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Physico-Chemical Characterization and Fertility Status of Semi-Arid Calcareous Soils in Tehsil Domail, District Bannu, Pakistan

Muhammad Tariq
Departments of Soil & Environmental Sciences, The University of Agriculture, Peshawar 25000, Pakistan

Zahoor Khan*
Department of Environmental Sciences, University of Peshawar, 25120, KP, Pakistan

Hina Tariq
National Institute of Health (NIH), Islamabad

Muhammad Zakwan Hadeed
Green Sustainable Enviro-Engineering Pvt. Limited

Muhammad Junaid
Department of Environmental Sciences, University of Peshawar, 25120, KP, Pakistan

Arshad Ali
Department of Environmental Sciences, University of Peshawar, 25120, KP, Pakistan

Muhammad Nouman
Department of Environmental Sciences, University of Peshawar, 25120, KP, Pakistan

Nasir Khan
Department of Environmental Sciences, University of Peshawar, 25120, KP, Pakistan
Pakistan Email: zahoorkhan@uop.edu.pk

ABSTRACT

Soil fertility assessment is essential for sustainable agricultural productivity, particularly in semi-arid regions where land degradation and nutrient depletion are prevalent. Tehsil Domail in District Bannu, Pakistan, remains underrepresented in national soil studies despite its agricultural significance and fragile agro-ecological conditions. This study was conducted to evaluate the physico-chemical properties and fertility status of soils in Tehsil Domail. A total of twelve composite soil samples were collected from six different villages at a depth of 0–30 cm during August 2024. Samples were air-dried, ground, sieved, and analyzed for pH, electrical conductivity (EC), texture, bulk density, particle density, organic matter (OM), and lime content using standard laboratory procedures. Results revealed that soils were neutral to slightly alkaline, with pH values ranging from 7.10 to 7.65. Electrical conductivity

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ranged from 0.36 to 0.48 dS m^{-1}, indicating non-saline conditions suitable for general crop production. Soil texture varied from sandy loam to loam, with bulk density between 1.33 and 1.46 g cm^{-3}, favorable for root penetration and aeration. Organic matter content was low to medium, ranging from 0.82% to 1.08%, reflecting typical dryland conditions. Lime content ranged from 5.0% to 6.3%, indicating calcareous soils that may influence phosphorus availability. In conclusion, the soils of Tehsil Domail possess moderate physical fertility but require organic amendments and regular monitoring to enhance long-term productivity. This study provides baseline data for sustainable land management and recommends the application of farmyard manure or biochar, along with routine soil testing, to maintain soil health in the region.

Keywords: Soil Fertility, Physico-Chemical Properties, Semi-Arid Region, Organic Matter, Calcareous Soils, District Bannu.

Introduction

Soil serves as a fundamental medium for agricultural productivity, nutrient cycling, and environmental stability. Its physico-chemical properties including pH, electrical conductivity (EC), texture, organic matter content, and nutrient status directly influence plant growth, microbial activity, and water dynamics. These attributes are particularly critical in arid and semi-arid regions, where high evapotranspiration, low rainfall, and anthropogenic pressures such as deforestation and intensive traditional farming accelerate soil degradation and nutrient depletion (Ali et al., 2020; Hussain and Ghafoor, 2019).

Tehsil Domail, located in District Bannu, Khyber Pakhtunkhwa, Pakistan, is characterized by a semi-arid climate, rugged topography, and limited water resources. Despite its agricultural potential, the region remains largely unexplored in terms of systematic soil fertility assessment. National and provincial soil studies have primarily focused on other districts such as Peshawar, Swat, Buner, and Kohat, revealing significant spatial variability in soil pH, organic matter, and macronutrients under different land uses and elevation gradients (Khan et al., 2017; Salam et al., 2020; Fida et al., 2011; Parveen et al., 2018). For instance, Yaseen et al. (2024) demonstrated that land use type (forested, cultivated, or barren) strongly influences organic carbon and nitrogen levels in arid zones. Similarly, Ilyas et al. (2022) reported that higher elevation plantations retain more organic matter and exhibit better soil structure compared to lowland areas. However, no comprehensive soil characterization has been conducted for Tehsil Domail, leaving a critical knowledge gap for sustainable land management and crop optimization in this fragile agro-ecological zone.

Calcareous soils, common in southern Khyber Pakhtunkhwa, often exhibit low organic matter and reduced phosphorus availability, necessitating region-specific fertilizer recommendations (Ahmed et al., 2021; Qureshi and Mujeeb, 2020). Without baseline soil data, farmers and land managers in Tehsil Domail rely on generalized practices that may lead to inefficient nutrient use, declining yields, or environmental harm. Therefore, systematic assessment of local soil properties is essential to guide sustainable agriculture, water conservation, and soil rehabilitation efforts. This study

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was conducted to evaluate the physico-chemical properties of soils in Tehsil Domail, District Bannu. Such an assessment is particularly urgent given the region's increasing cultivation intensity and gradual replacement of traditional fallow periods with continuous cropping (Khan et al., 2020). Furthermore, rising input costs for chemical fertilizers demand that farmers apply nutrients based on actual soil needs rather than blanket recommendations (Bhatti et al., 2007). The physical properties of soil, including bulk density and texture, directly influence water infiltration and root development, which are critical for rainfed and supplemental irrigation systems common in semi-arid Bannu (Hussain and Ghafoor, 2019).

In addition, lime content exceeding 5% can fix phosphorus into unavailable forms, thereby reducing fertilizer use efficiency unless properly managed (Sharif et al., 2004). Recent studies by Rahman et al. (2024) have demonstrated that organic amendments such as biochar can improve pH balance and nutrient availability in calcareous soils, suggesting potential rehabilitation strategies for Tehsil Domail. Consequently, the baseline data generated from this investigation will not only inform local nutrient management but also contribute to regional soil databases for future meta-analyses and land use planning in similar agro-ecological zones of Khyber Pakhtunkhwa (Salam et al., 2020; Yaseen et al., 2024). The findings aimed to provide baseline fertility data for researchers and extension workers, Assist farmers in adopting site-specific nutrient management practices and Support sustainable land use planning in semi-arid calcareous environments of Pakistan.

Materials and Methods

Research Study Area

The study was conducted in Tehsil Domail, District Bannu, Khyber Pakhtunkhwa, Pakistan. The region lies between 32.68°N and 70.60°E, characterized by a semi-arid climate with hot summers, mild winters, and average annual rainfall ranging from 250 to 400 mm. The topography consists of intermountain valleys, alluvial plains, and denuded hill slopes (Figure 1). Agriculture is predominantly rainfed with supplemental irrigation from tube wells and small perennial streams.

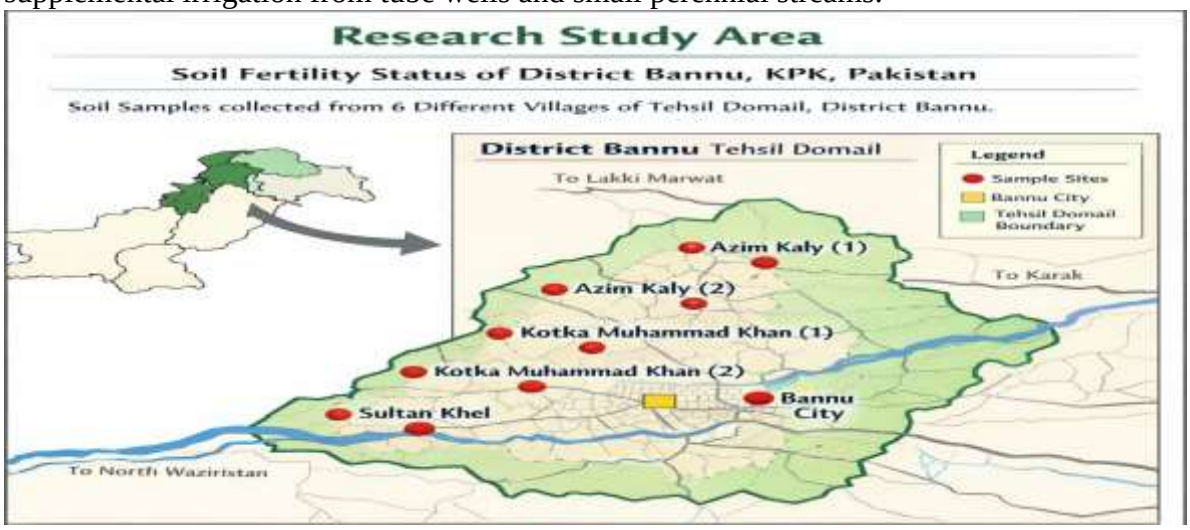

Figure1: Spatial distribution of soil sampling sites across six villages in Tehsil Domail, District Bannu, Khyber Pakhtunkhwa, Pakistan.

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Experimental Design and Soil Sampling

A total of twelve composite soil samples were collected during August 2024 from six different villages of Tehsil Domail, namely Azim Kaly, Kotka Muhammad Khan, Shah Hussain Kaly, Abad Khel, Landi Jalandar, and Bandar Kaly. From each village, two separate fields were selected based on farmer cooperation and accessibility. From each field, three subsamples were collected randomly at a depth of 0–30 cm using a stainless steel auger. The three subsamples were thoroughly mixed to form one composite sample per field, yielding a total of twelve samples. Each composite sample was approximately 500 g in weight. Samples were placed in clean, labeled polythene bags, sealed, and transported to the laboratory.

Table 1: Details of Soil Sample Collected from the Tehsil Domail District Bannu

Location	GPS Coordinates	Sample Depth
Azim Kaly (1)	32.9641° N, 70.5789° E	0-30 cm
Azim Kaly (2)	32.9567° N, 70.5642° E	0-30 cm
Kotka Muhammad Khan (1)	32.9402° N, 70.5461° E	0-30 cm
Kotka Muhammad Khan (2)	32.9328° N, 70.5327° E	0-30 cm
Sultan Khel	32.9215° N, 70.5134° E	0-30 cm
Tappi	32.9104° N, 70.4986° E	0-30 cm

Sample Preparation

In the laboratory of the Department of Soil and Environmental Sciences, The University of Agriculture, Peshawar, the soil samples were spread on clean paper sheets and air-dried at room temperature for 7–10 days. After complete drying, samples were gently crushed using a wooden pestle and mortar and passed through a 2 mm nylon sieve to remove gravel, roots, and other debris. The sieved soils were stored in clean plastic jars for subsequent analysis.

Analytical Procedures

Soil pH

Soil pH was determined using a 1:5 soil-to-water suspension following the method of McLeon (1982). Ten grams of air-dried soil was weighed into a 100 mL plastic bottle, and 50 mL of distilled water was added. The suspension was shaken on a horizontal shaker for 30 minutes and allowed to stand for 10 minutes. The pH meter (Model: Jenway 3510, UK) was calibrated using standard buffer solutions of pH 4.0, 7.0, and 9.0 at room temperature before measuring the pH of each suspension.

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Electrical Conductivity (EC)

Electrical conductivity was measured on the same 1:5 soil-water suspension used for pH determination following the procedure described by Richard (1954). After pH measurement, the suspension was filtered through Whatman No. 42 filter paper. The EC of the filtrate was measured using a calibrated EC meter (Model: HANNA HI 98311, Romania). Results were expressed in deciSiemens per meter (dS m^{-1}).

Soil Texture

Soil texture was determined by the hydrometer method as described by Koehler et al. (1984). Fifty grams of air-dried soil was placed in a 500 mL dispersion cup. Fifty milliliters of sodium hexametaphosphate solution (5%) was added as a dispersing agent, and the volume was made up to 300 mL with distilled water. The suspension was shaken on an electric shaker for 5 minutes and then transferred to a 1 L graduated cylinder. Distilled water was added to bring the volume to 1 L. A hydrometer was gently immersed into the suspension, and the first reading was taken after 40 seconds (sand fraction). The second reading was taken after 2 hours (silt + clay fraction). The temperature was recorded to correct hydrometer readings. Sand, silt, and clay percentages were calculated using standard formulas, and textural classes were determined using the USDA textural triangle.

Bulk Density

Bulk density was determined by the core method as described by Blake and Hartge (1984). Undisturbed soil cores were collected from each field at 0–30 cm depth using a stainless steel core cylinder of known volume (5 cm height × 5 cm diameter). The cores were oven-dried at 105°C for 24 hours until constant weight.

Particle Density

Particle density was determined using the pycnometer method. Twenty grams of air-dried, sieved soil was placed in a 50 mL pycnometer bottle. Distilled water was added, and the bottle was shaken to remove entrapped air. The bottle was filled with distilled water, and the mass was recorded. The particle density was calculated using the formula:

Particle Density (g cm−3)=Mass of oven-dry soil (g)Volume of soil particles (cm3)Particle Density (g cm−3)=Volume of soil particles (cm3)Mass of oven-dry soil (g)

Organic Matter

Soil organic matter was determined by the Walkley-Black wet oxidation method as described by Nelson and Sommers (1996). One gram of air-dried soil (passed through 0.5 mm sieve) was placed in a 500 mL conical flask. Ten milliliters of 1 N potassium dichromate ($K_2Cr_2O_7$) was added, followed by 20 mL of concentrated sulfuric acid (H_2SO_4). The mixture was swirled gently and allowed to stand for 30 minutes. Thereafter, 200 mL of distilled water and 10 mL of orthophosphoric acid (85%) were added. Fifteen drops of diphenylamine indicator were added, and the solution was titrated against 0.5 N ferrous sulfate ($FeSO_4$) until the color changed from violet to

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green.

Lime Content (Calcium Carbonate Equivalent)

Lime content was determined by the acid-neutralization method described by the U.S. Salinity Laboratory Staff (1954). Two grams of air-dried soil was placed in a 250 mL conical flask, and 25 mL of 0.5 N HCl was added. The mixture was heated on a hot plate until boiling and then boiled gently for 5 minutes. After cooling to room temperature, the excess acid was titrated against 0.5 N NaOH using phenolphthalein as an indicator.

Data Analysis

The analytical data were compiled and processed using Microsoft Excel (version 2019). Descriptive statistics including mean, minimum, maximum, and standard deviation were calculated for each parameter. Results were compared with standard critical limits for soil fertility classification as proposed by Rashid et al. (2018) and Bhatti et al. (2007).

Results and Discussion

Soil pH and Electrical Conductivity

The pH of the soil samples ranged from 7.10 to 7.95, with a mean value of 7.48 ± 0.29 (Figure 2; Table 2). The lowest pH (7.10) was recorded in Kotka Muhammad Khan, while the highest (7.95) was observed in Abad Khel. These values indicate neutral to slightly alkaline conditions across the study area. Electrical conductivity (EC) ranged from 0.36 to 0.48 dS m^{-1}, with a mean of 0.42 ± 0.04 dS m^{-1}. All EC values were well below the critical threshold of 2.0 dS m^{-1}, confirming that the soils are non-saline and suitable for general crop production (Rashid et al., 2018). The pH values observed in this study (7.10–7.95) indicate neutral to slightly alkaline conditions, which are typical for semi-arid regions where high evapotranspiration and low rainfall promote the accumulation of basic cations near the soil surface (Ali et al., 2020).

These findings are consistent with earlier reports from similar agro-ecological zones in Khyber Pakhtunkhwa. Bhatti et al. (2007) reported pH values ranging from 6.0 to 8.0 across irrigated fields of KP, while Durrani (2006) found a mean pH of 7.90 at the Serai Naurang Research Station. Sharif et al. (2004) also recorded pH between 7.9 and 8.03 in persimmon orchards of Charsadda. The slightly higher pH observed in Abad Khel (7.95) may be attributed to local variations in parent material or irrigation water quality. The EC values (0.36–0.48 dS m^{-1}) confirm non-saline conditions across Tehsil Domail, as all values are well below the 2.0 dS m^{-1} threshold considered safe for most crops (Rashid et al., 2018). These results align with Parveen et al. (2018), who reported non-saline conditions in vegetable-growing areas of Peshawar, and with Fida et al. (2011), who found similar EC ranges in guava orchards of Kohat. However, the EC values in the present study are considerably lower than those reported by Khan (2007) at ARI Tarnab Farm (4.5 dS m^{-1}), indicating that salt accumulation is not yet a critical issue in Tehsil Domail. Nevertheless, long-term monitoring is recommended, particularly in irrigated fields where improper water management can lead to secondary salinization (Qureshi and Mujeeb, 2020).

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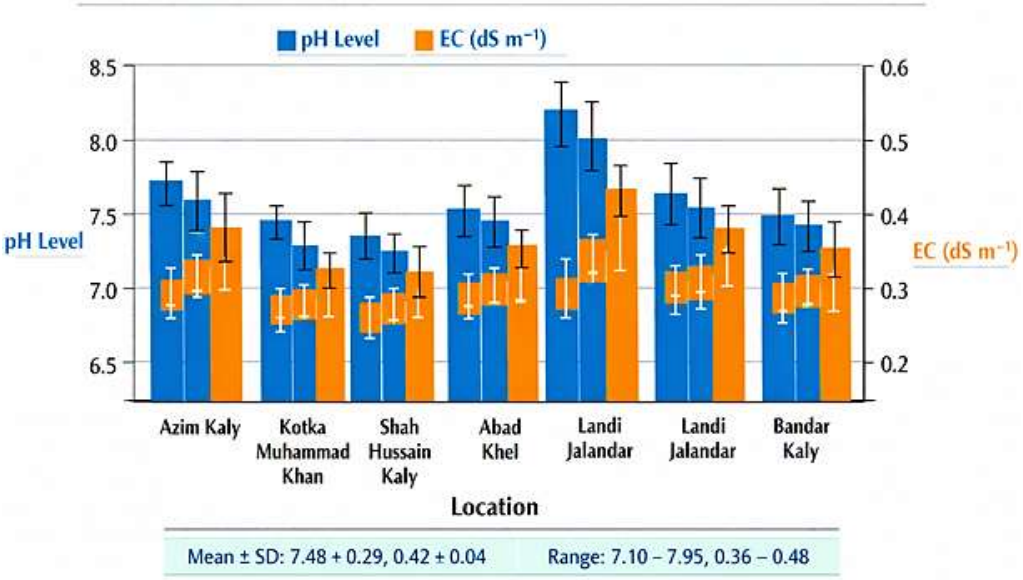

Figure 2: pH and Electrical Conductivity (EC) of Soil Samples from Tehsil Domail, District Bannu

Table 2. pH and Electrical Conductivity (EC) of Soil Samples from Tehsil Domail, District Bannu

Location	pH Level	EC (dS m⁻¹)
Azim Kaly	7.35	0.42
Azim Kaly	7.60	0.38
Kotka Muhammad Khan	7.10	0.46
Kotka Muhammad Khan	7.50	0.44
Shah Hussain Kaly	7.20	0.41
Shah Hussain Kaly	7.45	0.39
Abad Khel	7.95	0.36
Abad Khel	7.85	0.48
Landi Jalandar	7.55	0.40
Landi Jalandar	7.65	0.36
Bandar Kaly	7.25	0.48
Bandar Kaly	7.55	0.40
Mean ± SD	7.48 ± 0.29	0.42 ± 0.04
Range	7.10 – 7.95	0.36 – 0.48

Soil Texture, Bulk Density, and Particle Density

Soil texture varied across the study sites, with sandy loam, loam, and silt loam being the dominant textural classes (Figure 3: Table 3). Sandy loam was the most frequent texture (41.7% of samples), followed by loam (33.3%) and silt loam (25.0%). Bulk density ranged from 1.33 to 1.46 g cm^{-3}, with a mean of 1.41 ± 0.04 g cm^{-3}, which falls within the ideal range (<1.6 g cm^{-3}) for healthy root growth and aeration (Hussain and Ghafoor, 2019). Particle density values were consistent across all samples, ranging from 2.60 to 2.64 g cm^{-3} (mean 2.62 ± 0.01 g cm^{-3}), typical for

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mineral soils with low organic matter content.

The predominance of sandy loam, loam, and silt loam textures in Tehsil Domail reflects the alluvial and colluvial origin of soils in the Bannu basin. These textural classes are favorable for agricultural use as they provide adequate drainage, root penetration, and water-holding capacity (Khan et al., 2020). The prevalence of loamy textures is consistent with Durrani (2006), who reported silt loam texture with 66.72% silt at Serai Naurang, and with Sharif et al. (2004), who found predominantly silt loam in Charsadda orchards. However, Bhatti et al. (2007) reported more variable textures across KP, including clay loam and sandy clay loam, suggesting that Tehsil Domail has relatively uniform and favorable texture for cultivation.

Bulk density values ranging from 1.33 to 1.46 g cm^{-3} are within the optimal range (<1.6 g cm^{-3}) for plant root growth and microbial activity (Hussain and Ghafoor, 2019). These values are similar to those reported by Ilyas et al. (2022) for pine plantation soils in Mansehra and Peshawar, where bulk density ranged from 1.30 to 1.50 g cm^{-3}.

The low bulk density observed in silt loam samples (1.33–1.38 g cm^{-3}) reflects better aggregation and porosity compared to sandy loam samples (1.42–1.46 g cm^{-3}). Particle density values (2.60–2.64 g cm^{-3}) are typical for mineral soils and indicate that organic matter content is low enough not to significantly alter particle density (Bohn et al., 1985).

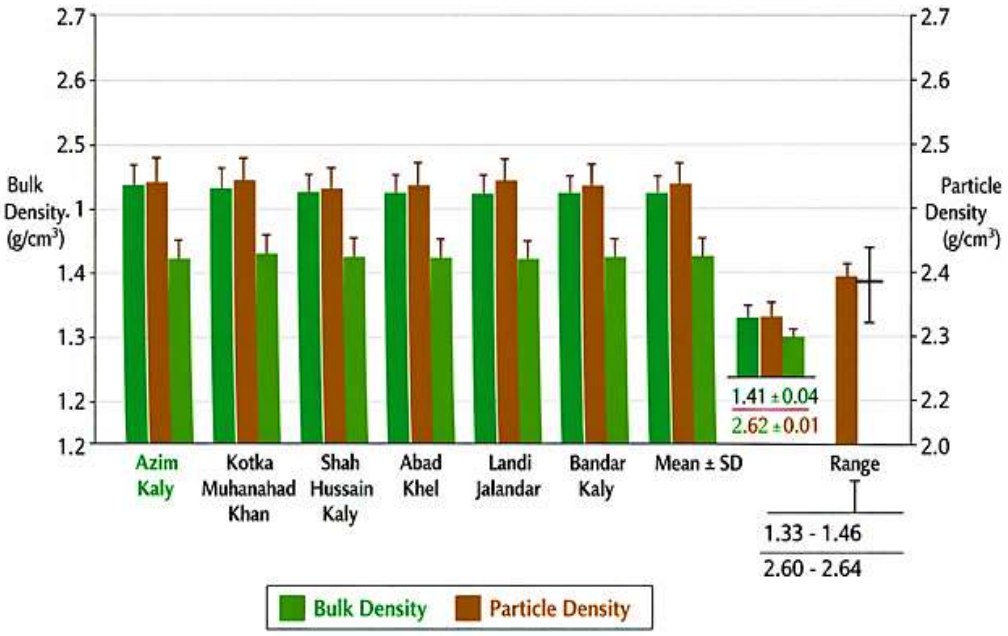

Figure 3: Soil Texture, Bulk Density, and Particle Density of Soil Samples from Tehsil

Table 3. Soil Texture, Bulk Density, and Particle Density of Soil Samples from Tehsil Domail

Location	Soil Texture	Bulk Density (g cm^{-3})	Particle Density (g cm^{-3})

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Azim Kaly	Sandy loam	1.43	2.63
Azim Kaly	Loam	1.37	2.61
Kotka Muhammad Khan	Sandy loam	1.46	2.60
Kotka Muhammad Khan	Loam	1.43	2.64
Shah Hussain Kaly	Silt loam	1.36	2.62
Shah Hussain Kaly	Sandy loam	1.42	2.61
Abad Khel	Loam	1.46	2.63
Abad Khel	Silt loam	1.33	2.61
Landi Jalandar	Sandy loam	1.42	2.60
Landi Jalandar	Loam	1.42	2.61
Bandar Kaly	Silt loam	1.38	2.64
Bandar Kaly	Sandy loam	1.42	2.60
Mean ± SD	—	1.41 ± 0.04	2.62 ± 0.01
Range	—	1.33 – 1.46	2.60 – 2.64

Organic Matter and Lime Content

Organic matter (OM) content ranged from 0.82% to 1.09%, with a mean value of 0.94 ± 0.09% (Figure 4: Table 4). According to fertility classification standards, 23% of the samples fell into the low OM category (<0.86%), while the remaining 77% were in the medium range (0.86–1.29%). No sample exhibited high organic matter (>1.30%). Lime content ranged from 5.2% to 6.3%, with a mean of 5.8 ± 0.44%, indicating that all soils were calcareous to strongly calcareous. The organic matter content of soils in Tehsil Domail (0.82–1.09%) falls within the low to medium range, a common characteristic of semi-arid dryland soils where high temperatures and low moisture limit biomass production and accelerate organic matter decomposition (Ahmed et al., 2021). These results are comparable to several regional studies. Bhatti et al. (2007) reported similarly low OM values across irrigated fields of KP, while Durrani (2006) found OM as low as 0.49% at Serai Naurang. Parveen et al. (2018) reported that 27–55% of soil samples in Peshawar's vegetable-growing areas were deficient in organic matter. The slightly higher OM values observed in Shah Hussain Kaly (1.08%) and Abad Khel (1.09%) may be attributed to localized inputs of farmyard manure or recent fallow periods (Rahman et al., 2024).

The low OM status has direct implications for soil fertility. Organic matter is a primary source of nitrogen, phosphorus, and sulfur, and it enhances cation exchange capacity, water retention, and soil structure (Smita and Sangita, 2015). Therefore, the majority of soils in Tehsil Domail would benefit from organic amendments such as farmyard manure, compost, or biochar. Rahman et al. (2024) demonstrated that biochar application significantly improved pH balance and increased nitrogen and phosphorus availability in maize fields of Peshawar, suggesting a viable rehabilitation strategy for calcareous, low-OM soils.

Lime content ranging from 5.2% to 6.3% classifies these soils as moderately to strongly calcareous. These values are comparable to those reported by Bhatti et al. (2007), who found lime content between 3% and 24% across KP, and by Fida et al. (2011), who reported 15–25% lime in Kohat guava orchards. Calcareous soils present both opportunities and challenges. On one hand, calcium carbonate helps buffer soil pH and provides calcium for plant nutrition. On the other hand, high lime content

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reduces the availability of phosphorus by forming insoluble calcium phosphates, and can also limit the availability of micronutrients such as iron, zinc, and manganese (Marchener, 1991).

Consequently, phosphorus fertilizers applied to these soils may have lower use efficiency unless banded or applied in combination with organic acids or biochar (Rahman et al., 2024).

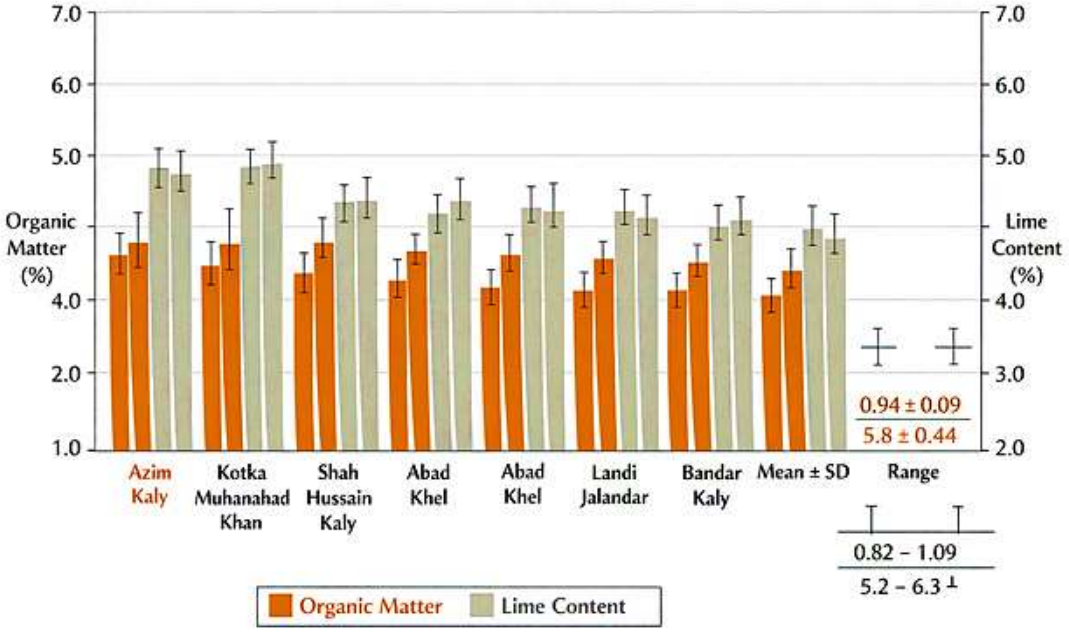

Figure 4: Organic Matter and Lime Content of Soil Samples from Tehsil Domail

Table 4. Organic Matter and Lime Content of Soil Samples from Tehsil Domail

Location	Organic Matter (%)	Lime Content (%)
Azim Kaly	0.83	5.3
Azim Kaly	0.94	6.2
Kotka Muhammad Khan	0.89	5.9
Kotka Muhammad Khan	0.93	6.2
Shah Hussain Kaly	1.08	5.2
Shah Hussain Kaly	0.87	5.9
Abad Khel	0.97	6.3
Abad Khel	1.09	5.5
Landi Jalandar	0.82	5.7
Landi Jalandar	0.97	6.2
Bandar Kaly	1.05	5.2
Bandar Kaly	0.85	5.3
Mean ± SD	0.94 ± 0.09	5.8 ± 0.44
Range	0.82 – 1.09	5.2 – 6.3

Implications for Sustainable Agriculture

The findings of this study have several practical implications for farmers and land managers in Tehsil Domail. First, the non-saline, neutral-to-alkaline pH, and

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favorable physical properties indicate that the soils are suitable for a wide range of field crops, including wheat, maize, and vegetables, provided that environmental conditions are favorable (Yaseen et al., 2024). Second, the low organic matter content necessitates the regular application of organic amendments to sustain long-term productivity. Third, the calcareous nature of these soils requires careful phosphorus management, including the use of phosphorus-solubilizing bacteria or organic amendments to enhance availability (Akhtar et al., 2010).

The spatial variability observed across villages underscores the importance of site-specific nutrient management rather than blanket fertilizer recommendations (Shah et al., 2012). As demonstrated by Salam et al. (2020) in Swat, GIS-based mapping of soil fertility indicators can greatly enhance precision agriculture in topographically complex regions like Tehsil Domail. Future research should expand the sample size, include macronutrient (N, P, K) and micronutrient (Zn, Cu, Fe, Mn) analysis, and employ geospatial techniques to develop detailed soil fertility maps for the entire district.

Conclusion

This study provides the first systematic assessment of physico-chemical properties of soils in Tehsil Domail, District Bannu. The soils are neutral to slightly alkaline (pH 7.10–7.95), non-saline (EC 0.36–0.48 dS m^{-1}), and have favorable physical characteristics, including sandy loam to loam textures and optimal bulk density (1.33–1.46 g cm^{-3}), making them suitable for most field crops. However, the study also reveals critical fertility constraints. Organic matter content is low to medium, ranging from 0.82% to 1.09%, with 23% of samples falling into the deficient category. This low organic matter status, typical of semi-arid dryland soils, limits nitrogen availability, reduces cation exchange capacity, and impairs soil structural stability (Ahmed et al., 2021). Additionally, the calcareous nature of these soils (lime content 5.2–6.3%) poses a challenge for phosphorus availability, as calcium phosphates form readily, reducing fertilizer use efficiency Additionally, calcareousness (lime content 5.2–6.3%) may reduce phosphorus availability. These limitations necessitate regular application of organic amendments such as farmyard manure or biochar, along with phosphorus-efficient fertilization strategies.

Despite these limitations, the overall fertility status of Tehsil Domail soils suggests moderate agricultural potential if appropriate management practices are adopted. The non-saline, well-structured, and neutral-to-alkaline soils provide a solid foundation for crop production. The primary management needs are the regular application of organic amendments (farmyard manure, compost, or biochar) to build soil organic matter, and the use of phosphorus-efficient fertilization strategies, such as band placement or co-application with organic acids or phosphorus-solubilizing microorganisms

The study has limitations, including small sample size (n=12) and the absence of macro- and micronutrient analysis. Future research should expand sampling, include complete nutrient profiling, and employ GIS-based mapping for precision agriculture.

In conclusion, the soils of Tehsil Domail possess adequate physical properties but require organic matter buildup and careful nutrient management to sustain long-term agricultural productivity in this semi-arid region.

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Conflicts of Interest

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