39%) salinity levels, while the remaining 43% were classified as very low (0.9%), high (12%), very high (12%) and excessively high (19%) salinity status (Fig. 4). However, the spatial interpolation map of EC demonstrated the heterogeneity in salinity levels, with higher salinity observed in specific areas, such as Kazi Ahmed and Sakrand, which may pose challenges for agricultural productivity (Fig. 5).

Soil pH

Soil pH ranged from 7.25 to 8.47, with an average of 7.76 and a mode of 7.82, and minimal spatial variability as indicated by a low coefficient of variability (2.67%), as presented in Table 3. Based on the categorization limits proposed by Ankarman and Richard (1989), the majority of soils (75%) were medium alkaline, followed by 16% classified as slightly alkaline, and 9% as strongly alkaline. Although, Ankerman and Richard (1989) classification highlighted that the majority of soils (75%) were medium alkaline, 16% were slightly alkaline, and 9% were strongly alkaline across the study area (Fig. 6). The spatial distribution map of soil pH is

Table 2: Soil types and textures of district Shaheed Benazirabad, Sindh

Soil types and soil texture	Soil samples (%)
Loamy slightly medium-textured soil	76.40
Loam	28.60
Silt loam	43.50
Silt	4.30
Loamy moderately medium-textured soil	06.00
Silty Clay Loam	0.90
Sandy Clay Loam	1.70
Sandy or coarse-textured soil	19.9
Sand	0.90
Sandy Loam	19.00

Table 3: Descriptive statistics of different soil physico-chemical properties of district Shaheed Benazirabad, Sindh

Statistical measures	EC (dSm^{-1})	pH	Organic matter (%)	ABDTPA-P (mg kg^{-1})	ABDTPA-K (mg kg^{-1})
Minimum	0.02	7.25	0.08	0.28	32.0
Maximum	0.54	8.47	1.91	7.74	395.0
Mean	1.46	7.76	0.83	2.26	128.5
Mode	0.87	7.87	0.89	2.98	119.00
Standard Deviation	1.13	0.2	0.46	1.56	75.8
Standard Error	0.10	0.01	55.70	68.87	59.0
CV %	77.39	2.5	0.08	0.28	32.0

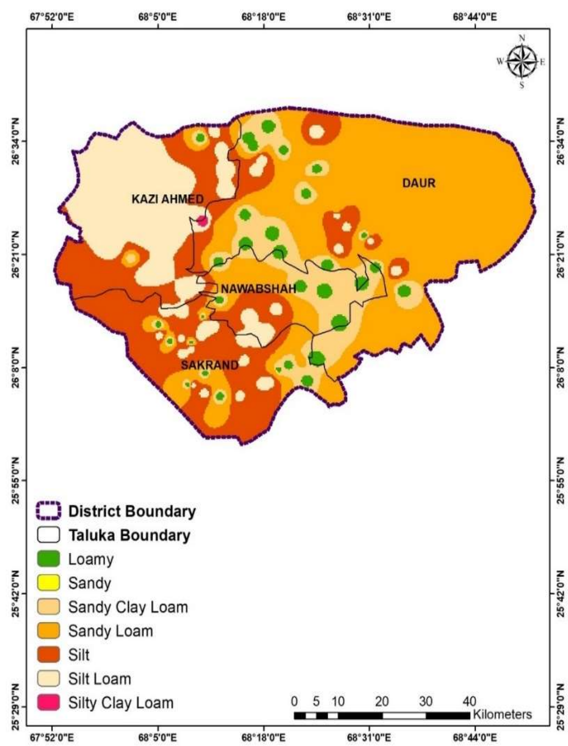

Fig. 3: Spatial distribution of soil texture in district Shaheed Benazirabad, Sindh

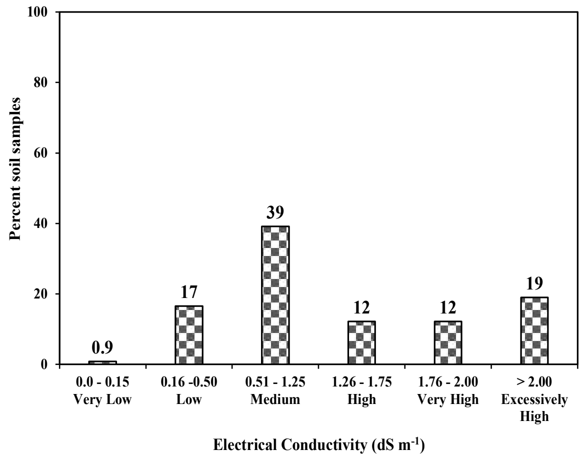

Fig. 4: Categorization of soil salinity in district Shaheed Benazirabad (following Sonon *et al*. 2015)

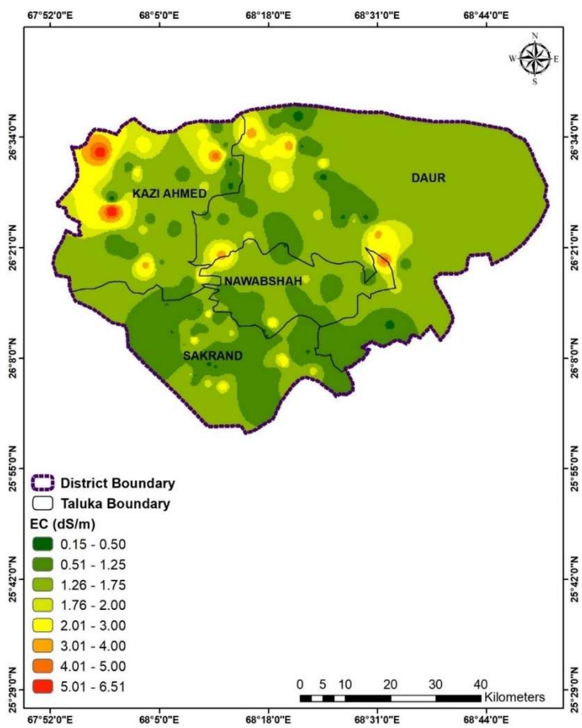

Fig. 5: Spatial distribution of soil salinity (based on EC) in district Shaheed Benazirabad, Sindh

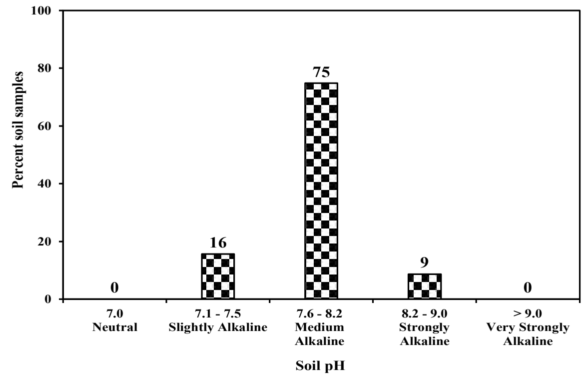

Fig. 6: Categorization of soil pH in district Shaheed Benazirabad, Sindh (after Ankerman and Richard 1989)

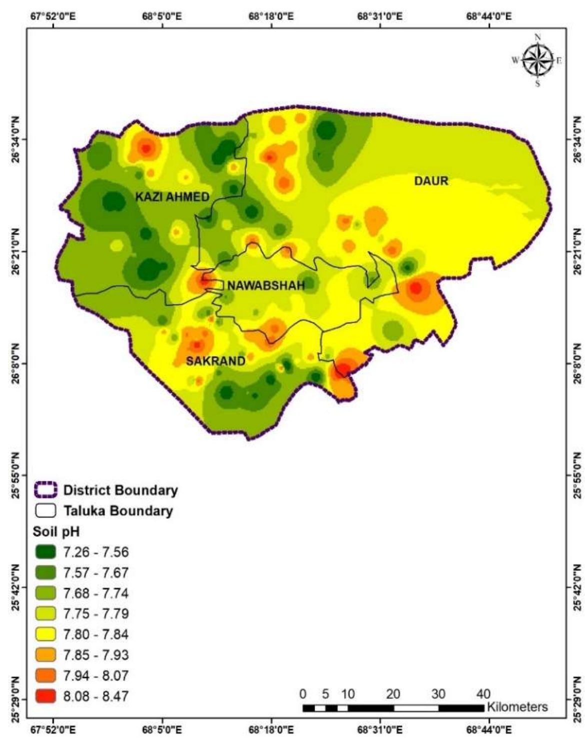

Fig. 7: Spatial distribution of soil pH in district Shaheed Benazirabad, Sindh

presented in Fig. 7, which confirms the dominance of medium alkaline soils, with slightly alkaline areas primarily concentrated near Nawabshah Taluka and negligible areas of strongly alkaline soils.

Soil organic matter

Soil organic matter ranged from 0.08 to 1.91%, with a mean value of 0.83% and a mode of 0.89% over the study area (Table 3). Based on the classification proposed by Rashid (1996), almost half of the soils (48%) were found to be deficient in their organic matter content, while the remaining 53% had either medium (36%) or high (17%) organic matter content (Fig. 8). Furthermore, the spatial distribution exhibited that organic matter content across the study area was falling in low organic matter zones particularly in regions near Nawabshah and Sakrand, while areas with medium or high organic matter content are sparse and limited to specific pockets near Kazi Ahmed and Daur Talukas (Fig. 9).

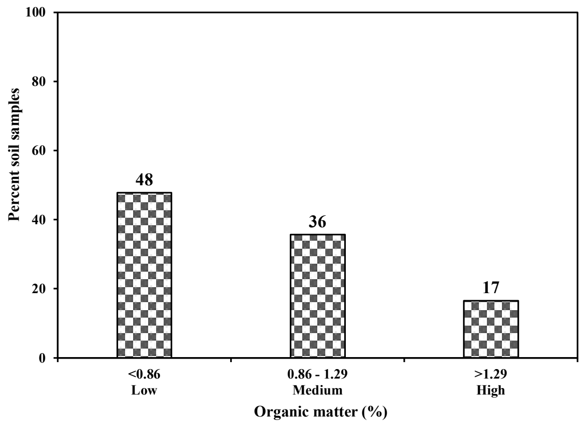

Fig. 8: Categorization of soil organic matter in district Shaheed Benazirabad (following Rashid 1996)

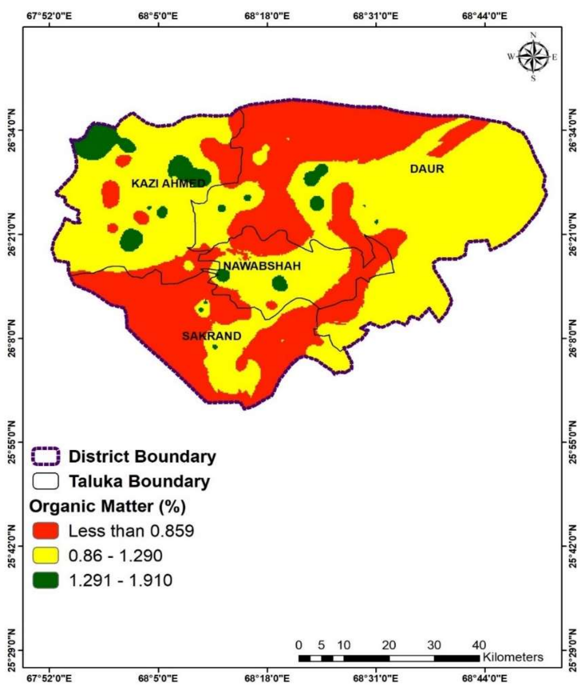

Fig. 9: Spatial distribution of soil organic matter in district Shaheed Benazirabad, Sindh

Soil phosphorus

Soil ABDTPA-extractable phosphorus content ranged from 0.28 to 7.7 mg kg^{-1}, with the average values of 2.26 mg kg^{-1} and a mode of 2.98 mg kg^{-1}, reflecting negligible spatial variability over the study area (Table 3). Based on the classification given by Soltanpour and Schwab (1977), the majority of soils samples (89%) were low in phosphorus, 10% had marginal phosphorus, and only 2% were adequate level of phosphorus (Fig. 10). The spatial interpolation map revealed that most areas, including Nawabshah, Sakrand, and parts of Daur, recorded low phosphorus levels, while regions near Kazi Ahmed measured marginal P. Notably,

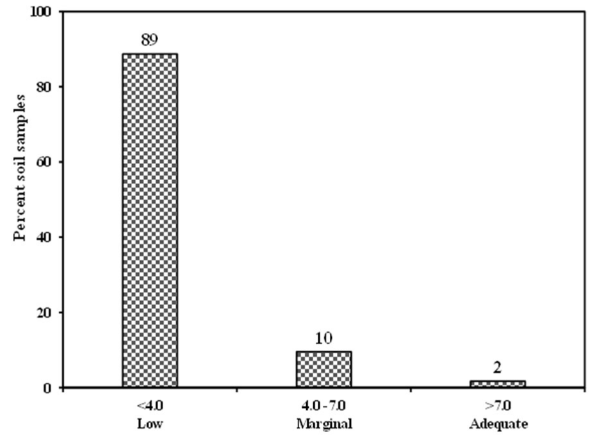

Fig. 10: Categorization of soil ABDTPA-P content in district Shaheed Benazirabad, Sindh (following Soltanpour and Schwab 1977)

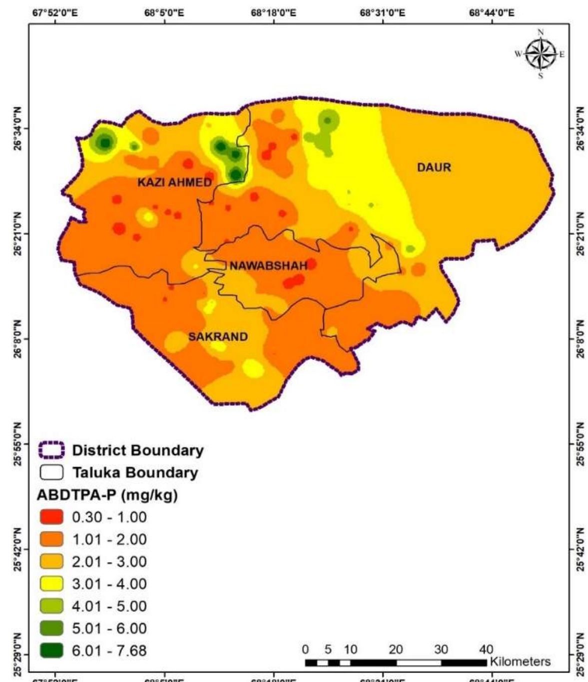

Fig. 11: Spatial distribution of soil phosphorus in district Shaheed Benazirabad, Sindh

Majority of soils of district Shaheed Benazirabad were predicted to have low ABDTPA-P (Fig. 11).

Soil potassium

Soil ABDTPA-extractable K content was measured to range from 32 to 395 mg kg^{-1}, with an average value of 128.5 mg kg^{-1} and a mode of 119 mg kg^{-1} (Table 3). The categorization of soil K according to Soltanpour and Schwab, (1977) criteria, suggested that (44%) of the soils determined to have adequate K, 41% were marginal, and 15% were low in potassium content (Fig. 12). The spatial variability mapping demonstrated that areas near Kazi Ahmed and Nawabshah

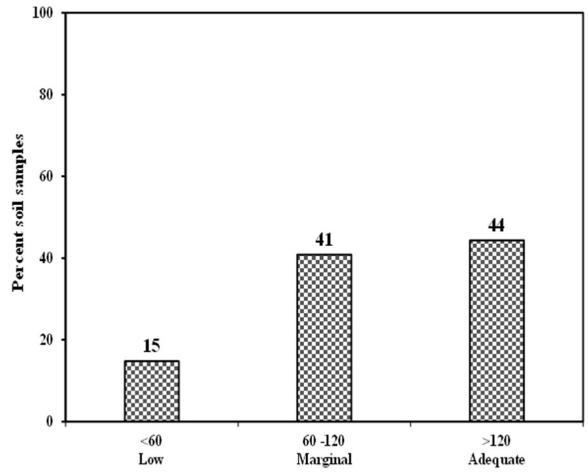

Fig. 12: Categorization of soil ABDTPA-K content in district Shaheed Benazirabad, Sindh (following Soltanpour and Schwab 1977)

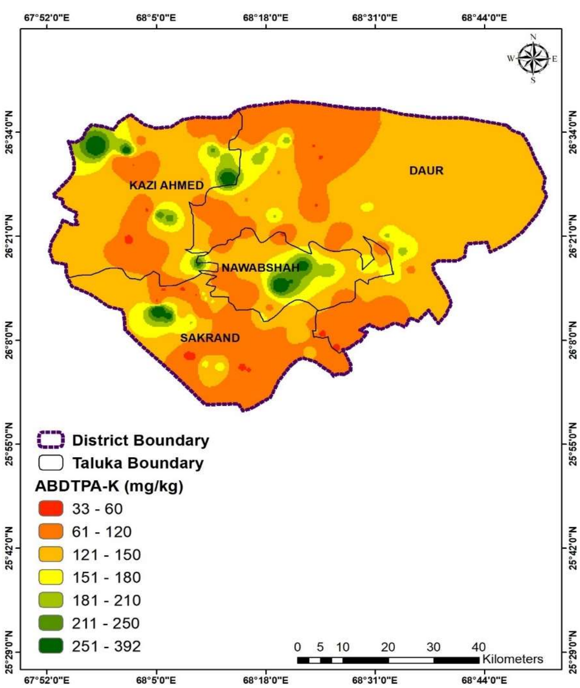

Fig. 13: Spatial distribution of soil potassium in district Shaheed Benazirabad

Talukas showing higher potassium levels, while Sakrand and Daur Talukas measured low to marginal potassium levels (Fig. 13).

Crop sustainability potential

Even though these soils had different characteristics, different crops were grown for different durations. Among the crops sustaining in these areas included wheat, sugarcane, banana, cotton, mustard (Table 1). The sustainability of the long and short duration crops in Shaheed Benazirabad district indicated farming potential of these soils, despite differences in their textural and physico-chemical properties (Table 2).

Discussion

The present study was conducted to evaluate the soil physicochemical properties of district Shaheed Benazirabad, Sindh, Pakistan, and to develop GIS-based maps for effective soil management, fertilizer recommendations, and future agricultural planning. The results revealed that most of the soils had sandy or coarse-texture soils (sandy loam) followed by loamy slightly medium-texture soils (silt loam), and loamy moderately medium-textured soil types were (3%), medium to excessively saline, medium alkaline pH, almost half of the soils had low organic matter, low to medium in P and adequate to marginal in K (Table 2; Fig. 4, 6, 8, 10, 12). Our finding are in accordance with a recent study, Maurya *et al.* (2024) who analyzed 40 randomly samples of soil and reported that most of the soils were slightly to medium alkaline, non-saline, almost low in N and medium in P, and K. Jamali *et al.* (2023) highlighted that district Tando Allahyar soils were mostly loamy medium-textured, low to medium in saline, and strong to medium alkaline in reaction, with low organic matter content, medium to adequate P content and adequate K content. Similarly, Saraz *et al.* (2023) highlighted that soils of Mirpurkhas district were clayey, medium to high in salinity, slightly to moderately alkaline, and low in P with adequate K. In the neighboring regions, Abdullah *et al.* (2022) analyzed 1654 soil samples of ten union councils of Tehsil Athara-Hazari's district Jhang, Punjab, Pakistan, and reported that most soils were found to be inadequate in available P and extractable K was found medium to adequate. Rehman *et al.* (2021) analyzed 3002 soil samples from farmer's fields in the Gujar Khan Area of Rawalpindi district of Punjab Province, Pakistan. The majority of soils were found low in organic matter and available P, while adequate in available K. Also, another study by Jamil *et al.* (2021) in Sahiwal district, where most of the soils were low available P, but adequate in K with non-saline conditions. Studies from other regions, such as Sharma *et al.* (2022) in Nagpur, India, and Kumar (2023) in Bihar, India, also revealed soils that were predominantly alkaline, low in organic carbon, and deficient in P but adequate in K.

Globally, Long *et al.* (2022) found that the soils of Western China were slightly acidic to slightly alkaline with very low in organic matter, low in available nitrogen (N) and phosphorous. Likewise, Gao *et al.* (2019) analyzed 555 soil samples collected from Renshou content, Sichuan Basin, China, and reported that soils ranged from 0.34 to 2.57 mg kg^{-1} in total nitrogen, 0.10 to 1.72 mg kg^{-1} in total P, and the total K content ranged from 2.51 to 16.58 mg kg^{-1}. Waqar *et al.* (2017) reported that the soil pH of the study area ranged from 7.2 to 10.2, with organic matter averaging 0.83% and extractable K ranging from 30 to 400 mg kg^{-1}, which aligns with the findings of this study. Hussain *et al.* (2019) highlighted the selected soil properties of a potato-growing area in a mountainous region of Gilgit-Balochistan. Soils were loam to silty loam in texture, medium to strongly alkaline in reaction, low to medium in salinity, medium in organic matter, adequate in N and adequate in K. They further reported that soils of three union councils of district Sakardu, Gilgit-Balochistan were slightly acidic to slightly alkaline in reaction, non-saline, organic matter were adequate. Moreover, Rawal *et al.* (2018) mapped and analyzed 131 soil samples collected from the Sunsari district of Nepal and found that soils had silty clay loam, silty loam, and clay loam texture, the majority of soils were acidic while some soils had their pH levels categorized as slightly alkaline. These comparisons suggest that the study area's soils share common characteristics with soils in similar agro-ecological zones, including deficiencies in organic matter and phosphorus and variability in salinity and potassium availability. This highlights the need for region-specific soil fertility management strategies, focusing on improving organic matter content and phosphorus availability, while optimizing potassium use for sustainable agricultural productivity.

A thorough analysis of these findings for the best use of these soil resources for climate smart agriculture revealed that district Shaheed Benazirabad is characterized by the contrasting presence of different types of soils from heavy to light texture. Taluka Nawabshah and Sakrand are dominated by highly fertile fine-textured loamy soils that generally retain more moisture, and coarse-textured sandy loamy soils which hold low moisture. Moreover, Taluka Kazi Ahmed and Daur are dominated by coarse-textured sandy and medium-textured silty clay loam soils, suggesting great spatial variability (Fig. 3). The coarse-textured sandy soils of the district may require immediate attention owing to their low moisture and nutrient retention capacities rendering them unsuitable for the cultivation of water-intensive crops unless sufficient irrigation is available. Efficient irrigation practices, viz. drip irrigation and split application of chemical fertilizers is recommended for such soils for sustainable agriculture (Brady and Weil 2017). Furthermore, heavy-textured soils can be managed through integrated plant nutrition strategies to enhance the health of soils and make them more resilient to climate changes. Hence, zone-specific resource management strategies can make the region more adaptable to water scarcity and climate stress. Growing crops that thrive on low moisture content, viz. sorghum, millets, and legumes in zones where coarse-textures soils are dominated, following efficient nutrient management strategies promote healthy environments and ensures food security (Lal 2016).

Very low to highly saline soils dominated the whole district, in addition to very high to extremely high saline pockets present in Taluka Kazi Ahmed and Daur (Fig. 5). These soils require the application of fertilizers that contribute less to salinity, viz. urea, ammonium sulphate, diammonium phosphate and potassium sulphate, in addition to integration plant nutrition management strategies involving the available organic amendments (Brady and Weil 2017). Moreover, in very low to medium salinity areas crops like wheat, maize, rice, chickpeas, lentils, and carrots can be grown, while in areas with high to very high salinity barley, sorghum, pearl millet, sugarbeet, quinoa and salicornia can be grown (Ghafoor *et al.* 2004; Qadir and Schubert 2024). Slightly to medium alkaline soils dominated the whole district, with an exception of some strongly alkaline patches (Fig. 7) suggesting the use of acidic nature nitrogenous fertilizers, e.g. ammonium sulphate and urea which lower soil pH after nitrification (Tisdale *et al.* 2003), phosphatic fertilizers with higher solubility, viz. DAP and SSP (Brady and Weil 2017), potassium sulphate to avoid salt buildup (Mengel and Kirkby 2001), and Zn-EDTA and Fe-EDDHA to address Zn and Fe deficiencies (Imas 2000). Wheat, barley, cotton and chickpea can efficiently utilize applied nutrients and are recommended for slightly to medium alkaline zones while rice or sorghum crops are suggested for strongly alkaline patches (Rengel 2011).

Organic matter was deficient in Taluka Sakrand and Daur, however, it was comparatively better in Kazi Ahmed and Nawabshah (Fig. 9). Hence, the farmers should adopt integrated plant nutrition management strategies to enhance the soil physical conditions in these areas as suggested by other workers (Brady and Weil 2017; Jamali *et al.* 2023; Saraz *et al.* 2023). Soil P was deficient in the whole district, except few areas of Taluka Kazi Ahmed and Daur (Fig. 11) confirming earlier reports about its deficiency in Pakistani soils (Memon 1996). Soil K was found to be deficient to medium in many areas of district, despite it being adequate in most areas (Fig. 13). Earlier, Zia-ul-hassan *et al.* (2008) also highlighted K mining from the soils of Sindh. Hence, keeping these spatial variations in mind, balance P and K nutrition following 4R nutrient stewardship and selecting correct type of fertilizer products, as mentioned above, is advisable for these soils to harvest their full potential (Tisdale *et al.* 2003; Brady and Weil 2017; Imas 2000; Mengel and Kirkby 2001). Long and short duration crops growing in these soils (Table 1) are a testament of their potential to be utilized in agricultural farming systems.

Conclusion

Shaheed Benazirabad district is characterized by contrasting presence of different types of soils textures ranging from heavy to light and the dominance of slightly to highly saline soils, with the presence of very high to extremely high saline pockets in Taluka Kazi Ahmed and Daur. Moreover, slightly to medium alkaline soils dominated the whole district, with the exception of some strongly alkaline patches. Organic matter was deficient in Taluka Sakrand and Daur, however, it was comparatively better in Kazi Ahmed and Nawabshah. Soil P was deficient in the whole district, except for the few areas of Taluka Kazi Ahmed and Daur, while soil K was found deficient to medium in many areas, despite it being adequate in most areas of the district. We recommend the use of these spatial variability maps for site- and/or zone-specific climate resilient practices for better environments and sustainable agriculture.

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Author Contributions

OAM collected, processed and analyzed soil samples, reviewed literature, NAT supervised laboratory work and wrote first draft of the paper, ZHS conceived the idea, supervised whole study performed statistical analysis, reviewed and edited all drafts of manuscript and submitted the paper as corresponding author, MSM developed soil spatial variability maps, IAJ assisted in data processing and formatted final draft of the manuscript, JAA and ND verified soil analyses data, developed charts, and provide useful comments on the first draft of the manuscript.

Conflict of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author

Ethics Approval

Not applicable to this paper.

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