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Soil Spatial Variability Mapping of District Badin, Sindh

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ABSTRACT

Site-specific nutrient management is essential for intensive farming due to widespread nutrient deficiency related issues. Therefore, this study was aimed at determining soil spatial variability and mapping of district Badin. A total of 133 composite soil samples with the depth of 0-20 cm were collected from five talukas of district Badin including Tando Bago, Shaheed Fazul Rahu, Talhar, Badin and Matli. All major cropping areas were also involved in sampling. The soil analyses were performed for texture, electrical conductivity (EC 1:2), pH (1:2), organic matter (OM) and AB-DTPA-extractable P and K. The soils of district Badin were dominantly loamy moderately to coarse texture including sandy loam (82%). The EC varied from 0.4 to 10.72 dSm⁻¹ (Mean: 3.59 dS m⁻¹, Median: 2.90 dS m⁻¹, Mode: 1.59 dS m⁻¹). Majority of the soils had excessively high (69.2%) to medium salinity (15%). The soil pH ranged from 6.79 to 8.5 (Mean: 7.93 Median: 7.98, Mode: 7.99). Majority of soils were medium alkaline (84%). Furthermore, OM ranged from 0.09 to 1.8% (Mean: 0.77%, Median: 0.78%, Mode: 0.31%). Majority of soils had low (71.4%) to medium (24.1%) OM content. The ABDTPA-P ranged from 1.0 to 12.0 mg kg⁻¹ (Mean: 3.9 mg kg⁻¹, Median: 3.7 mg kg⁻¹, Mode: 3.3 mg kg⁻¹). Majority of soil samples had low (56%) to marginal (40%) ABDTPA-P. The ABDTPA-K content ranged from 24.2 to 290 mg kg⁻¹ (Mean: 123 mg kg⁻¹, Median: 106 mg kg⁻¹, Mode: 67.8 mg kg⁻¹). Majority of soils had marginal (29%) to adequate (45%) ABDTPA-K. The maps developed in this study provide a preliminary spatial baseline for identifying areas of contrasting soil conditions, supporting targeted soil testing and informing future site-specific soil and nutrient-management strategies.

KEYWORDS: Soil spatial variability, mapping, district, Badin, Sindh

INTRODUCTION

Spatially variable nutrient management is vital for intensive agriculture because soil physicochemical properties and nutrient availability to plants are affected by different soil related factors (Rafique *et al.*, 2023). Intensive agricultural practices using hybrid seeds and applying chemical fertilizers indiscriminately have resulted in decreased soil fertility. This has increased the demand for efficient soil fertility management (Singh *et al.*, 2025). Traditionally, general fertilizer recommendations based on average values have resulted in either under or excessive application of nutrient inputs affecting crop yield (Anand *et al.*, 2025).

Soil testing is an effective strategy to analyze soil fertility and related soil heterogeneity in the field for the best fertilizer recommendations to enhance soil productivity (Malla *et al.*, 2020).

Soil spatial variability indicates the difference in soil physicochemical properties across various agro-ecological regions, hence, affects soil productivity (Kousar *et al.*, 2025; Fayyaz *et al.*, 2025). This is mainly attributed to soil forming factors and soil management practices (John *et al.*, 2021). Soil

variability may occur over a small distance to large distance in kilometers. Therefore, assessing such variability is highly important to use fertilizers efficiently for better crop yields requiring comprehensive knowledge about spatially variable nutrients (Kousar *et al.*, 2025; Dhiman *et al.*, 2025).

Geographical Information System (GIS) based soil mapping plays considerable role in dealing with soil spatial variability in order to formulate the efficient fertilizer management strategies (Kumar *et al.*, 2024; Jamali *et al.*, 2023). Most commonly used geospatial methods are found to be Inverse Distance Weighting (IDW) and ordinary kriging in mapping soils (Dongare *et al.*, 2022).

The soils of Pakistan are currently confronted with deficiencies of major essential nutrients, viz nitrogen (N) up to ~100%, phosphorus (P) around 80-90%, and potassium (K) up to 30-40% (Zia-ul-hassan *et al.*, 2008; Jamali *et al.*, 2023; Saraz *et al.*, 2023). The specific geographical differences in soil properties of various agroecological regions are associated with several factors, including different fertilizer needs of different crops. To deal with such variability, it becomes indispensable to assess soil fertility status,

which helps in balanced plant nutrition and a step towards promoting sustainable agriculture (Zia-ul-hassan *et al.*, 2008). Due to lack of information about soil fertility, farmers misunderstand the soil conditions and over or under apply specific nutrients such as misunderstanding of K availability in Pakistani soils as adequate nutrient coupled with increased prices of K fertilizers, farmers rarely apply this nutrient (Zia-ul-hassan *et al.*, 2014).

The significance of GIS in determining soil spatial variability for variable rate fertilizer technology has been highlighted by various studies recently in Sindh province. These studies have interpolated soil properties and developed thematic maps using GIS tools, for instance, Saraz *et al.* (2023) conducted a study in Mirpurkhas using IDW method and reported that most soils were clayey, high to excessively high in surface salinity and deficient in P. Similarly, Mari *et al.* (2025) developed thematic maps of various soil properties in Shaheed Benazirabad utilizing IDW. Jamali *et al.* (2023) elaborated that the soils of Tando Allahyar district were dominantly loamy-textured, low in electrical conductivity, deficient in P, and high in K. In a latest research, banana growing soils of Tando Muhammad Khan have been reported to be silt loam, deficient in P and high in K (Ujjan *et al.*, 2025).

Globally many latest studies have emphasized the significance of GIS in soil spatial variability mapping. Keshavarzi *et al.* (2025) studied spatial variability and delineated management zones using GIS techniques in arid region of Iran demonstrating the need to apply nutrients precisely. Shaalan *et al.* (2025) developed soil properties maps in Awan, Egypt.

The district Badin is a coastal district on the left bank of the River Indus, with hot and humid summers and moderate winters. The cultivated area of district Badin is 281,067 hectares. The major crops grown during Rabi season are wheat and fodder while rice and

sugarcane are commonly grown during Kharif season (FAO, 2017). Despite the presence of modern, swift and cost-effective methods to investigate soil spatial variability and to analyze nutrient status for site specific and better nutrient management, no detailed study has been conducted so far in district Badin, which is economically and agriculturally important district of Sindh. Keeping in view of the economic and agricultural significance of district Badin and the key roles of GIS in interpolating soil spatial variability, this study was conducted to determine selected soil physicochemical properties and available phosphorus (P) and potassium (K) status and to develop spatial variability maps of the sampled agricultural soils of District Badin.

MATERIAL AND METHODS

This study was planned to determine selected soil physicochemical properties and available phosphorus (P) and potassium (K) status and to develop spatial variability maps of the sampled agricultural soils of District Badin, by developing the soil spatial variability maps, using advanced techniques. The study comprised collecting soil samples from 133 selected farms of 65 union councils of five talukas involving different crops in district Badin, viz. Matli, Talhar, Shaheed Fazul Rahu, Badin and Tando Bago, representing different major cropping areas with broad geographical coverage (Figure 1).

Developing shapefile of study area: For conducting soil sampling across the selected farms, deh-wise map of district Badin was obtained from the Deputy Commissioner Office, district Badin. The shapefile of district Badin was developed in Google Earth Pro® and ArcMap® 10.8 (<http://www.esri.com>). The geographical coordinates (latitude and longitude) of the soil sampling sites were recorded with handheld GPS device Magellan® Triton™ 200.

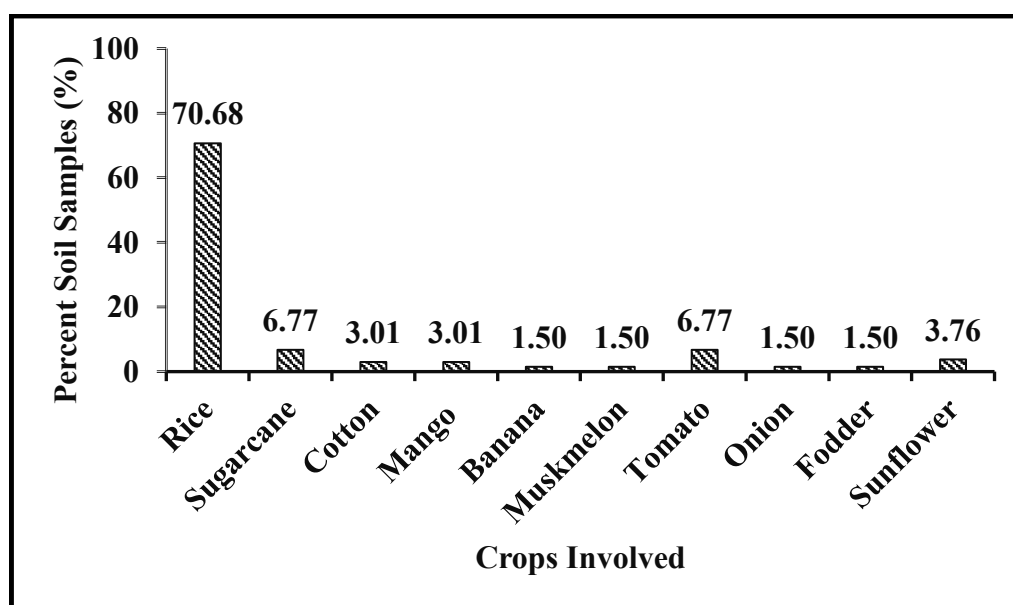


Figure. 1. Diversification of crops involved in soil sampling

Soil sampling and processing: Soil sampling was conducted during November and December 2024. In total 133 different farms were selected randomly across the district Badin for soil sampling. The samples were distributed among five talukas (Matli, Talhar, Shaheed Fazul Rahu, Badin and Tando Bago) based on the area size of each taluka. Then, within Taluka, agriculturally important union councils were selected. A stainless-steel auger was used to collect the soil samples to avoid contamination. Surface soils with depth of 0-20 cm from 20 cores were collected from various soils under different crops across the study area (Ryan *et al.*, 2001). The sampling network was intended to provide broad district-scale coverage for soil characterization and thematic spatial visualization rather than to constitute a statistically optimized network for formal geostatistical prediction (Figure 2).

Analysis of soil properties: The soil samples were analyzed in an air-conditioned laboratory (25±2°C) for selected soil physicochemical properties, including soil texture, pH, electrical conductivity (EC 1:2 soil-water extract), organic matter (OM), and ABDTPA-extractable phosphorus (P) and potassium (K), at the Plant Nutrition Laboratory, Department of Soil Science, Sindh Agriculture University, Tandojam. Soil texture was determined using the Bouyoucos hydrometer method, and textural classes were assigned according to the USDA soil-texture classification system. Soil pH, EC1:2 (Sonon *et al.* (2015) and organic matter content were determined as described by (Ryan *et al.*, 2001), while ABDTPA-extractable P and K were determined as outlined by (Sultanpour & Schwab, 1977). The necessary quality control

measures were properly observed during the soil analyses.

Descriptive statistics: Conventional descriptive statistics such as minimum, maximum, mean, mode, standard deviation and coefficient of variation were performed in MS excel 2010.

Categorization of soil parameters: The categorization of soil properties followed standard references, as mentioned elsewhere (Ankerman & Richard, 1989; Sonon *et al.*, 2015; Mari *et al.*, 2025), for better understanding.

Spatial interpolation and variability mapping: The spatial interpolation of the measured soil variables was performed in ArcGIS 10.8 using the Inverse Distance Weighted (IDW) deterministic interpolation technique to generate continuous district-scale thematic surfaces from the geographically referenced observations. IDW assigns greater influence to observations located closer to an unsampled location and was used in the present study to visualize the broad spatial distribution and relative contrasts of the measured soil properties across the agricultural landscape. The resulting maps were interpreted as spatial representations of the observed sampling pattern rather than as independently validated prediction surfaces.

The present study was designed primarily for district-scale soil characterization and thematic mapping rather than for development and validation of a formal geostatistical prediction model. Accordingly, experimental variogram modelling, comparison of alternative spatial prediction algorithms and independent cross-validation were beyond the scope of the original analytical framework.

RESULTS

The findings showed that soils of district Badin varied significantly. The descriptive statistics of this study are given below (Table 1).

Table 1. Descriptive statistics of soil physicochemical properties of district Badin

Statistical measures	EC (dS m ⁻¹)	pH	SOM (%)	ABDTPA-P (mg kg ⁻¹)	ABDTPA-K (mg kg ⁻¹)
Minimum	0.40	6.79	0.09	1.0	24.2
Maximum	10.72	8.50	1.80	12.0	290.0
Mean	3.59	7.93	0.77	3.9	123.0
Median	2.90	7.98	0.78	3.7	106.0
Mode	1.59	7.99	0.78	3.3	67.8
Standard Deviation	2.30	0.24	0.31	1.9	75.6
Standard Error	0.20	0.02	0.03	0.2	6.6
CV (%)	64.20	3.00	39.60	50.1	61.5

Soil Texture: The soils of district Badin varied from coarse to fine textured soils. Most soils were sandy loam (82%) followed by loam (9%). Spatial

variability map illustrated that most of soils were sandy loam followed by loamy sand (Table 2, Figure 3).

Table 2. Soil types and textural classes found in district Badin, Sindh (n=133)

Soil types and Texture	Soil Samples (%)
Sandy or Coarse Textured soil	84.3
Sandy loam	82.0
Loamy Sand	2.3
Loamy Slightly medium-textured soil	11.3
Loam	9
Silt Loam	2.3
Loamy moderately-textured soil	6.6
Clay loam	2.3
Sandy Clay Loam	2.3

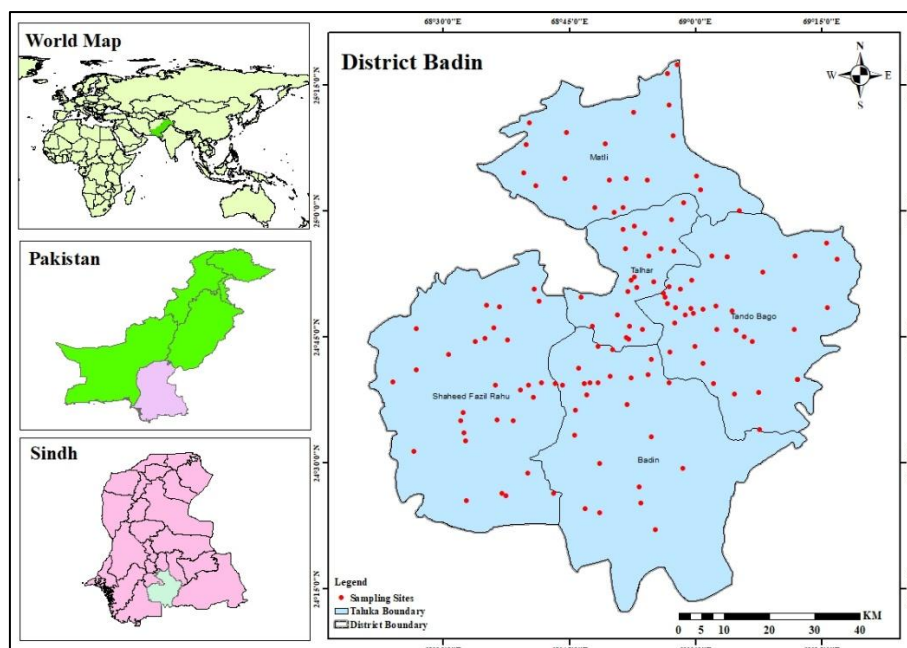


Figure 2. Study Area Map of district Badin, Sindh, Pakistan

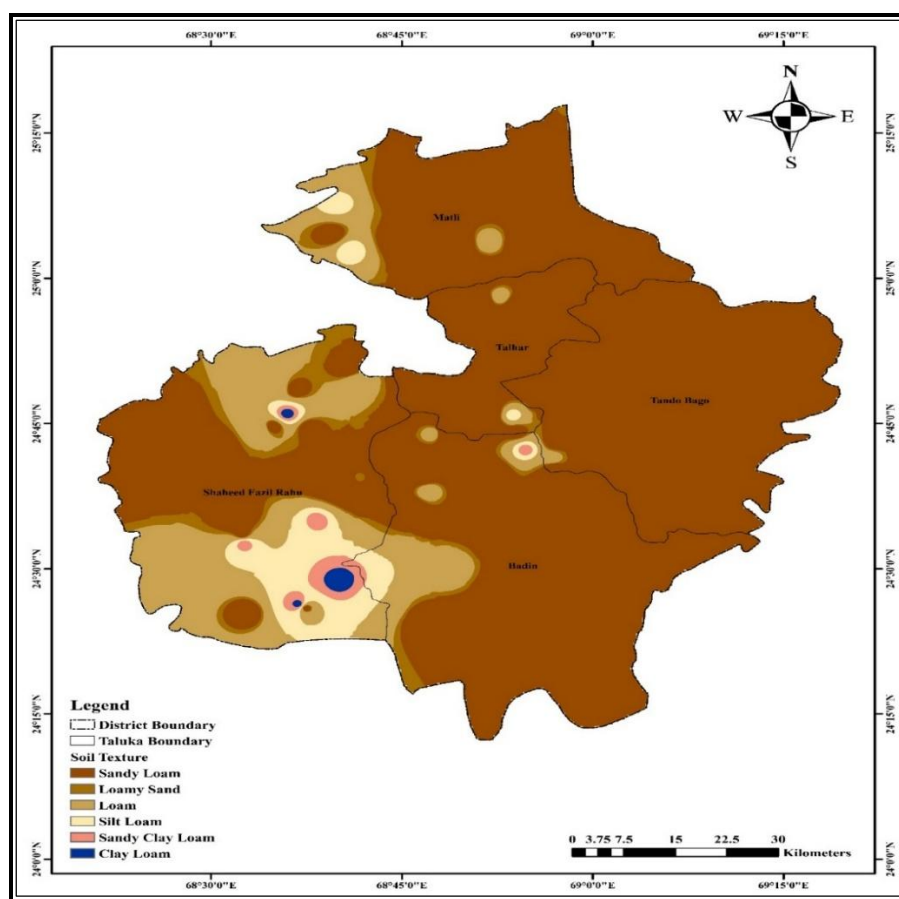


Figure 3. Distribution of soil texture in district Badin, Sindh, Pakistan

Electrical Conductivity (dS m^{-1}): The electrical conductivity (EC) of district Badin varied from 0.4 dS m^{-1} to 10.72 dS m^{-1} , with an average of 3.59 dS m^{-1} . The most frequent values of EC were 1.59 dS m^{-1} . The coefficient of variation was 64.2%, indicating relatively high dispersion of EC values among the

sampled soils (Table 1). The majority of soils were high to excessively high (84.2%) in salinity status (Figure 4). The spatially interpolated EC map showed that soils of Badin are dominantly high to excessively high in surface salinity (Figure 5).

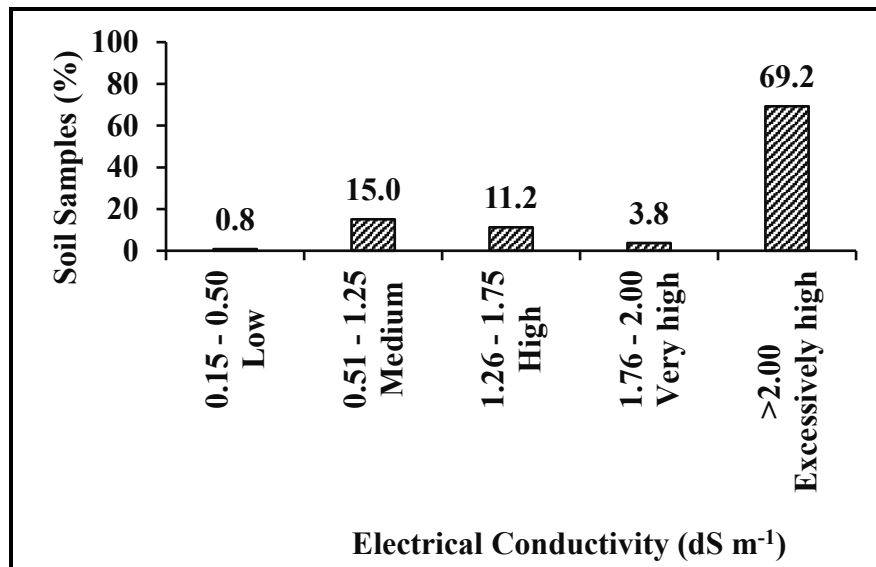


Figure 4. Categorization of soils of district Badin, Sindh, Based on soil salinity (Sonon *et al.*, 2015).

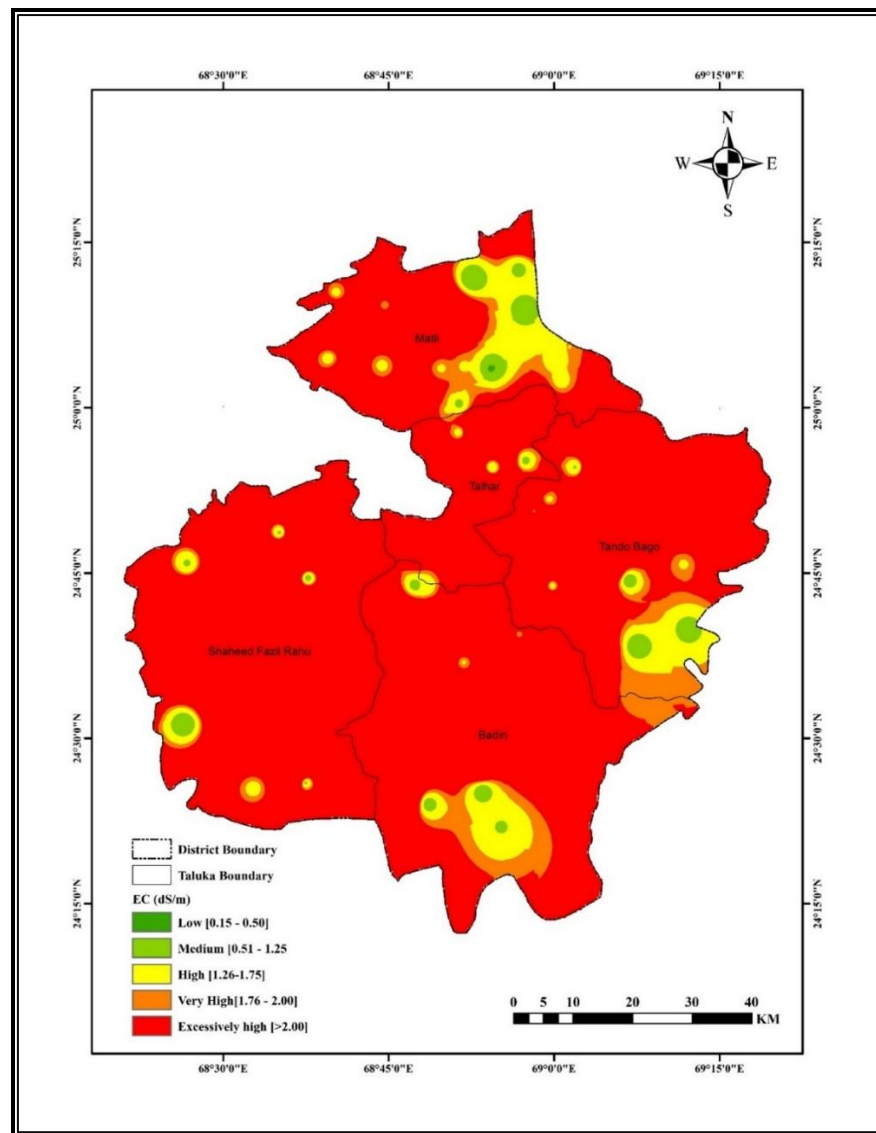


Figure 5. Spatially distributed soil salinity map of district Badin, Sindh, Pakistan

Soil pH: The soil pH of district Badin varied from slightly acidic to medium alkaline. The soil pH values ranged from 6.79 to 8.5, with an average value of 7.93 while the most repeated value was 7.99. The coefficient of variation was only 3.0%, indicating very low dispersion of pH values among the sampled soils

(Table1). Most soils (84%) were medium alkaline (Figure 6) in reaction followed by slightly alkaline (9%). The spatially variable map demonstrated that soils of study area were dominantly medium alkaline in reaction (Figure 7).

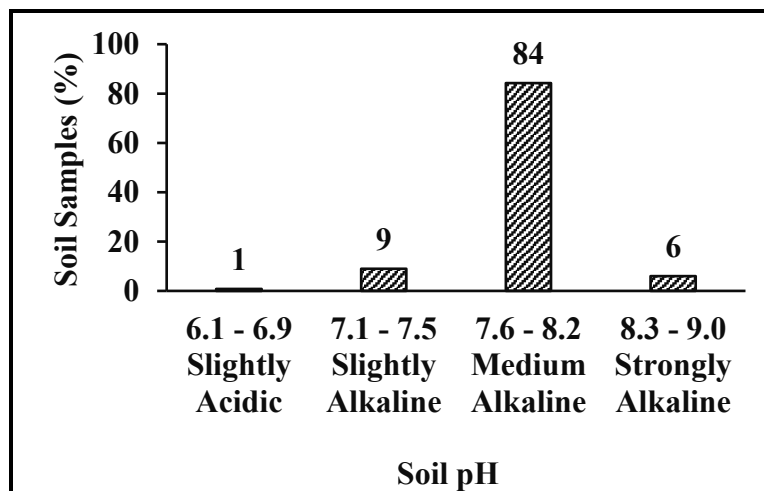


Figure 6. Categorization of soils of district Badin, Sindh, Based on soil pH (Ankerman & Richard, 1989).

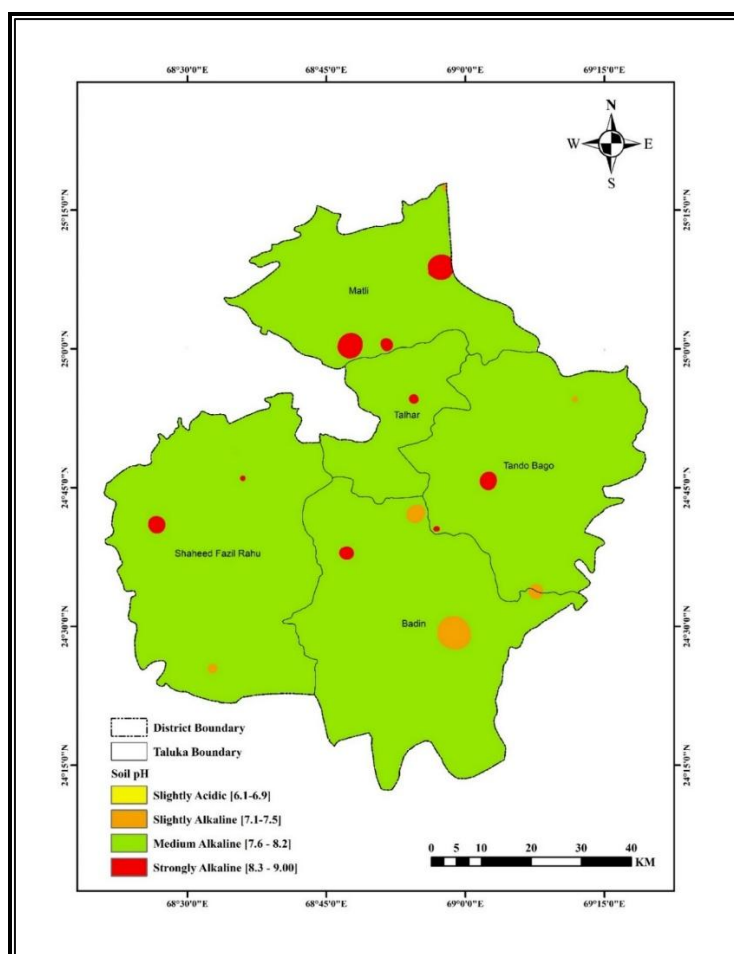


Figure 7. Spatially distributed soil pH map of district Badin, Sindh, Pakistan

Organic Matter (%): Organic matter ranged from 0.09% to 1.8%, with mean value of 0.77% and the most frequent value was 0.78%. The coefficient of variation was 39.6%, indicating moderate dispersion of organic matter values among the sampled soils (Table 1). The

majority of soils (71.4%) were found to be deficient in organic matter followed by medium (24.1%) (Figure 8). The spatially variable map elaborated that soils of district Badin were deficient in organic matter while minor areas were found to be adequate (Figure 9).

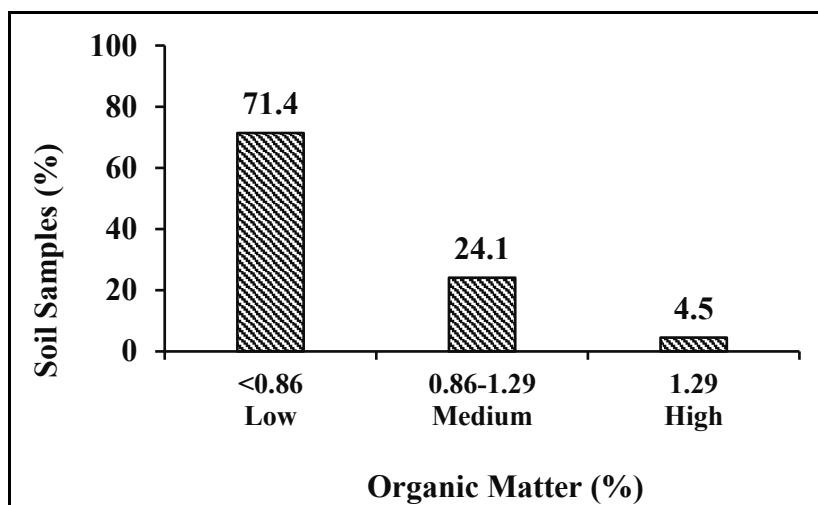


Figure 8. Categorization of soils of district Badin, Sindh, based on organic matter (%) (Rashid, 1996)

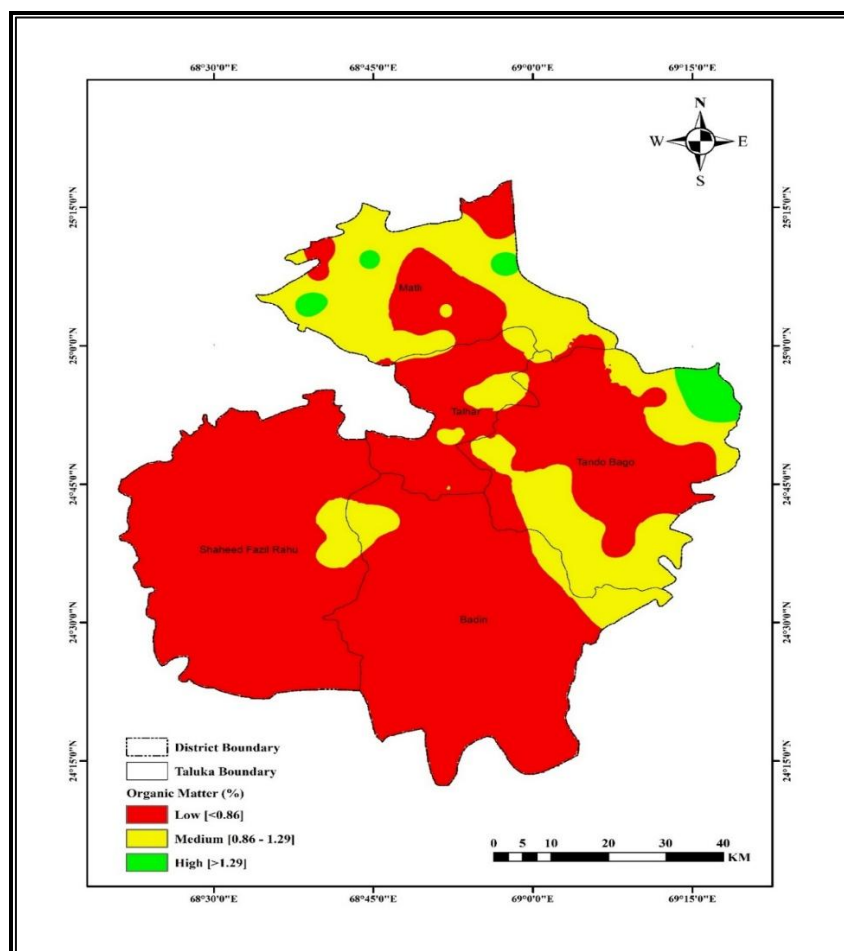


Figure 9. Spatially distributed soil organic matter (%) map of district Badin, Sindh, Pakistan

ABDTPA-P (mg kg^{-1}): ABDTPA-P ranged between 1.0 to 12 mg kg^{-1} , with an average value of 3.9 mg kg^{-1} and most common value was reported to be 3.3 mg kg^{-1} . The coefficient of variation was 50.1%, indicating high dispersion of ABDTPA-P values among the

sampled soils (Table 1). Furthermore, the majority of soils in district Badin were predominantly P deficient (56%), followed by marginal (40%) (Figure 10). Map of ABDTPA-P demonstrated that the soils were dominantly deficient in P (Figure 11).

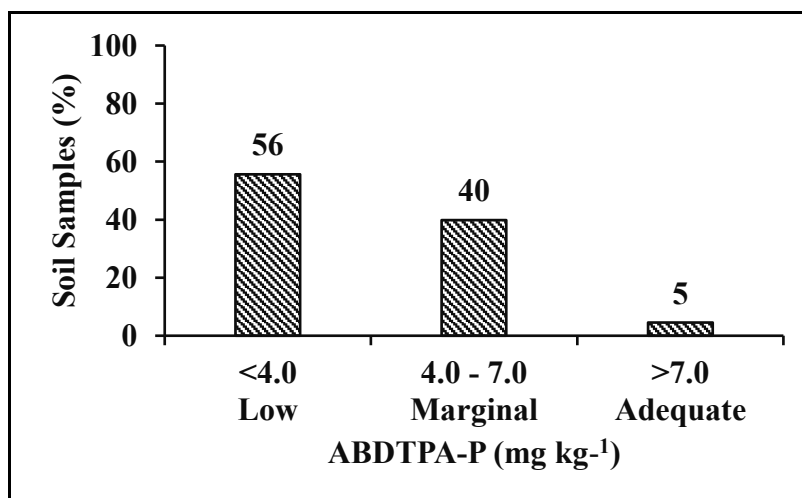


Figure 10. Categorization of soils of district Badin, based on ABDTPA-P content (Sultanpour & Schwab, 1977)

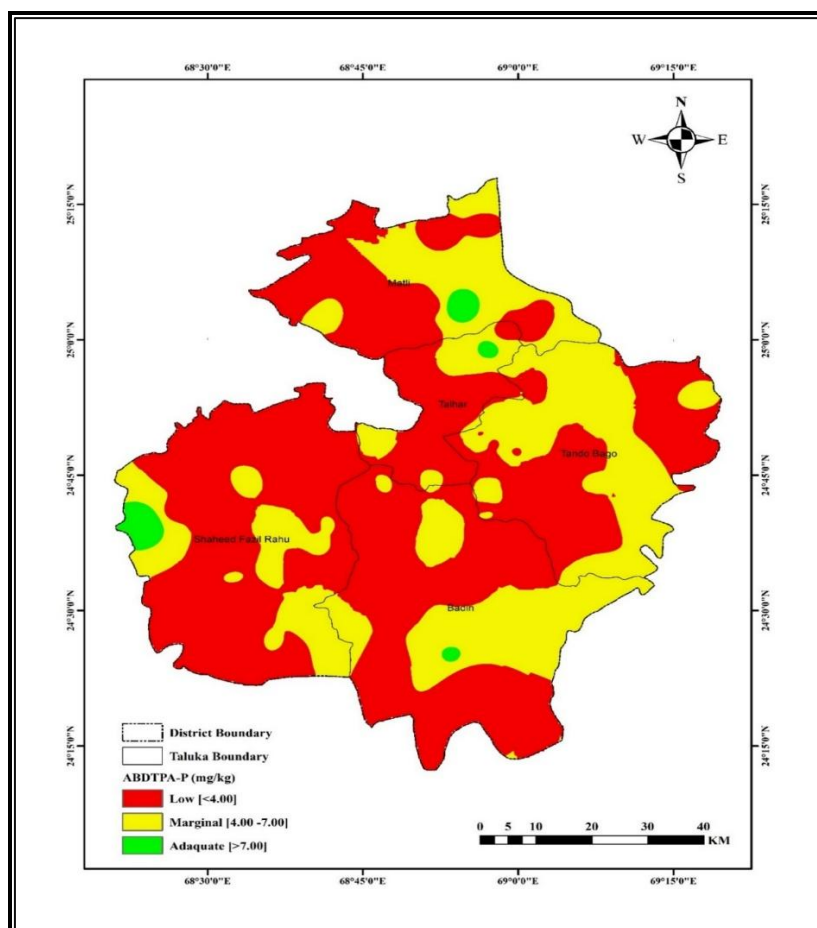


Figure 11. Spatially distributed ABDTPA-P map of district Badin, Sindh, Pakistan

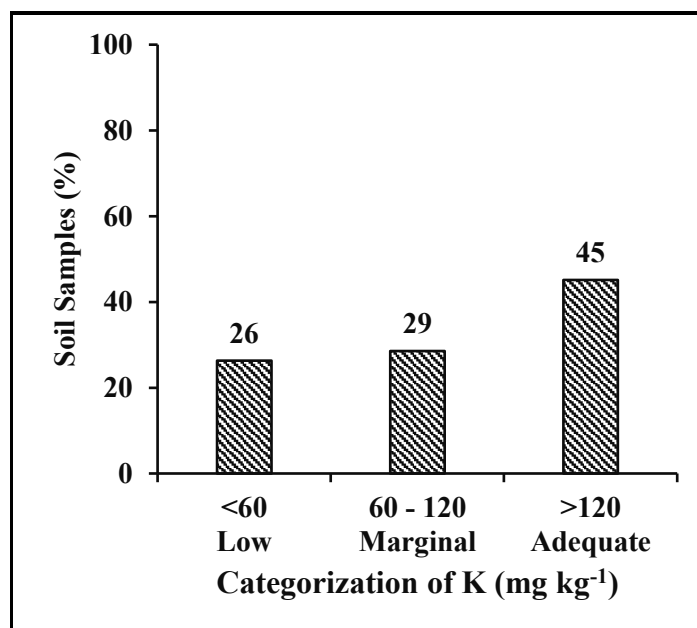


Figure 12. Categorization of soils of district Badin, Sindh, based on ABDTPA-K content (Sultanpour & Schwab, 1977)

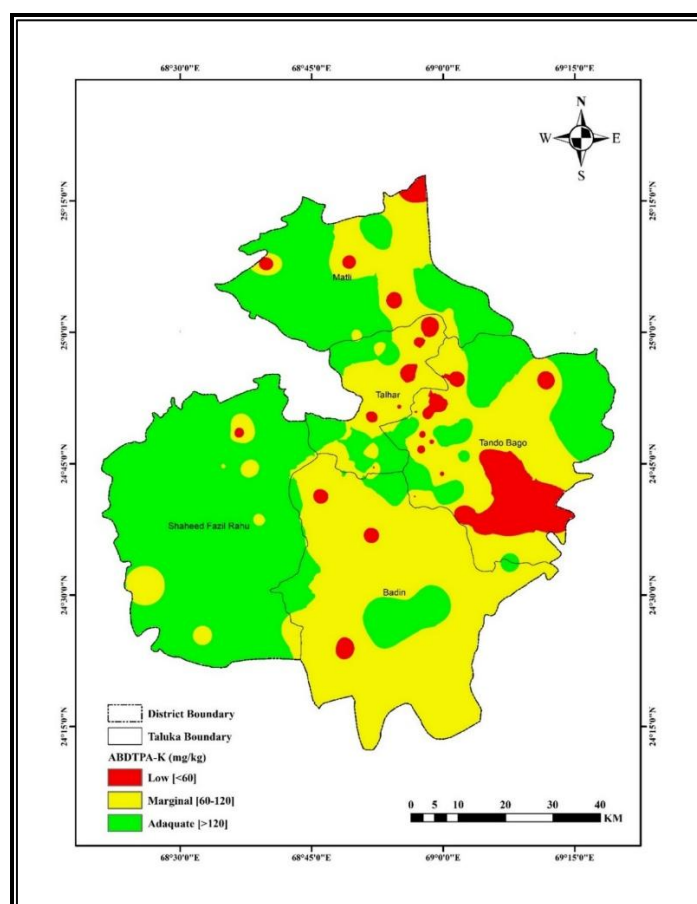


Figure 13. Spatially distributed ABDTPA-K map of soils of district Badin, Sindh, Pakistan (Sultanpour & Schwab, 1977)

ABDTPA-K (mg kg⁻¹): The ABDTPA-K varied from 24.2 mg kg⁻¹ to 290 mg kg⁻¹, with average value of 123 mg kg⁻¹, and the most frequent value was 67.8 mg kg⁻¹

¹. The coefficient of variation was 61.5%, indicating relatively high dispersion of ABDTPA-K values among the sampled soils (Table 1). The results further

highlighted that K was adequate (45%) followed by marginal (29%) dominantly. (Figure 12). The map illustrated that the soils of district Badin were dominantly adequate in K, while some sites were observed to be marginal and low in ABDTPA-K content (Figure 13).

DISCUSSION

The findings of the present study provide a farm-level representation of the spatial variation of selected soil properties across the agricultural areas of District Badin. Farm management practices result in high spatial variability while soil forming factors resulting in low spatial variability in a certain area (Cambardella *et al.*, 1994; Fayaz *et al.*, 2025). The physicochemical properties of Sindh province showed a pattern of strong spatial variability specifically in lower Sindh including district Badin where different factors such as shallow ground water, sea water intrusion and irrigation management were responsible for it (FAO, 2017).

In present study, soil spatial variability mapping of district Badin highlighted high heterogeneity in most of the soil physicochemical properties, providing a preliminary spatial baseline for targeted soil testing and future site-specific soil and nutrient-management strategies. The observed spatial variability of soil properties may reflect differences in soil characteristics, cropping systems and associated agricultural management practices across the sampled areas. This variability may be associated with multiple factors, including intrinsic factors such as parent material, topography, climate, organisms and time, as well as extrinsic factors related to cropping systems, fertilizer and water management, and land preparation. Generally, farm management practices may contribute to greater spatial variability, while soil-forming factors may contribute to relatively lower variability within a given area. The physicochemical properties of lower Sindh, including District Badin, may also be influenced by factors such as shallow groundwater, seawater intrusion and irrigation management (FAO, 2017).

The findings of current study highlighted sandy loam as the dominant texture followed by loam. This is largely due to the deposition environment of parent material and deltaic alluvial nature associated with Indus delta.

The predominantly found sandy loam texture in district Badin offers improved soil physical properties for plant growth including better drainage and aeration in different areas.

Our study corroborates with a previous study, which showed that broad categories of soil textures are found throughout Sindh ranging from sandy loam to loam soils in northern and central districts, while deltaic districts including Thatta, Sujawal and Badin are predominated by fine-textured soil texture varying from clay loam to clay due to deltaic conditions highlighting fine-texture nature of the belt (FAO, 2017). Curiously, numerous soil spatial variability mapping related studies conducted in Sindh as well as in Pakistan have found similar variability in soil texture

varying from coarse to fine textured soils in different districts (Jamali *et al.*, 2023; Mari *et al.*, 2025), and might be attributed due to the variations in the sampling population, study objectives and the time period between the studies, specially the present study which was focused on geographically distributed cultivated agricultural soils.

The soil electrical conductivity (EC) results of the present study highlighted spatial heterogeneity throughout the district Badin, ranging from low to excessively high salinity. Predominantly, soil samples were found under excessively high salinity, followed by medium, illustrating the area was severely affected by salinity. The dominantly found excessively high surface salinity might be due to low quality shallow ground water, waterlogging, unavailability of drainage facilities, sea water intrusion and use of saline water for irrigation purposes in the long run. As reported by FAO (2017) soil salinity showed increasing trend from northern districts to southern deltaic districts, specifically, Sujawal, Badin and Thatta were severely affected by different types of salinity.

Our study confirms previous findings in the literature regarding GIS-based soil mapping, showing similar soil salinity variability ranging from very low to excessively high salinity while comparatively higher salinity in coastal and irrigated districts of Sindh province (Chohan *et al.*, 2023; Saraz *et al.*, 2023; Mari *et al.*, 2025). Contrastingly, non-coastal agricultural regions such as district Tando Allahyar and others showed dominantly low surface soil salinity representing variation in deep ground water, no waterlogging and better irrigation management (Kalhor *et al.*, 2015; Islam *et al.*, 2025). Present study demonstrated soil salinity as major agricultural constraint supporting importance of GIS-based soil spatial heterogeneity mapping for better understanding of salinity patterns in the study area for adopting reclamation strategies and selecting salt tolerant crop varieties.

The findings of current study reported that soil pH of district Badin were dominantly medium alkaline in reaction, ranging from slightly acidic to strongly alkaline. The predominant medium alkaline soil pH is attributed to high temperatures, low precipitation, calcareous parent material, excessively high salinity, and poor organic matter content. Our results are in line with as reported by FAO (2017) which indicated that soils of Sindh province varied from slightly to moderately alkaline in reaction, while observing strong alkalinity in lower districts including Thatta and Badin due to large extent of salt affected soils and calcareous nature of deltaic parent material.

Numerous past studies support our results illustrating that alkaline soils are largely characterized by soils of irrigated parts of Punjab and Sindh (Kalhor *et al.*, 2015; Memon *et al.*, 2023; Sultana *et al.*, 2023). Similarly, spatial distribution maps of soil pH developed in different GIS-based studies conducted in Sindh province showed that district Thatta, Mirpur

Khas and Shaheed Benazirabad are dominated by medium alkaline soil pH (Chohan *et al.*, 2023; Saraz *et al.*, 2023; Mari *et al.*, 2025). In contrast to that, humid mountainous areas with high rainfall areas were predominantly occupied by acidic to neutral soil pH, highlighting dominant effect of soil forming factors specifically, climate and parent material on spatially distributed soil pH (Malla *et al.*, 2020; Poudel *et al.*, 2025). The comparatively low soil pH variability observed in our study is in close agreement with as reported by Khan *et al.* (2019), strongly supporting the idea that soil pH varies less in comparison to other soil physicochemical properties.

The soils of district Badin were poor in organic matter content with majority of soil samples falling in low to medium categories owing to intensive agricultural practices, low or no addition of crop residue, arid climate resulting in comparatively higher organic matter decomposition. Majority of soils in Sindh province are deficient in organic matter commonly observed in coastal districts including Badin, where salt affected soils discourage plant growth resulting in lower biomass production ultimately reducing organic matter in soil (FAO, 2017). Furthermore, literature advocates that low organic matter content in soil is largely observed under intensive farming practices carried out in Sindh and other parts of the country (Jamali *et al.*, 2023; Fayyaz *et al.*, 2025).

Similar other studies have reported that organic matter was poor in majority of coastal district of Thatta, even though comparatively suitable soil texture was found (Kalhor *et al.*, 2015). Contrary to that, specific land uses such as forest and zero tillage soils were found to be high in organic matter highlighting the significance of soil cover and addition of organic matter for sustainable agriculture (Yadav *et al.*, 2022; Geleta *et al.*, 2025). The poor status of organic matter in district Badin as reported by current study is a big concern for the farming community, because it affects soil productivity by affecting soil nutrients availability, physical properties and microbial population.

Soil phosphorus (P) deficiency was widespread across district Badin ranging from low to marginal. P unavailability is a big crop productivity limiting factor, which may be due to lime content, medium alkaline soil pH, and precipitation of P as insoluble compounds of calcium.

Soils of Sindh province are predominantly deficient in available P varying from low to marginal in different districts with deficiency increasing towards southern districts which experience severe P deficiency mainly because of P fixation under alkaline and saline soil conditions (FAO, 2017). In addition, increased prices of phosphatic fertilizers limit their application and misconceptions regarding its availability in soil may further deteriorate the situation (Chohan *et al.*, 2015; Arain *et al.*, 2017).

Interestingly, our findings are in good agreement of the soil spatial variability mapping research in Sindh

and other parts of Pakistan have shown varying trend from low to marginal in P limiting the crop yields (Saraz *et al.*, 2023; Islam *et al.*, 2025). Moreover, studies have illustrated medium to low P soils highlighting the influence of alkaline and calcareous nature of soils on P availability (Malla *et al.*, 2020; Maurya *et al.*, 2024). The spatial distribution of P as visualized by GIS-based maps developed in this study identified P-deficient areas, guiding to adopt site-specific P fertilizer management in an effective way for achieving better crop yields.

The current study reported that soil potassium (K) varied from marginal to adequate with most of the soils belonging to adequate category. The sufficient range of K in most of the soils may be due to the micaceous nature of Pakistani soils which are considered as K rich minerals, including illite and feldspars deposited by river as alluvial material acting as indigenous soil K reservoirs and become available upon weathering (Wakeel & Ishfaq, 2022).

K is found to be adequate throughout Sindh province including district Badin because of Mica rich parent material; however, deficiency of K can occur at under intensive crop production (FAO, 2017). Likewise, many studies conducted in Sindh as well as in other parts of the country have reported that K was in sufficient range despite the common deficiency of P and nitrogen (Mari *et al.*, 2025; Rachamalla *et al.*, 2025). Spatial K distribution observed in this study confirms that soils should not be treated as blanket fertilizer applications. Similarly, GIS-based spatial variability studies at national and international level have illustrated different patterns of K variability in cultivated areas, highlighting the significance of site-specific K stewardship (Malla *et al.*, 2020).

Overall, the results of this study are also in line with the widespread nutrient deficiencies reported in Pakistani soils, such as N is reported to be deficient in 100% soils, P around 80-90%, and K up to 30-40% soils (Zia-ul-hassan *et al.*, 2008). Likewise, the K findings of current study agree with those of (Zia-ul-hassan *et al.*, 2014), who attributed under application of the nutrient to the low addition of K fertilizers in Pakistani soils because of predominant misconception among the farming community that soils of Pakistan contain adequate level of K. In similar way, results of district Badin are in strong consistent with the provincial level findings as reported by FAO, (2017) showing multiple soil fertility problems.

In a nutshell, the findings of current study proved that soil spatial variability mapping is a powerful strategy to for site-specific management of soil resources based on precise understanding of soil properties for achieving sustainability in one of the agriculturally important districts of Sindh province.

CONCLUSIONS

The spatial variability maps of District Badin showed that the sampled agricultural soils were dominantly sandy loam followed by loam,

predominantly high to excessively high in salinity, medium alkaline in pH, low in organic matter, deficient in available P, and marginal to adequate in available K. Overall, the GIS-based thematic maps provided a district-scale representation of the spatial distribution of selected soil physicochemical properties and available P and K in the sampled agricultural soils of Badin. The maps provide a preliminary spatial baseline for identifying areas of contrasting soil conditions, supporting targeted soil testing and informing future site-specific soil and nutrient-management strategies. They should not, however, be interpreted as independently validated variable-rate fertilizer recommendations.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTION

HK: Soil sampling and analyses and wrote all drafts of the manuscript, Zia-ul-hassan: Conceived the idea, supervised study, and edited all drafts of manuscript, NAT: Data processing and developing maps, ND: Facilitated in some chemicals and soil analyses, and JAA: Data presentation and format and style of paper. All authors endorsed and approved the final draft.

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