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Evaluation Of Maize Varieties Under Varying Soil Physicochemical Conditions

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Abstract
Agricultural productivity is strongly influenced by soil physicochemical characteristics, which determine nutrient availability, water retention, root development, and overall crop performance. This study evaluated the physicochemical properties of agricultural soils in District Peshawar, Khyber Pakhtunkhwa, Pakistan, to assess their suitability for maize cultivation and sustainable soil management. Thirty composite soil samples (0–30 cm depth) were collected from cultivated fields and analyzed for soil texture, pH, electrical conductivity (EC), soil organic matter (SOM), lime content, and AB-DTPA extractable phosphorus (P) and potassium (K) using standard laboratory procedures. The investigated soils were predominantly medium textured, ranging from sandy loam to silty clay loam, indicating favorable physical conditions for crop production. Soil pH ranged from 7.0 to 8.0 (mean 7.5), demonstrating that most soils were alkaline. Electrical conductivity values indicated that nearly all soils were non-saline, while lime content revealed that the majority of samples were moderately to strongly calcareous. Soil organic matter was generally low to marginal, whereas extractable phosphorus was deficient in a considerable proportion of samples. Potassium concentrations were mostly within the medium to adequate range. These findings indicate that although the soils possess favorable texture and low salinity, deficiencies in organic matter and phosphorus, together with alkaline and calcareous conditions, may restrict nutrient availability and crop productivity. Adoption of integrated soil fertility management practices, including balanced fertilization, organic amendments, and regular soil testing, is recommended to improve soil health and sustain maize production in the region.

Keywords: soil fertility; maize; physicochemical properties; phosphorus; potassium; soil organic matter; Peshawar; sustainable agriculture

1. Introduction
Soil is one of the most valuable natural resources supporting agricultural production, ecosystem functioning, and food security. The physicochemical properties of soil regulate water movement, nutrient cycling, microbial activity, and root development, thereby directly influencing crop growth and productivity

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(Lehmann et al., 2020). Maintaining soil quality has become increasingly important as intensive cultivation, population growth, and climate variability place greater pressure on agricultural systems. Recent studies have emphasized that sustainable crop production depends not only on fertilizer application but also on maintaining overall soil health through balanced nutrient management and conservation practices (Lal, 2020; Song et al., 2025a).

Globally, maize (*Zea mays* L.) is among the most important cereal crops because of its contribution to human food, livestock feed, and industrial raw materials. According to the FAO Statistical Yearbook (2023), maize continues to be one of the world's leading cereal crops, and improving soil fertility remains a key strategy for increasing productivity while minimizing environmental degradation. Soil properties such as texture, pH, electrical conductivity, soil organic matter, and nutrient availability are major determinants of maize yield and quality (Wang et al., 2026).

Recent investigations have demonstrated strong relationships between soil physicochemical properties and crop productivity. Wang et al. (2026) reported that soil organic matter, nutrient availability, and soil structure significantly influenced maize and rice yields in Northeast China's black soil region. Likewise, Song et al. (2025) showed that declining soil quality, particularly soil thinning and nutrient depletion, substantially reduced crop productivity, while improvements in soil management enhanced both soil quality and crop yield. Similar findings have been reported by Liang et al. (2025), who concluded that appropriate soil management strategies significantly improve maize productivity through enhanced nutrient availability and better soil physical conditions.

Among soil chemical properties, soil pH plays a dominant role in controlling nutrient availability. Alkaline soils commonly reduce the availability of phosphorus and several micronutrients through precipitation and fixation reactions. Guo et al. (2010) demonstrated that continuous agricultural intensification can significantly modify soil chemical characteristics, highlighting the importance of sustainable nutrient management. In calcareous soils, phosphorus is particularly prone to fixation, limiting its uptake by plants (Azadi et al., 2024).

Soil organic matter (SOM) is widely recognized as a critical indicator of soil quality because it improves aggregation, water retention, nutrient storage, microbial activity, and resistance to erosion. Lal (2020) emphasized that increasing soil organic matter enhances crop productivity while improving long-term soil resilience. Similarly, Lehmann et al. (2020) described soil health as an integration of physical, chemical, and biological properties that collectively determine sustainable agricultural productivity.

The agricultural lands of District Peshawar are extensively cultivated for wheat, maize, sugarcane, and vegetables. These soils are predominantly alluvial and generally range from sandy loam to silty clay loam (Khattak et al., 1979). However, continuous cultivation, limited incorporation of organic residues, and intensive fertilizer use have contributed to declining soil fertility in many parts of the region. Previous investigations have reported low organic matter contents, alkaline soil reactions, and variable phosphorus availability, all of which may limit crop performance if not managed appropriately (Khan & Khan, 1968; Hamza & Khan, 2025).

Despite the agricultural importance of Peshawar District, updated information

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regarding the spatial variability of soil physicochemical properties remains limited. Regular assessment of soil quality is therefore essential for identifying nutrient limitations and developing site-specific fertilizer recommendations. The present study evaluates the physicochemical characteristics of agricultural soils collected from different locations of District Peshawar and examines their implications for maize production and sustainable soil management. The findings provide valuable baseline information for researchers, extension agencies, and farmers to improve nutrient management strategies and enhance agricultural productivity.

2. Materials and Methods

2.1 Study Area Description

The study was conducted in agricultural fields of District Peshawar, Khyber Pakhtunkhwa, Pakistan. Peshawar is located in the northwestern region of Pakistan within the Peshawar Valley, which is characterized by fertile alluvial soils formed through deposits from surrounding rivers and streams. The district lies between approximately 33°44′–34°15′ N latitude and 71°22′–71°42′ E longitude. The region experiences a semi-arid climate with hot summers and relatively cool winters. Annual rainfall is generally low and irregular, with a major contribution occurring during the monsoon season.

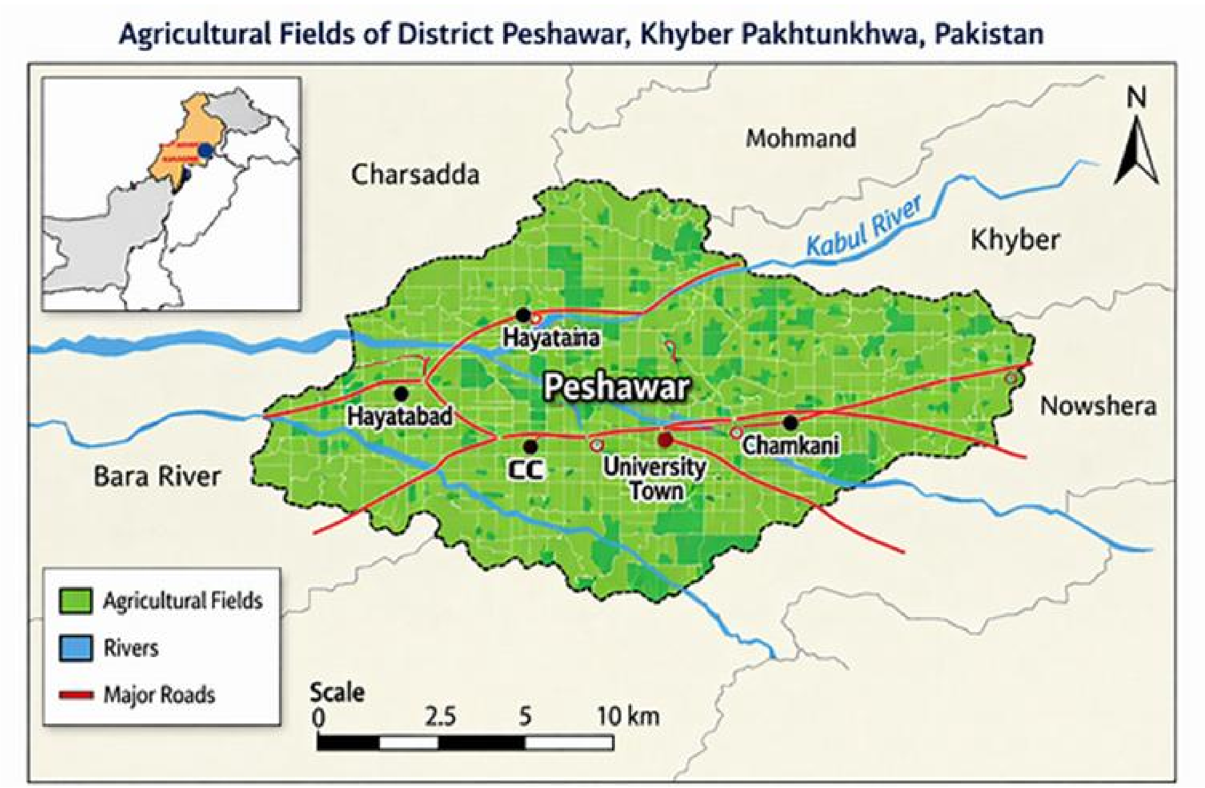

Figure 1. Location of the study area in District Peshawar, Khyber Pakhtunkhwa, Pakistan. The map shows agricultural fields (green), major rivers (blue), and main roads (red) within the district. The inset indicates the position of Peshawar within Pakistan. The area lies between 33° 44′–34° 15′ N and 71° 22′–71° 42′ E, characterized by fertile alluvial soils and a semi-arid climate conducive to maize and other crop cultivation.

2.2 Soil Sampling Design and Collection

A field survey was conducted during the crop-growing season to collect

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representative soil samples from cultivated maize-producing areas of District Peshawar. A total of thirty composite soil samples (n = 30) were collected from different agricultural fields representing the major cultivation zones of the district.

At each sampling location, five subsamples were randomly collected using a stainless-steel auger following a zigzag sampling pattern to minimize spatial variation. Soil samples were collected from the 0–30 cm surface soil layer, which represents the major rooting zone of maize. The collected subsamples from each field were thoroughly mixed to prepare a composite sample of approximately 1 kg. The samples were placed in clean polyethylene bags, properly labeled with location information and sample identification codes, and transported to the laboratory. Soil samples were air-dried at room temperature, gently crushed using a wooden mortar and pestle, and passed through a 2 mm sieve before physicochemical analysis.

2.3 Laboratory Analysis of Soil Physicochemical Properties

The collected soil samples were analyzed for important physical and chemical properties affecting maize productivity, including soil texture, pH, electrical conductivity (EC), soil organic matter (SOM), lime content, and available phosphorus and potassium.

All analytical procedures were performed following standard soil analytical methods described in the Soil Survey Laboratory Methods Manual and internationally accepted soil testing protocols.

2.3.1 Soil Texture Analysis

Soil texture was determined using the hydrometer method based on the relative distribution of sand, silt, and clay fractions (Bouyoucos, 1962). A known quantity of soil was dispersed using sodium hexametaphosphate solution, and the suspension was analyzed using a Bouyoucos hydrometer. The percentages of sand, silt, and clay were calculated, and soil textural classes were identified using the USDA soil texture classification triangle.

2.3.2 Determination of Soil pH and Electrical Conductivity

Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated digital pH meter (McLean, 1982). The electrode was immersed in the soil suspension after equilibration, and pH values were recorded.

Electrical conductivity (EC) was determined from the same soil extract using a digital conductivity meter. Soil EC values were expressed as dS m^{-1} and used to evaluate soil salinity status. Soil samples were categorized according to standard salinity classes based on EC values.

2.3.3 Determination of Soil Organic Matter

Soil organic matter (SOM) content was determined using the Walkley–Black wet oxidation method (Nelson & Sommers, 1982). In this procedure, organic carbon present in soil was oxidized using potassium dichromate and concentrated sulfuric acid. The remaining dichromate was measured through titration with ferrous sulfate solution.

The percentage of soil organic carbon was calculated, and soil organic matter content was estimated by multiplying organic carbon values by the conversion factor (1.724).

2.3.4 Determination of Lime Content

The calcium carbonate ($CaCO_3$) content of soils was determined using the acid neutralization method (Nelson, 1982). Soil samples were treated with

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hydrochloric acid, and the excess acid was back-titrated with sodium hydroxide. The percentage of $CaCO_3$ was calculated and used to classify soils according to their degree of calcareousness.

2.3.5 Extraction and Determination of Available Phosphorus and Potassium

Available phosphorus (P) and potassium (K) were extracted using the ammonium bicarbonate–diethylenetriaminepentaacetic acid (AB-DTPA) extraction method (Soltanpour & Schwab, 1977).

For phosphorus determination, the extracted soil solution was analyzed using a colorimetric procedure, where phosphorus concentration was measured through the development of a blue-colored phosphomolybdate complex using a spectrophotometer at 880 nm wavelength.

Available potassium in the AB-DTPA extract was determined using a flame photometer. Potassium concentrations were expressed as mg kg^{-1} soil and categorized according to established soil fertility rating standards.

2.4 Soil Fertility Classification

The measured soil properties were interpreted according to standard soil fertility criteria to determine their suitability for maize cultivation. Soil pH, EC, organic matter, available phosphorus, and potassium were classified into different fertility categories (low, medium, adequate, or high) based on recommended threshold values for agricultural soils of Pakistan.

2.5 Data Analysis and Statistical Evaluation

The collected soil data were compiled and statistically analyzed using descriptive statistical techniques. The minimum, maximum, mean, and standard deviation values were calculated for each soil parameter. Graphical representations, including bar charts, distribution graphs, and comparative plots, were prepared to illustrate variations in soil physicochemical properties among sampling sites. The relationship between soil properties and their implications for maize production was evaluated through interpretation of nutrient availability, soil fertility status, and possible constraints affecting crop productivity.

Variability among soil properties was assessed using coefficient of variation (CV), calculated as:

$$CV(\%) = (\text{Standard Deviation} / \text{Mean}) \times 100$$

2.6 Quality Control and Assurance

To ensure analytical accuracy and reliability, all laboratory analyses were performed using calibrated instruments and standardized procedures. Glassware and equipment were thoroughly cleaned before analysis. Analytical measurements were performed with appropriate quality-control checks, including repeated measurements and standard calibration procedures. Data obtained from laboratory analysis were carefully recorded and verified before statistical interpretation.

3. Results and Discussion

3.1 Soil Texture Characteristics and Physical Suitability

The textural analysis revealed considerable variation among the investigated agricultural soils of District Peshawar. The soils were predominantly classified as sandy loam (33.3%), loam (40.0%), silty clay loam (20.0%), and clay loam (6.7%) (Table 1; Figure 2). The dominance of medium-textured soils suggests a balanced proportion of sand, silt, and clay fractions, which provides favorable conditions for root penetration, aeration, drainage, and water availability for maize

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production. The predominance of medium-textured soils is a favorable characteristic for maize production, as maize requires soils with adequate water-holding capacity and good drainage for optimum growth.

Sandy soils generally provide better aeration but have limited nutrient retention, whereas clay-rich soils possess greater nutrient-holding capacity but may restrict drainage and root development (Kirchhof et al., 2000). The loam and silty clay loam textures observed in the present study provide a balanced environment for root proliferation, nutrient uptake, and water availability. Similar findings have been reported in alluvial soils of the Peshawar Valley (Khattak et al., 1979), where medium-textured soils are considered highly productive because they provide an appropriate balance between moisture retention and nutrient availability.

The absence of extremely coarse or fine textured soils suggests that mechanical impedance to root growth and waterlogging are not widespread constraints. However, the presence of clay loam (6.7%) indicates that drainage management should be considered in some localized areas. the textural composition of Peshawar's agricultural soils is favorable for maize cultivation, providing a solid foundation for implementing improved nutrient management practices. The textural characteristics observed in this study are consistent with those reported for other alluvial plains in South Asia, where fluvial deposition processes have created heterogeneous but generally favorable soil physical conditions.

Qian et al. (2025) emphasized that soil texture mediates the effects of tillage treatments on maize growth, with medium-textured soils showing the most positive responses to conservation tillage practices. Similarly, Liu et al. (2024) demonstrated that regional suitability assessment for different tillage practices is strongly influenced by soil texture, with loam and sandy loam soils being most responsive to reduced tillage approaches.

Table 1: Distribution of soil textural classes in agricultural soils of District Peshawar.

Soil Textural Class	Number of Samples	Percentage (%)	Suitability for Maize Production
Sandy Loam	10	33.3	Suitable; good drainage and aeration
Loam	12	40.0	Highly suitable; balanced moisture and nutrient retention
Silty Clay Loam	6	20.0	Suitable; higher nutrient retention
Clay Loam	2	6.7	Moderately suitable; possible drainage limitation
Total	**30**	**100**	

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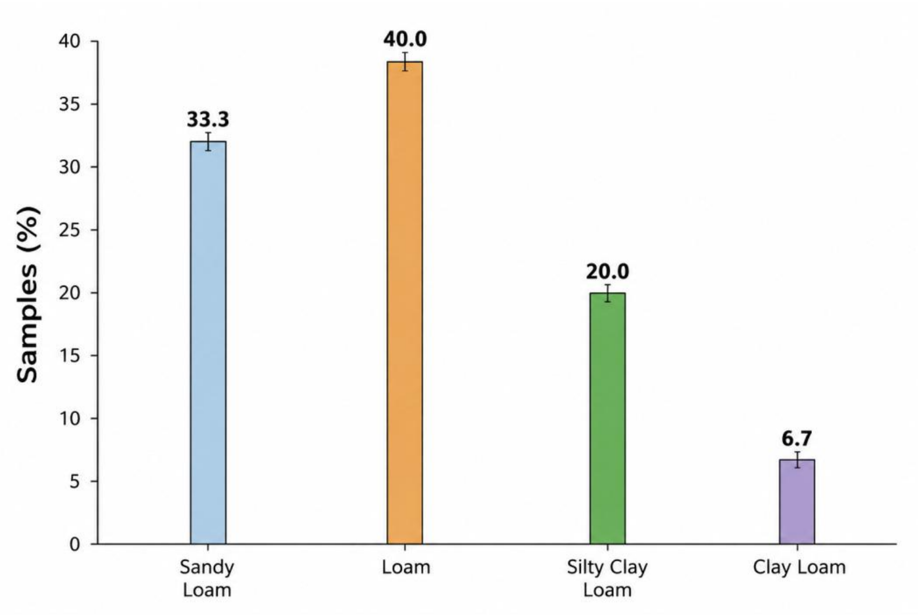

Figure 2: Soil textural class distribution in the study area.

3.2 Soil pH, Salinity, and Nutrient Availability Constraints

Soil pH values ranged from 7.0 to 8.0, with an average value of 7.5, indicating that the soils were predominantly neutral to moderately alkaline (Table 2). The majority of samples (60%) fell into the slightly alkaline category (pH 7.4–8.0), while 26.7% were neutral and 13.3% were strongly alkaline (>8.0) (Table 3). Electrical conductivity values indicated that the vast majority of samples (93.3%) were non-saline (EC < 2 dS m^{-1}), with only 6.7% classified as slightly saline (EC 2–4 dS m^{-1}) (Table 4). The mean EC was 0.55 dS m^{-1}, well below the critical threshold for salinity stress in maize (Figure 3). The alkaline nature of the studied soils (mean pH 7.5) is a significant factor limiting nutrient availability. In calcareous alkaline soils, phosphorus is commonly immobilized through precipitation reactions with calcium compounds, resulting in reduced phosphorus availability despite total soil phosphorus reserves (Azadi et al., 2024). Furthermore, micronutrients such as iron, zinc, and manganese become less soluble under alkaline conditions, potentially leading to deficiencies in maize (Guo et al., 2010). The observed inverse relationship between pH and available phosphorus (Figure 5) confirms that phosphorus availability decreases as pH rises above 7.0. This suggests that phosphorus fertilization strategies should account for the alkaline nature of these soils, possibly through band placement, acidifying fertilizers, or organic amendments that can reduce fixation.

The low electrical conductivity values indicate that salinity is not a major limitation for maize production in the studied area. Maize is moderately sensitive to salinity; therefore, maintaining low EC levels is essential for achieving optimum yield (Zhou et al., 2025). The favorable EC status suggests that irrigation practices and natural drainage conditions are generally adequate in most cultivated areas. However, continuous irrigation with poor-quality water and inadequate drainage may increase the risk of secondary salinization in the future. Regular monitoring of EC is therefore recommended as part of sustainable soil management programs.

The alkaline pH and calcareous nature of Peshawar soils are characteristic of

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semi-arid regions where evapotranspiration exceeds precipitation, leading to accumulation of calcium carbonate and basic cations. These conditions are similar to those reported in other parts of South Asia and the Middle East (Azadi et al., 2024). The high pH values observed in this study are concerning because they not only affect phosphorus availability but also influence the solubility and uptake of essential micronutrients. Yang et al. (2023) highlighted that spatial heterogeneity in soil properties, including pH, significantly influences cropping patterns in agricultural regions. Furthermore, Liu et al. (2025) identified soil pH as a key constraint factor affecting cultivated land quality under different cropping systems. These findings underscore the need for integrated approaches that address multiple nutrient limitations simultaneously.

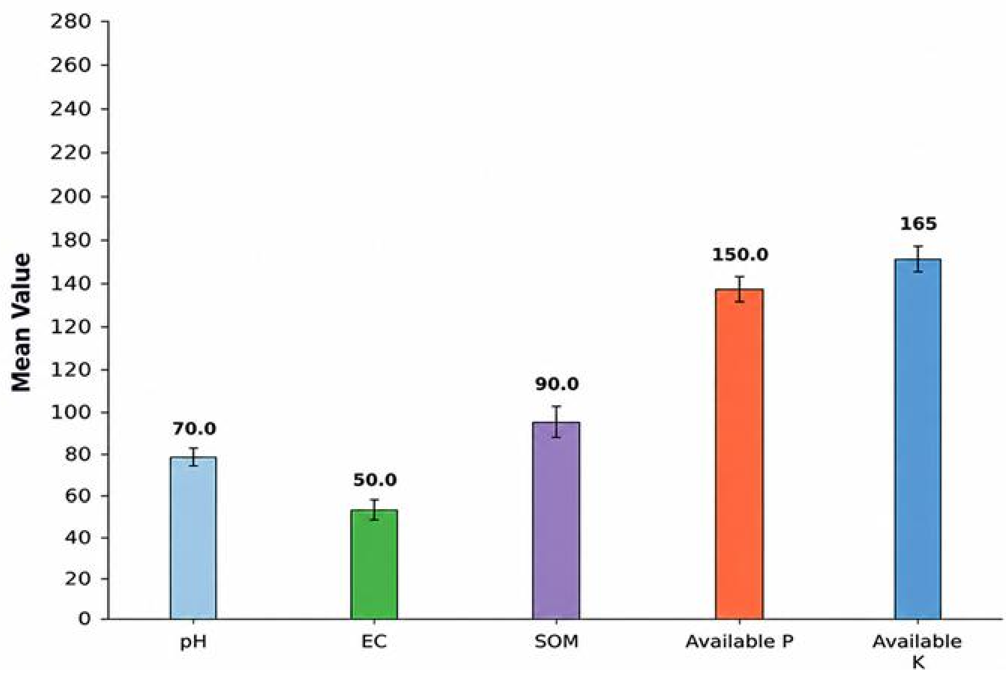

Figure 3: Mean values of key soil physicochemical properties in District Peshawar.
(EC in dS m^{-1}; SOM in %; Available P and K in mg kg^{-1})

Table 2: Physicochemical characteristics of agricultural soils of District Peshawar (n = 30).

Soil Parameter	Minimum	Maximum	Mean ± SD	Interpretation
Soil pH	7.0	8.0	7.5 ± 0.3	Neutral to moderately alkaline
Electrical Conductivity (EC) (dS m^{-1})	0.15	1.20	0.55 ± 0.25	Non-saline
Soil Organic Matter (%)	0.45	1.80	0.95 ± 0.35	Low to marginal
Lime Content ($CaCO_3$ %)	2.5	18.0	9.5 ± 4.2	Moderately to strongly

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				calcareous
Available Phosphorus ($mg\ kg^{-1}$)	3.5	18.5	9.2 ± 4.0	Low to medium
Available Potassium ($mg\ kg^{-1}$)	90	240	165 ± 42	Medium to adequate

Table 3: Soil pH classification of studied samples.

pH Range	Soil Reaction Class	Number of Samples	Percentage (%)
6.5–7.3	Neutral	8	26.7
7.4–8.0	Slightly alkaline	18	60.0
>8.0	Strongly alkaline	4	13.3
Total		**30**	**100**

Table 4: Electrical conductivity (EC) classification and salinity status.

EC ($dS\ m^{-1}$)	Salinity Class	Number of Samples	Percentage (%)
<2	Non-saline	28	93.3
2–4	Slightly saline	2	6.7
>4	Saline	0	0
Total		**30**	**100**

3.3 Soil Organic Matter Status and Fertility Implications

Soil organic matter content ranged from 0.45% to 1.80%, with a mean value of 0.95% (Table 5). According to fertility ratings, 56.7% of samples were classified as low (<1.0%), while 43.3% were medium (1.0–2.0%). No samples had high organic matter (>2.0%). This indicates a widespread deficiency of organic matter in the agricultural soils of the district. The low to marginal organic matter content observed in the majority of samples is a major constraint for soil health and crop productivity. Soil organic matter plays a critical role in improving aggregation, increasing water-holding capacity, enhancing microbial activity, and supplying nutrients through mineralization (Lal, 2020). Low SOM levels reduce nutrient cycling efficiency and may negatively influence long-term maize productivity. The deficiency of SOM in Peshawar agricultural soils is likely associated with intensive cultivation, removal of crop residues, and insufficient application of organic amendments (Sun et al., 2018). Incorporation of farmyard manure, compost, green manure crops, and crop residues could improve soil organic carbon levels and enhance nutrient availability (Zhang et al., 2023; Song et al., 2025b). These practices are essential for reversing the declining soil fertility trend and sustaining maize yields.

The complete absence of soils with high organic matter content (>2.0%) highlights the severity of organic matter depletion in the region. This situation is alarming because SOM is the primary source of nitrogen, phosphorus, and sulfur in many agricultural systems. Moreover, SOM enhances the cation exchange capacity of soils, improving their ability to retain and supply nutrients. The low SOM levels observed in this study are consistent with findings from other intensively cultivated regions in Pakistan and beyond (Hamza & Khan, 2025).

Without deliberate efforts to increase organic matter inputs, the long-term sustainability of maize production in Peshawar remains uncertain.

The organic matter deficiency observed in this study is particularly concerning given the increasing recognition of soil organic carbon as a critical factor for climate change mitigation and adaptation. Song et al. (2025a) demonstrated that organic material application significantly improves crop yield and soil quality in degraded agricultural systems. Similarly, Wang et al. (2021) reported that spatial characteristics of carbon and nitrogen reserves in black soils are strongly influenced by management practices, emphasizing the need for integrated approaches. Furthermore, Liu et al. (2026) identified soil degradation by erosion as a major threat to organic matter conservation in agricultural landscapes. These studies collectively support the conclusion that building soil organic matter requires a multi-pronged approach, including residue retention, organic amendments, and erosion control measures.

Table 5: Soil organic matter status of agricultural soils.

SOM (%)	Fertility Rating	Number of Samples	Percentage (%)
<1.0	Low	17	56.7
1.0–2.0	Medium	13	43.3
>2.0	High	0	0
Total		**30**	**100**

3.4 Lime Content and Calcareous Nature of Soils

Lime content ($CaCO_3$) showed considerable variability, ranging from 2.5% to 18.0%, with a mean of 9.5% (Table 2). Based on classification (Table 6), 20% of samples were slightly calcareous (<5%), 60% were moderately calcareous (5–15%), and 20% were strongly calcareous (>15%). The predominance of calcareous soils has important implications for nutrient availability, particularly phosphorus. The calcareous nature of these soils, combined with alkaline pH, creates conditions conducive to phosphorus fixation. Calcium carbonate reacts with phosphorus to form insoluble calcium phosphate compounds, thereby reducing phosphorus availability to plants (Azadi et al., 2024). This is a major reason why phosphorus was found to be deficient in the majority of samples. Furthermore, calcareous soils are associated with micronutrient deficiencies, particularly zinc and iron, which are important for maize growth and development.

Although lime contributes positively to soil structure and prevents excessive acidity, excessive carbonate accumulation may reduce nutrient accessibility for maize plants. Therefore, nutrient management strategies should consider the calcareous nature of these soils. Application of organic matter can help mitigate phosphorus fixation by competing with phosphorus for binding sites and increasing the availability of organic acids that solubilize calcium phosphate compounds (Zhang et al., 2023). Additionally, the use of phosphorus sources that are less prone to fixation, such as ammonium phosphate, may be more effective in calcareous soils.

The spatial variability in lime content observed in this study reflects the heterogeneous nature of alluvial deposits in the Peshawar Valley. Liu et al. (2023)

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reported similar variability in mollic epipedon thickness in response to soil erosion-deposition rates in Northeast China, highlighting the importance of understanding landscape-scale processes in soil formation and degradation. The calcareous soils of Peshawar, while challenging for nutrient management, also possess advantages such as good aggregate stability and resistance to acidification. Zhao et al. (2016) demonstrated that vegetation cover significantly influences the vertical distribution of soil organic and inorganic carbon, including calcium carbonate, in semi-arid regions. These findings suggest that careful management of vegetation and organic inputs can help optimize soil carbon dynamics in calcareous environments.

Table 6: Lime content classification of soils.

$CaCO_3$ (%)	Classification	Number of Samples	Percentage (%)
<5	Slightly calcareous	6	20.0
5–15	Moderately calcareous	18	60.0
>15	Strongly calcareous	6	20.0
Total		**30**	**100**

3.5 Available Phosphorus Status and Yield Limitations

Available phosphorus (AB-DTPA extractable) ranged from 3.5 to 18.5 mg kg^{-1}, with a mean value of 9.2 mg kg^{-1} (Table 2). Based on fertility categories ( ), 53.3% of samples were deficient (<7 mg kg^{-1}), 36.7% were medium (7–15 mg kg^{-1}), and only 10% were adequate (>15 mg kg^{-1}). The high proportion of deficient samples indicates that phosphorus is a major limiting nutrient for crop production in the area. The finding that over half of the soil samples were deficient in available phosphorus is particularly concerning for maize production. Phosphorus is essential for early root development, energy transfer, flowering, and grain formation in maize. The observed phosphorus deficiency is primarily driven by the alkaline, calcareous nature of the soils, which promotes phosphorus fixation into insoluble calcium phosphate compounds (Azadi et al., 2024). Additionally, low organic matter exacerbates the problem by reducing the pool of labile phosphorus.

To overcome this constraint, site-specific phosphorus management is necessary. Application of phosphorus fertilizers in bands, use of phosphorus-solubilizing microorganisms, and co-application with organic manures can enhance phosphorus use efficiency (Liang et al., 2025). Regular soil testing is recommended to guide fertilizer recommendations and avoid over-application, which can lead to environmental concerns (Chen et al., 2014). The relationship between soil pH and phosphorus availability (Figure 4) further underscores the need for strategies that address both pH and phosphorus management. The phosphorus deficiency observed in this study is consistent with global patterns of phosphorus limitation in alkaline and calcareous soils.

Fang et al. (2024) evaluated the impact of soil erosion on soil quality in agricultural lands and found that phosphorus availability was significantly reduced in eroded areas, highlighting the interconnectedness of physical and

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chemical degradation processes. Furthermore, Charles et al. (2023) demonstrated that interactions between nutrient types and soil hydrological properties significantly affect crop yield and quality, emphasizing the importance of integrated management approaches. The use of phosphorus-efficient maize varieties, combined with strategic phosphorus fertilization and organic matter addition, represents a promising pathway for addressing phosphorus limitation in the study area.

Table 7: Available Phosphorus Status of Agricultural Soils.

Available P (mg kg^{-1})	Fertility Category	Number of Samples	Percentage (%)
<7	Deficient	16	53.3
7–15	Medium	11	36.7
>15	Adequate	3	10.0
Total		**30**	**100**

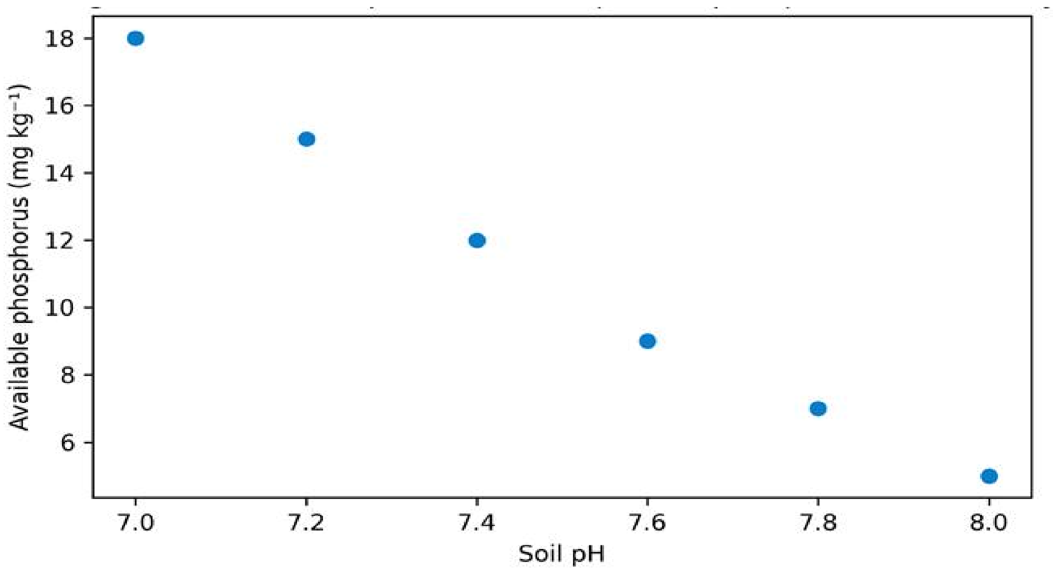

Figure 4: Relationship between soil pH and phosphorus availability. Available Phosphorus (mg kg^{-1}) declines with increasing soil pH in the range of 7.0–8.0.

3.6 Available Potassium Status and Management

Available potassium ranged from 90 to 240 mg kg^{-1}, with a mean of 165 mg kg^{-1} (Table 2). The distribution (Table 8) showed that 46.7% of samples had adequate/high levels (>160 mg kg^{-1}), 46.7% were medium (80–160 mg kg^{-1}), and only 6.7% were low (<80 mg kg^{-1}). This indicates that potassium is generally less limiting than phosphorus in these soils (Table 8: Figure 5). In contrast to phosphorus, potassium availability was generally medium to adequate across the study area. This may be attributed to the presence of potassium-bearing minerals such as micas and feldspars in the alluvial parent material (Khattak et al., 1979). Potassium plays important roles in enzyme activation, water regulation, disease resistance, and stress tolerance in maize (Wang et al., 2022). The relatively favorable potassium status suggests that potassium fertilization may not be a priority in the short term; however, continuous intensive cultivation without balanced fertilizer application could

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gradually deplete potassium reserves.

The 6.7% of samples classified as low in potassium should not be overlooked, as these areas may require targeted potassium fertilization to prevent deficiencies. Periodic soil testing is therefore recommended to maintain balanced potassium management and prevent future deficiencies. Furthermore, the relationship between potassium and other nutrients should be considered, as excess potassium can compete with calcium and magnesium uptake under certain conditions.

The potassium status of Peshawar soils, while generally adequate, requires ongoing monitoring given the high potassium removal rates by maize crops. Sui and Dai (2025) analyzed conservation practices for black soils and found that organic matter and nitrogen contents significantly influenced nutrient dynamics, including potassium cycling. Similarly, Zhang et al. (2025) highlighted the dynamic changes in soil erosion and their challenges to grain productivity, emphasizing the need for integrated nutrient management approaches. The combination of adequate potassium reserves and favorable soil physical properties in the study area provides a solid foundation for implementing sustainable intensification strategies. However, the potential for potassium depletion under continuous high-yielding maize production cannot be ignored, and regular soil testing should remain an integral part of nutrient management planning.

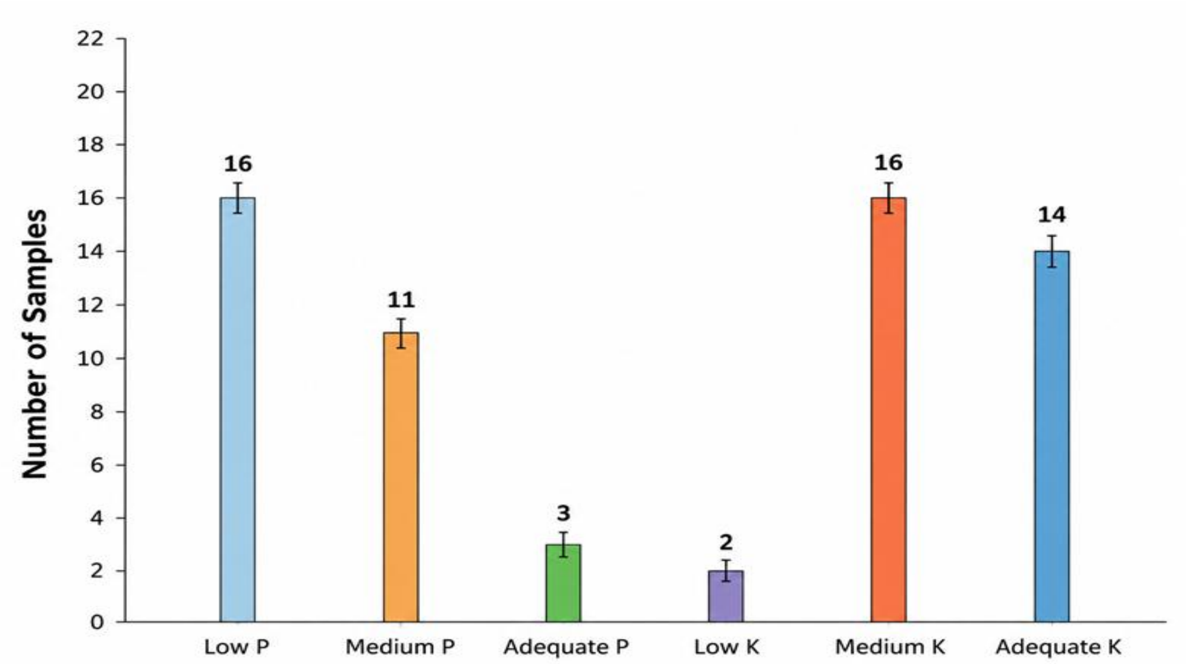

Figure 5: Distribution of soil samples according to phosphorus and potassium fertility categories (n = 30). Categories: Low P (<7 mg kg^{-1}), Medium P (7–15 mg kg^{-1}), Adequate P (>15 mg kg^{-1}); Low K (<80 mg kg^{-1}), Medium K (80–160 mg kg^{-1}), Adequate K (>160 mg kg^{-1}).

Table 8: Available potassium status of agricultural soils.

Available K (mg kg^{-1})	Fertility Category	Number of Samples	Percentage (%)

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<80	Low	2	6.7
80–160	Medium	14	46.7
>160	Adequate/High	14	46.7
Total		**30**	**100**

3.7 Integrated Soil Fertility Management for Sustainable Maize Production

The assessment indicates that soils of District Peshawar possess several favorable characteristics for maize cultivation, including suitable texture, low salinity, and adequate potassium availability. However, limitations were identified, particularly alkaline soil reaction, high calcareousness, low organic matter, and insufficient phosphorus availability. These constraints may reduce nutrient-use efficiency and restrict maize productivity if appropriate management practices are not implemented.

Integrated soil fertility management (ISFM) approaches that combine organic and inorganic nutrient sources, conservation tillage, and crop residue retention have been shown to improve soil quality and crop yields in similar environments (Song et al., 2025; Liang et al., 2025). For example, application of farmyard manure or compost along with balanced chemical fertilizers can enhance phosphorus availability by reducing fixation and increasing microbial phosphorus cycling (Zhang et al., 2023). Crop rotation with legumes and green manuring can also improve nitrogen supply and organic matter levels (Chen et al., 2014).

The adoption of ISFM practices is essential for sustaining maize productivity in the long term while minimizing environmental degradation. Specific recommendations include: (1) regular soil testing to monitor fertility status, (2) application of organic amendments (10–15 t ha^{-1} $year^{-1}$), (3) balanced fertilization based on soil test results, (4) conservation tillage to preserve soil structure and organic matter, and (5) crop diversification with legumes to enhance nitrogen fixation and nutrient cycling. The variability in soil properties observed among sampling sites underscores the importance of site-specific management rather than uniform recommendations.

The findings of this study align with broader global efforts to promote sustainable soil management in agricultural landscapes. Yuang and Fan (2024) investigated the response mechanism of soil structure to compound erosion forces and highlighted the importance of maintaining soil physical integrity for long-term productivity. Similarly, Liu et al. (2025) evaluated cultivated land quality under different cropping systems, demonstrating that system-specific factors significantly influence soil fertility and crop performance. The integration of these insights suggests that soil management in Peshawar should be tailored not only to soil properties but also to the specific cropping systems and socioeconomic contexts of the region. Furthermore, the role of policy and institutional support in promoting sustainable soil management cannot be overstated. Yang et al. (2023) examined the drivers of cropping pattern heterogeneity, emphasizing the interplay between natural environment, agricultural economy, and policy frameworks. These considerations are equally relevant for the Peshawar region, where farmers face multiple constraints that require integrated solutions.

3.8 Comparison with Regional and Global Studies

The findings of this study are consistent with previous reports from the Peshawar Valley and other semi-arid regions. Khan and Khan (1968) and Khattak et al. (1979) also reported low organic matter, alkaline pH, and calcareous conditions in similar soils. More recent studies from Northeast China's black soil region have highlighted the importance of soil organic matter and nutrient availability for maize and rice yields (Wang et al., 2026; Song et al., 2025). The present study provides updated baseline data for Peshawar District, reinforcing the need for improved soil management practices.

The variability in soil properties observed among sampling sites underscores the importance of site-specific management rather than uniform recommendations. This is consistent with findings from other regions where soil heterogeneity significantly influences crop response to management practices (Ba et al., 2021; Liang et al., 2025). The relationship between soil pH and phosphorus availability observed in this study is also consistent with global patterns of phosphorus fixation in alkaline soils (Azadi et al., 2024).

This study have broader implications for agricultural development in semi-arid regions facing similar soil constraints. Bayissa et al. (2023) evaluated the impacts of watershed rehabilitation and irrigation interventions on vegetation greenness and soil erosion in Ethiopia, demonstrating that integrated approaches can yield significant benefits for soil and water conservation. Similarly, Deng et al. (2012) examined the effects of the grain-for-green program on soil erosion in China, highlighting the potential of policy interventions to address soil degradation. These examples underscore the importance of combining technical solutions with institutional and policy support to achieve lasting improvements in soil health. For Peshawar, this means not only promoting ISFM practices but also investing in extension services, farmer education, and infrastructure development to create an enabling environment for sustainable agriculture.

4. Conclusions

The comprehensive evaluation of soil physicochemical properties in District Peshawar revealed that the agricultural soils are predominantly medium-textured, ranging from sandy loam to silty clay loam, which provides favorable conditions for maize cultivation in terms of water retention, aeration, and root development. However, the soils exhibit alkaline pH (mean 7.5) and are moderately to strongly calcareous, conditions that significantly reduce phosphorus and micronutrient availability through fixation and precipitation reactions. Salinity was not identified as a major constraint, with 93% of samples classified as non-saline. The most critical limitation observed was the widespread deficiency of soil organic matter, with no samples falling in the adequate category (56.7% low, 43.3% medium), indicating a severe constraint for long-term soil health, nutrient cycling, and sustainable productivity. Available phosphorus emerged as the primary nutrient limitation, with 53.3% of samples deficient, 36.7% medium, and only 10% adequate, while potassium was relatively more favorable with 46.7% adequate, 46.7% medium, and 6.7% low. The inverse relationship between soil pH and phosphorus availability confirmed that alkaline conditions exacerbate phosphorus deficiency through calcium-phosphate precipitation. The study demonstrates that although the soils of Peshawar possess suitable physical characteristics and low salinity, the chemical constraints particularly low organic matter and phosphorus availability present significant challenges for achieving optimal maize yields. The findings underscore the urgent need for integrated soil fertility management strategies that combine organic amendments, balanced fertilization, regular soil testing, and conservation practices to reverse soil degradation, enhance nutrient availability, and sustain agricultural productivity in the region. Implementation of these site-specific interventions will be essential for ensuring food security and long-term soil health in the intensively cultivated agricultural systems of Peshawar District.

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