Reviewing depth-wise nutrients status in Punjab

Abstract

Punjab, which is well-known for its agricultural output, has significant difficulties in preserving soil fertility in the face of intensive farming methods. The depth-wise distribution of nutrients in Punjab's soils is examined in this review, which is important to comprehend agricultural sustainability.This review investigates the status of key macronutrients—Nitrogen (N), Phosphorus (P), and Potassium (K)—and overall soil fertility across different soil layers in Punjab. In the surface layer (0-15 cm), available N ranges from 124.14 to 132.23 kg/ha, P from 18.56 to 21.44 kg/ha, and K from 149.17 to 286.67 kg/ha. The subsurface layer (15-30 cm) shows N between 102.55 to 107.95 kg/ha, P from 14 to 16.43 kg/ha, and K from 11.16 to 18 kg/ha. At greater depths (30-45 cm), N ranges from 83.66 to 89.06 kg/ha, P from 8.42 to 8.84 kg/ha, and K from 63.33 to 80 kg/ha. Punjab's soils, comprising clayey, sandy, loamy, and alluvial types, exhibit varying nutrient retention and water-holding capacities, significantly affecting crop suitability and soil fertility. Alluvial soils, dominant in the fertile plains, support a diverse range of crops due to their high nutrient content and excellent water-holding capacity. Loamy soils, with their balanced texture, are ideal for wheat and pulses, whereas sandy soils in southwestern Punjab require careful management for crops like millets due to their high permeability and low nutrient retention. Clayey soils, prevalent in regions like Jalandhar, are suitable for water-intensive crops such as rice but pose challenges related to drainage. This review highlights the importance of understanding NPK nutrient distribution and soil fertility to inform effective soil management practices, aiming to enhance agricultural productivity in Punjab.

Keywords: Nutrients, Soil depths, Nitrogen, Phosphorus, Potassium

INTRODUCTION

Food production is now self-sufficient thanks to the green revolution, meeting the needs of an expanding population. But because nutrients are being drawn out of soil reserves, this has also resulted in a decrease in the amount of nutrients in the soil (Dhaliwal et al., 2023). It is now known that Indian soils in particular have poor crop nutrient availability, which lowers soil fertility and reduces crop productivity. Food security is seriously threatened by this reduction in the availability of nutrients (Yadav et al., 2016; Shukla et al., 2022). For agricultural production to be sustainable, plants need a balanced diet. Intensive tillage, monoculture, the use of high-yielding cultivars, and uneven fertilizer application are some of the methods used by modern agricultural systems to exploit nutrients. Furthermore, there is a deficiency in the application of organic manures, inadequate recycling, crop residue burning, soil erosion, uneven topography, and careless use of irrigation water (Bhattacharyya et al., 2015). A balanced application of organics, fertilizers, and biofertilizers is essential for long-term soil fertility maintenance (Bhatt et al., 2020).

Punjab is a state known for its rich soils and high agricultural productivity, and agriculture is the main industry there. However, this productivity is highly dependent on the soil's nutrient status, which affects crop yield and quality directly (Yadav et al., 2016). To better understand and manage soil fertility, ensure sustainable agricultural practices, and increase crop productivity, it is imperative to review the depthwise nutrient status of Punjab's soils. Soil nutrient status is not only horizontally but vertically variable. Applying fertilizer more precisely and effectively is made possible by depthwise analysis, which offers a thorough understanding of nutrient distribution at different soil depths (Dhaliwal et al., 2023). This method assists in meeting the nutrient requirements of various crops with differing root systems and patterns of nutrient uptake.

The high-yielding crop varieties, widespread use of chemical fertilizers, and multiple cropping systems characteristic of Punjab's intensive agricultural practices have resulted in notable alterations to the soil nutrient dynamics (Singh et al., 2020; Kuldeep, 2021). These practices may eventually lead to reduced soil fertility, nutrient imbalances, and soil degradation. In order to guide corrective actions to restore soil health, a depth-wise review of soil nutrients can provide insights into the extent of nutrient depletion or accumulation at different soil layers.

A number of soil properties affect the macro- and micronutrient availability to plants. Stronger yields are supported by healthy soils because they improve our knowledge of the biological, physical, and chemical characteristics of soil. This knowledge improves yield potential, mitigates nutrient and water stress, and strengthens root health (Das et al., 2022). Crop nutrient requirements are influenced by the physical-chemical properties of the soil and its nutrient status

(Bhatt et al., 2022). Understanding the health and productivity of trees requires accurate knowledge of the nutrient status of the soil as well as the nutrient content of plants.

Furthermore, comprehension of Punjab's agriculture's long-term sustainability depends on this review. Farmers and agronomists can create targeted soil management strategies that promote balanced nutrient availability and prevent environmental problems like soil erosion and groundwater contamination by identifying nutrient excesses or deficiencies.

Importance of Comprehensive Soil Assessment for Agricultural Productivity

Evaluation of soil fertility and suitability for agricultural productivity requires a thorough assessment of the physical, chemical, and biological characteristics of the soil. Root growth, nutrient distribution, and water availability in the soil profile are all influenced by physical characteristics of the soil, such as texture, structure, and porosity (Yang et al., 2021). A soil's chemical characteristics, such as pH, EC, organic matter content, and nutrient levels (nitrogen, phosphorus, potassium, etc.), are important markers of soil health and nutrient availability for plant uptake (Yadav et al., 2019; Kwiatkowski and Harasim, 2020; Niemiec et al., 2020). A crucial component of soil organic matter decomposition and nutrient cycling is microbial activity, which is evaluated by biological properties.Based on its specificity and sensitivity, each nutrient analysis method is chosen to precisely measure the corresponding nutrient content in soil samples. These analyses offer crucial information that agricultural practitioners need to make well-informed decisions about soil management techniques, such as applying fertilizer, liming, and other amendments, in order to maximize soil fertility and long-term crop productivity.

Soils in Punjab

Punjab, known as the "Granary of India," has a variety of soil types that have a big impact on productive of its agriculture (Sidhu et al., 2020; Vatta and Budhiraja, 2020). The main types and textures of soil that are found in Punjab are clayey, sandy, loamy, and alluvial soils (Singh et al., 2021). Different types of crops have different properties that influence things like water retention, availability of nutrients, and crop suitability:

Table: Different soil types and soil textures according to Punjab districts.

Soil Type and Soil texture	Regions Found	Characteristics	Suitable Crops	Area	References
Alluvial Soils	Amritsar, Beas, Hari Ke	High nutrient content, excellent water-holding capacity, fertile, created by river deposits	Wheat, rice, corn, sugarcane, cotton, Kharif and Rabi crops	40,290 to 45,326 sq km	Dhaliwal *et al.*, 2019; Halder et al., 2020; Garg *et al.*,2022
Loamy Soils	Central Punjab (Ludhiana)	Balanced sand, silt, and clay; high fertility, moderate water-holding capacity, good drainage	Wheat, barley, pulses	6,043 to 7,051 sq km	Meena *et al.*, 2018
Sandy Soils	Southwest Punjab (Bathinda, Ferozepur)	High permeability, low water-holding capacity, quick drainage, nutrient leaching	Millets, watermelons, groundnuts	3,777 to 4,533 sq km	Singh *et al.*, 2021; Zade*et al.*, 2021; Krishan *et al.*, 2022
Clay Soils	Jalandhar, Ludhiana	Heavy and dense, high nutrient retention, poor drainage, waterlogging	Rice	4,029 to 6,295 sq km	Ahada and Suthar, 2018; Singh *et al.*, 2021; Cons, 2023

		issues			
Calcareous Soils	Patiala	High in calcium carbonate, alkaline, difficult nutrient access, especially for micronutrients	Managed crops with balanced nutrient supplies and pH levels	755 to 2,014 sq km	Kumar et al.,2018; Monga and Kumar, 2022
Desert Soils	Southwest edge (Sri Muktsar Sahib, Abohar, Fazilka)	Low organic matter, limited water-holding capacity, erosion-prone	Pearl millet, sorghum, some vegetables	1,007 to 1,259 sq km	Prakash *et al.*, 2020; Hadda*et al.*, 2023

District-wise nutrient availability in soil

The nutrient availability of Punjab soils varies significantly between districts, which is indicative of the region varied agricultural practices and conditions. Different pH levels and nutrient contents, for example, can be found in districts like Moga and Bathinda, which can have an impact on crop suitability and management techniques. The moderate levels of nitrogen and phosphorus, low salinity, and sufficient potassium in Moga slightly alkaline soils make them suitable for a wide range of crops. Bathinda, on the other hand, has soils that are highly alkaline, low salinity, have high levels of organic carbon in surface soils that decrease with depth, and high potassium levels. As a result, special modifications are needed for the best crop growth. This variation emphasizes how crucial district-specific soil management plans are to raising Punjab agricultural output.

Jalandhar District

In the Jalandhar area (2,632 km^2), total farming land is 236,000 hectares.The district soils exhibited an alkaline pH, with 59% of the area having a pH greater than 8.5. The electrical conductivity of these soils was below 1.0 dS/m. Organic carbon levels were low across all soils, with 86% of the area having organic carbon content below 0.35%. The available nitrogen content (58.33 kg/ha to 93.33 kg/ha) (Sahu *et al.,* 2024) phosphorus content in the soil samples ranged from 4.48 to 118.72 kg/ha, showing significant variability due to the use of different fertilizers in various experiments. Available potassium levels ranged between 134.2 and 431.2 kg/ha. The soils in Jalandhar often have moderate to low nitrogen levels (Sahu et al.,2024; Sharma et al.,2017). Intensive farming practices, especially the cultivation of high-yielding varieties, deplete nitrogen in the soil. Potassium levels in Jalandhar soils are typically adequate to moderate. Potassium deficiency is less common but can occur in areas with intensive crop cultivation (Rafie et al.,2019).

Ludhiana District

In the Ludhiana district, soil nutrient levels were characterized by the following standard deviations: nitrogen (N) at 416.31 ppm, phosphorus (P) at 254.36 ppm, and potassium (K) at 241.78 ppm. The soil pH averaged 7.04, indicating a slightly alkaline nature. Electrical conductivity (EC) values had a standard deviation of 214.30, suggesting variability in soil salinity across the district (Kanojia, and Sreekesh, 2022). These measurements provide a comprehensive understanding of soil nutrient availability and chemical properties in the Ludhiana district, essential for effective agricultural planning and management. Ludhiana soils often exhibit moderate to low nitrogen levels. Intensive cropping systems and insufficient nitrogen replenishment contribute to this deficiency. Phosphorus levels in Ludhiana soils are generally low (Dwivedi et al., 2017). This is due to high phosphorus fixation in the soil and inadequate use of phosphorus fertilizers. Potassium levels are typically adequate to moderate. Potassium deficiency is less common but can occur in areas with high crop intensification.

Amritsar District

In the Amritsar district, soil pH was observed to range from 4.7 to 8.2, with a mean value of 7.01. Electrical conductivity (EC) varied from 0.01 to 0.89 dS/m, with a mean value of 0.22 dS/m at 25°C. The organic carbon content in the sampled soils ranged from 0.15% to 0.91%, with a mean value of 0.54%. The available nitrogen (N) content ranged from 100.35 to 441.58 kg/ha, with an average value of 219.48 kg/ha. Available phosphorus (P) varied from 0.35 to

51.96 kg/ha, with a mean value of 8.13 kg/ha. The study indicates that about two-thirds of the sampled area exhibited low phosphorus levels, while one-third fell into the medium range. Phosphorus in the soil exists in a solid phase with varying degrees of solubility. When water-soluble phosphorus is added to the soil, it quickly converts to an insoluble solid phase by reacting with soil constituents. This rapid conversion, combined with intensive cropping and imbalanced fertilizer use, leads to higher phosphorus uptake by crops. The available potassium (K) content in the soils of Amritsar ranged from 23.52 to 566.04 kg/ha, with an average value of 262.11 kg/ha. This detailed analysis of soil properties in the Amritsar district provides crucial insights for optimizing fertilizer use and improving crop yields (Vaisnow et al., 2014).

Soils in Amritsar generally have moderate to low nitrogen levels due to intensive farming and high cropping intensity, which depletes nitrogen. Phosphorus levels in Amritsar soils are typically low due to high phosphorus fixation and inadequate application of phosphorus fertilizers (Sharma et al., 2019). Potassium levels are generally adequate to moderate. Potassium deficiency is less common but can occur in areas with intensive crop cultivation. The pH of soils in Amritsar ranges from 6.5 to 8.0, indicating neutral to slightly alkaline conditions. The EC values in Amritsar soils typically range from 0.2 to 1.0 dS/m, indicating non-saline to slightly saline conditions. The organic carbon content in Amritsar soils is generally low to moderate, ranging from 0.4% to 0.75%. Intensive farming and limited organic matter input contribute to low OC levels.

Gurdaspur District

The pH of soil samples from the Gurdaspur district ranged from slightly acidic to neutral, with values between 6.4 and 7.9. The mean pH value of the samples was within this range. Approximately 98.9% of soil samples had EC values ranging from 0.8 to 1.6 dS/m, indicating normal salinity levels and no sodic properties. This suggests that soluble salts may have leached from the surface to sub-surface soils or been transported through runoff. The organic carbon content in the soils of Gurdaspur varied from 0.30% to 1%, with an average value of 0.58%. Available phosphorus (P) in the soil ranged from 3.75 to 85.5 kg/ha, with a mean value of 22.3 kg/ha. The phosphorus status of soil samples was categorized as follows: 24.8% of samples were low, 28.8% were medium, 42.3% were high, and 4% were very high. Available potassium (K) in the soils ranged from 26.4 to 225 kg/ha, with an average value of 102.2 kg/ha. Overall, 92.7% of soil samples were observed to be low in potassium. This detailed analysis provides a comprehensive understanding of the soil fertility status in the Gurdaspur district, which is essential for effective agricultural planning and management (Verma et al., 2023). Soils in Gurdaspur typically have moderate to low nitrogen levels due to intensive agricultural practices and inadequate nitrogen replenishment. Phosphorus levels in Gurdaspur soils are generally low, primarily due to high phosphorus fixation and insufficient application of phosphorus fertilizers. Potassium levels are typically adequate to moderate. Potassium deficiency is less common but can occur in areas with high crop intensification.

Hosiarpur District

In Hoshiarpur district of Punjab, the soil exhibits a pH range from 6.5 to 9.3, indicating variability from slightly acidic to moderately alkaline conditions. The electrical conductivity of the soil samples, which measures the soil's salinity, spans from 0.16 to 0.67 mmhos/cm, suggesting low to moderate levels of soluble salts. Regarding soil organic carbon, (0.20-0.40%) of the soil samples show significant organic carbon content, reflecting the soil's ability to support crop growth and sustain microbial activity. Additionally, the minimum available nitrogen (221.94-226.47 kg/acre), phosphorus is recorded at 4.4-7.2 kg/acre and available K is 12-20 kg/acre, highlighting a critical nutrient level necessary for plant development and overall soil fertility (Sunita and Singh, 2020; Sikha et al., 2023). Soils in Hoshiarpur typically have moderate to low nitrogen levels due to intensive farming practices and inadequate nitrogen replenishment. Phosphorus levels in Hoshiarpur soils are generally low. This is primarily due to high phosphorus fixation in the soil and insufficient application of phosphorus fertilizers. Potassium levels are generally adequate to moderate. Potassium deficiency is less common but can occur in areas with intensive crop cultivation.

Pathankot District

Soils in Pathankot often exhibit moderate to low levels of nitrogen (Sharma et al., 2023). Intensive cultivation and insufficient nitrogen replenishment contribute to this deficiency. Phosphorus levels in Pathankot soils are generally low. High phosphorus fixation in the soil and inadequate use of phosphorus fertilizers are contributing factors. Potassium levels in Pathankot soils are typically adequate to moderate. However, localized deficiencies can occur in intensively cultivated areas. The chemical analysis of soil samples from Pathankot district revealed that the pH of 100% of the samples ranged between 6.5 and 8.7, indicating a range from slightly acidic to moderately alkaline conditions. Additionally, the electrical conductivity (EC) of all the samples was found to be below 0.8 dS/m, suggesting low levels of salinity across the district's soils (Singh and Singh, 2017). The organic carbon content in Pathankot soils is generally low to moderate, ranging from 0.4% to 0.75%. Continuous cultivation and limited organic matter input contribute to low OC levels.

Roopnagar District

In the soils of Rupnagar district, the pH ranged from slightly acidic to alkaline, with a mean value of 7.86. The electrical conductivity (EC) varied between 0.28 to 0.89 dS/m, with an overall mean of 0.51 dS/m, showing considerable variation depending on the topography. The soil organic carbon (OC) had an overall mean of 5.50 g/kg. The available nitrogen (N) content in farmers' fields exhibited a low range, varying from 173 to 392 kg/ha, with a mean of 275 kg/ha. The available phosphorus (P) content ranged from 6.36 to 30.0 kg/ha, with a mean of 14.9 kg/ha. Available potassium (K) ranged from 199 to 361 kg/ha, with a mean value of 279 kg/ha (Singh et al., 2021). Soils in Roopnagar often have varying levels of nitrogen, influenced by agricultural practices and fertilization. Intensive farming may deplete nitrogen levels, leading to deficiencies. Phosphorus levels in Roopnagar soils can vary but are generally moderate to low (Verma et al., 2016; Kumar et al., 2023). Factors such as phosphorus fixation and inadequate fertilizer use contribute to these variations. Potassium levels in Roopnagar soils are typically adequate. However, localized deficiencies can occur, especially in intensively cultivated areas.

FazilkaDistrict

Nitrogen deficiency is a significant concern in Fazilka. Intensive cultivation of wheat and rice, coupled with the overuse of urea, has led to a depletion of nitrogen in the soil. Studies indicate that around 70% of the agricultural land in Fazilka is nitrogen-deficient. This deficiency affects crop growth and yields, necessitating the adoption of balanced fertilization practices (Kaur and Kumar, 2022). Phosphorus levels in Fazilka's soils are generally adequate due to the regular application of phosphorus-based fertilizers. However, imbalances do occur, particularly in fields where there is an over-reliance on nitrogenous fertilizers, which can lead to a relative deficiency of phosphorus (Sandhu et al., 2022). Potassium deficiency is moderate to severe in various parts of Fazilka. Potassium is crucial for crop health and productivity, and its deficiency can lead to poor root development and reduced resistance to diseases. Soil tests have shown that approximately 50% of the soils in Fazilka are low in potassium (Srivastava, 2006). The decline in soil organic matter is a critical issue in Fazilka, exacerbated by intensive agricultural practices and inadequate crop residue management. Low organic carbon levels impact soil structure, nutrient availability, and overall soil health. Efforts to incorporate organic amendments, such as compost and green manure, are essential to improve soil organic matter content (Sangeet and Kumar 2020).

Bathinda District

The soils of Bathinda District exhibit a strongly alkaline pH value of 8.3, which may require specific management practices for certain crops that prefer more neutral conditions. The electrical conductivity (EC) is low, with values of 0.19 dS m-1 in surface soils and 0.17 dS m-1 in sub-surface soils, indicating non-saline conditions favorable for crop growth. The organic carbon content in surface soils is 4.9 g kg-1 but decreases with increasing soil depth, suggesting a need to incorporate organic matter to improve soil fertility. The available phosphorus (P) content ranges from 17.5 to 21.5 kg/ha, providing an adequate supply for plant growth. Potassium (K) levels are high, with 404 kg/ha available, ensuring strong plant structure and resistance to diseases (Yadav et al., 2016). Soils in Bathinda generally have low to medium nitrogen levels due to extensive cultivation of nitrogen-consuming crops like wheat and rice. Regular application of urea and other nitrogenous fertilizers is common to maintain productivity (Yadav et al., 2018). Phosphorus levels vary but often tend to be medium to low. Continuous cropping without adequate replenishment can lead to phosphorus depletion (Yadav et al., 2023). Potassium levels are generally sufficient, but in some areas, they can be marginal. Potassium fertilizers like muriate of potash are used to ensure adequate levels (Yadav et al., 2018).

Shri Muktsar Sahib District

Soils in Shri Muktsar Sahib often have low to medium nitrogen levels. The high cropping intensity depletes soil nitrogen, necessitating regular application of nitrogenous fertilizers like urea (Dhaliwal et al., 2018). The phosphorus content in the soils is generally in the medium range, but can vary. Continuous cropping without proper replenishment can lead to phosphorus depletion. Phosphatic fertilizers like DAP (Diammonium Phosphate) are commonly used (Dhaliwal et al., 2018). Potassium levels are usually sufficient, though in some cases they may be marginal. Potassium chloride (muriate of potash) is often applied to maintain adequate potassium levels (Thind and Kumar, 2021). The soils of the Muktsar district are alkaline in reaction with pH ranging from 7.27 to 9.92 with a mean value of 8.66. The total salts expressed as electrical conductivity (EC) varied from 0.11 to 6.69 with a mean value of 0.63 dS m-l. The majority of soil samples (84%) fall in the normal range (loamy sand (23%) > loam (17%) > silt loam (1%) > sand (1%).

Moga District

Soils in Moga generally have low to medium nitrogen levels. The frequent cultivation of high nitrogen-demanding crops like wheat and rice leads to nitrogen depletion. The soils of Moga District exhibit a slightly alkaline pH of 7.5, making them suitable for most crops with minimal pH adjustments. The electrical conductivity (EC) is 0.62 dS m-1, indicating low salinity and favorable conditions for crop growth without the risk of salt stress. The nitrogen content stands at 134.83 kg/ha, which is a moderate level essential for plant growth and optimal yields. Phosphorus content is 29.49 kg/ha, within the acceptable range for supporting root development and overall plant health. Potassium levels are at 172.55 kg/ha, which is adequate for ensuring strong plant structure and resistance to diseases (Panjgotra et al., 2019). Potassium levels are typically sufficient but can be marginal in some areas. Farmers use potassium chloride (muriate of potash) to ensure adequate potassium supply (Thind and Kumar, 2021).

Mansa District

The soils in Mansa typically exhibit low to medium nitrogen levels. The cultivation of nitrogen-demanding crops like wheat, rice, and cotton depletes soil nitrogen, necessitating regular application of nitrogenous fertilizers such as urea (Biratu et al. 2018). Phosphorus levels in the soils range from medium to low. Continuous cropping without adequate phosphorus replenishment can lead to phosphorus depletion. Farmers often use phosphatic fertilizers like DAP (Diammonium Phosphate) to maintain adequate phosphorus levels (Verma et al. 2005). Potassium levels are generally sufficient but can be marginal in some areas. Potassium fertilizers like muriate of potash are commonly used to ensure adequate potassium supply (Thind and Kumar, 2021).

Faridkot District

Faridkot district, located in Punjab, India, is primarily known for its agricultural productivity, particularly in wheat and cotton. The nutrient status of the district's soil and crops depends on various factors such as irrigation practices, crop rotation, and fertilization methods employed by local farmers. Typically, soil fertility in this region is managed through the application of fertilizers like urea, DAP (Di-Ammonium Phosphate), and potash, tailored to the specific needs of crops grown in the area (Cons 2023).

Depth-wise nutrient availability in soil

The availability of nutrients in the soil at different depths has a significant impact on plant growth, soil fertility, and total agricultural productivity (Havlin, 2020). Because of a number of variables, such as soil texture, organic matter content, microbial activity, and root activity, nutrient distribution changes with soil depth (Herrick and Wander, 2018). Optimizing crop yields and managing soil effectively require an understanding of this variability.

Surface Layer (0-15 cm): The highest concentrations of nutrients are usually found in the topsoil layer (Loide et al., 2020; Han et al., 2021). In the surface layer (0-15 cm), the available nitrogen (N) ranges from 124.14 to 132.23 kg per hectare, phosphorus (P) from 18.56 to 21.44 kg per hectare, and potassium (K) from 149.17 to 286.67 kg per hectare (Kaur and ZA, 2017). Because of the breakdown of manure, other organic inputs, and plant leftovers, this layer is rich in organic matter. Additionally, the topsoil has the highest level of microbial activity, which promotes the availability and mineralization of nutrients Meyer et al., 2018; Ali et al., 2021). Because essential nutrients like nitrogen (N), phosphorus (P), and potassium (K) are typically more prevalent in this layer, it is essential for the establishment of seedlings and the growth of young plants. But over time, intensive farming methods like constant cropping and insufficient fertilizer can exhaust these nutrients.

Subsurface Layer (15-30 cm): The movement of nutrients from the topsoil and root activity determine the availability of nutrients in the subsurface layer (Liang et al., 2019; Young et al., 2022). In the subsurface layer (15-30 cm), available N ranges from 102.55 to 107.95 kg per hectare, available P from 14 to 16.43 kg per hectare, and available K from 11.16 to 18 kg per hectare (Kaur and ZA, 2017). Because they are not very mobile, nutrients like phosphorus, which binds strongly to soil particles, may become less concentrated as one descends in depth. Notwithstanding, specific nutrients, such as nitrogen in the form of nitrate (NO3-), may seep into this stratum contingent on the characteristics of the soil, patterns of rainfall, or irrigation techniques (Amirhajloo et al., 2023). Numerous crop root systems penetrate this layer to obtain water and nutrients; however, the efficiency of nutrient uptake varies depending on the characteristics of the soil and the distribution of the roots.

Deeper Layers (30-45 cm and beyond): Nutrient concentrations usually drop even further into deeper soil layers (Marschner and Rengel, 2023). In deeper layers (30-45 cm), available N is between 83.66 to 89.06 kg per hectare, available P between 8.42 to 8.84 kg per hectare, and available K between 63.33 to 80 kg per hectare (Kaur and ZA, 2017). A reduced amount of organic matter inhibits microbial activity and the natural resupply of nutrients (Naylor et al., 2022). While some nutrients may still be present, conditions like soil compaction, decreased aeration, and decreased microbial populations frequently limit their availability. Though these nutrients are accessible to deep-rooted plants and some perennials, the deeper layers of soil provide less overall nutrient supply for most crops (Germon et al., 2020).

Availability of NPK in Punjab Soils:

The soils of Punjab are generally low in available nitrogen. In the Shivalik region, under different land use systems, available nitrogen varies significantly: agricultural lands have 50.2-225.8 kg/ha (Mahesh, 2022), forest lands have 62.7-174.6 kg/ha, afforested lands have 75.3-175.6 kg/ha, and non-arable lands have 112.9-263.4 kg/ha (Vashisht et al. 2020). In the submontane region, nitrogen levels are particularly low, ranging from 29.32-32.6 kg/ha, likely due to leaching and low vegetation cover (Maini et al. 2022). In southwestern Punjab, horticultural lands have the highest nitrogen content at 100.35 kg/ha, followed by croplands at 91.99 kg/ha, and uncultivated lands with the lowest at 3.65 kg/ha (Mandal et al. 2018). In sugarcane-growing areas, nitrogen availability ranges from 194.4-301.0 kg/ha (Verma et al. 2016). Agroforestry sites have an average nitrogen level of 145.5 kg/ha, while intensive rice-wheat cultivation areas average 106.60 kg/ha (Dhaliwal et al. 2020).

Soils across Punjab generally exhibit low to moderate levels of phosphorus availability. Approximately 36% of the state's area has less than 12 kg/ha of available phosphorus, averaging 5.1 kg/ha. About 18% of the area shows moderate levels, ranging from 12 to 22 kg/ha, with an average of 16.5 kg/ha. Around 19.6% of Punjab's area has phosphorus levels exceeding 22 kg/ha, averaging 32.6 kg/ha (Sharma et al. 2016). In agroforestry and intensive rice-wheat cultivation sites, the average available phosphorus levels are approximately 15.64 kg/ha and 12.65 kg/ha, respectively (Dhaliwal et al. 2020). In Bathinda, phosphorus availability ranges between 17.5 to 21.5 kg/ha (Yadav et al. 2016). In southwestern Punjab, under various land use systems, croplands have about 25.61 kg/ha of available phosphorus, horticultural lands have 25.03 kg/ha, and uncultivated lands have 13.03 kg/ha (Mandal et al. 2018). In the Shivalik foothills, phosphorus levels are approximately 32 kg/ha in horticultural lands, 30.4 kg/ha in farm forests, and 31.4 kg/ha in croplands (Bhople et al. 2020).

Soils in Punjab are generally rich in available potassium, with approximately 92% of the state's geographical area having more than 113 kg/ha of available potassium (Mahesh, 2022). The remaining 8% of the area has less than 113 kg/ha (Sharma et al. 2016). In agroforestry and intensive rice-wheat cultivation sites, the average available potassium levels are about 221.04 kg/ha and 179.20 kg/ha, respectively (Dhaliwal et al. 2020). In the submontane regions of Punjab under rainfed land use, available potassium ranges from 10.3 to 21.3 kg/ha (Maini et al. 2022). In the Shivalik region, soil available potassium varies across different land use systems: agricultural lands range from 42 to 300 kg/ha, forest lands from 60 to 264 kg/ha, afforested lands from 75 to 189 kg/ha, and non-arable lands from 36 to 96 kg/ha (Vashisht et al. 2020). Near the Shivalik hills, available potassium levels in horticultural lands are around 190 kg/ha, in forest lands approximately 186 kg/ha, and in croplands about 199 kg/ha ha (Bhople et al. 2020). Overall, the ample availability of potassium in Punjab soils supports robust agricultural productivity in various cropping systems across the region.

Factor influencing nutrients

Soil pH: A pH range of 6.0 to 7.0 is slightly acidic to neutral, which is where most nutrients are most soluble and readily available (Penn and Camberato, 2019, Neina, 2019). Soil pH has a major impact on these properties. A variety of chemical reactions and leaching cause nutrients like calcium, magnesium, molybdenum, phosphorus, potassium, nitrogen, and sulphur to become less available in acidic soils (pH 6.0). Phosphorus, iron, manganese, zinc, copper, and boron are among the nutrients that in alkaline soils (pH > 7.0) form insoluble compounds and become less available (Alam et al., 2020). The leaching potential and nutrient retention of sandy soils are higher than those of clay soils, which may have inadequate aeration but better nutrient retention. Soil texture also influences nutrient availability. The amount of organic matter in the soil is important because it improves soil structure, increases cation exchange capacity (CEC), supports microbial activity, acts as a reservoir for nutrients, and increases nutrient availability (Usharani *et al.*, 2019; Solly et al., 2019; Domingues et al., 2020; Ćirić et al., 2023). The soil's capacity to retain and exchange vital nutrients, or CEC, is a crucial component that affects the nutrients' availability to plants.

The soils in Punjab are generally alkaline, with most soils having a pH between 7.0 and 8. In Tarn Taran district, 92% of the soils are within the normal pH range, 7.3% have slightly higher pH levels, and 0.9% have the highest pH levels. In the sub-mountainous region of Rupnagar district, soil pH varies from 6.75 to 8.31 (Singh et al. 2021). In Bathinda, soil pH ranges from 8.27 to 8.52 ((Yadav et al. 2016; Vashisht et al. 2020), with an average of 8.31. In the Shivaliks of Indian Punjab, soil pH ranges from 6.9 to 9.4 in agricultural lands, 6.5 to 9.2 in forests, 8.2 to 9.3 in afforested areas, and 8.6 to 9.4 in non-arable lands. In the sub-mountain region, pH values decrease to between 6.4 and 6.9 due to leaching from rainfed land use. In the southwestern region of Punjab, soil pH ranges from 7.68 to 7.98 (Mandal et al. 2018). In the alluvial soils of Punjab, the mean pH in agroforestry sites is 8.00, while in rice-wheat cropping sites it is 7.89 (Dhaliwal et al. 2020; Mahesh, 2022).

Soil texture: A key factor affecting nutrient availability is soil texture, which is determined by the proportions of sand, silt, and clay particles in the soil (Ge et al., 2019; Ding et al., 2021). Larger particle sizes in sandy soils cause them to have high permeability and low water-holding capacity (Dhiman et al., 2023). This causes rapid drainage and increased nutrient leaching, which reduces the amount of nutrients that are available to plants. In contrast, clay soils, because of their fine particle size, have a high capacity to retain water and nutrients (Kome et al.,2019; Liao and Thomas, 2019). However, they may have inadequate drainage and aeration, which can result in nutrient imbalances and decreased availability because of wet conditions. Because they combine adequate water and nutrient retention with good drainage and aeration, loamy soils a balanced mixture of sand, silt, and clay offer the best conditions for nutrient availability (Abuarab et al., 2019; Pandao et al., 2024). The cation exchange capacity (CEC) of the soil is also influenced by its texture; soils rich in organic matter and clay typically have higher CEC values, which allows for better plant availability and nutrient retention (Kome et al., 2019; Havlin, 2020; Bashir et al., 2021). Therefore, controlling soil fertility and maximizing nutrient management techniques require an understanding of soil texture.

Electrical conductivity: The ability of the soil to conduct electrical current, or electrical conductivity (EC), is a crucial factor that affects the availability of nutrients (Corwin and Scudiero, 2020; Gondek et al., 2020). This ability is directly correlated with the concentration of soluble salts in the soil solution. Elevated EC values signify elevated salinity, which may cause an unbalance in soil nutrients, rendering certain nutrients more accessible while ion competition reduces the accessibility of others (Wali et al., 2021). Overabundance of soluble salts can lead to specific ion toxicities, like sodium (Na) or chloride (Cl) toxicity, which negatively impact plant growth, as well as osmotic stress in plants, which lowers their capacity to absorb water and nutrients. On the other hand, since there are less soluble ions in the soil solution, low EC levels typically translate into low nutrient availability (Penn and Camberato, 2019; Othaman et al., 2020). Extreme salinity levels either prevent or favor salt-tolerant microbial populations, which influences nutrient cycling processes (Zhang et al., 2024). Soil EC also affects microbial activity (Song et al., 2018; Zhang et al., 2019; Mhete et al., 2020; Karimi et al., 2020). Maintaining optimal nutrient availability and promoting healthy plant growth require an understanding of and ability to control soil EC, particularly in areas where irrigation techniques may affect the salinity of the soil.

The electrical conductivity (EC) of soil in Punjab is generally below 0.8 dS/m, indicating normal levels (Mahesh, 2022). In Bathinda, soil EC ranges from 0.16 to 0.26 dS/m, averaging 0.19 dS/m. In the sub-mountain region under rainfed conditions, EC values range from 0.09 to 0.23 dS/m. In sugarcane-growing areas, soil EC varies between 0.04 and 0.35 dS/m (Maini et al. 2022). Intensively cultivated soils show EC values ranging from 0.31 to 0.98 dS/m (Sharma et al. 2016). In southwestern Punjab, EC values are between 0.32 and 0.46 dS/m (Mandal et al. 2018). The average EC of soils in rice-wheat cultivation areas is 0.11 dS/m, and in agroforestry sites, it is 0.16 dS/m (Dhaliwal et al. 2020).

Organic Matter: Being a reservoir of nutrients and performing a variety of functions to keep soil healthy, organic matter is a crucial component affecting the availability of nutrients in soil. Organic matter, which is derived from decomposed plant and animal wastes, becomes available for plant uptake by mineralizing and releasing important nutrients like phosphorus, sulfur, and nitrogen (Duiker, 2021; Bashir et al., 2021; Islam et al., 2021). The addition of organic matter to soil improves its structure, which in turn creates an ideal environment for root development and nutrient absorption by increasing aeration, water infiltration, and retention (Singh et al., 2021; Antil et al., 2021; Virk et al., 2021). Furthermore, organic matter improves the soil's ability to hold onto key cations such as calcium, magnesium, and potassium, preventing leaching and guaranteeing plant availability (Brust, 2019; Mattos et al., 2020; Yahaya et al., 2023). This is known as the soil's cation exchange capacity, or CEC. A rich and dynamic microbial community is nourished by the presence of organic matter and is essential to the decomposition, nutrient cycling, and establishment of stable soil aggregates (Dhaliwal et al., 2019; Raza et al., 2023; Filipović et al., 2024). Organic matter is crucial for preserving soil fertility and guaranteeing sustainable agricultural productivity because it enhances soil structure, increases nutrient retention, and stimulates microbial activity.

Most soils in Punjab have medium to low organic carbon content, a condition exacerbated by intensive agriculture, excessive use of chemical fertilizers, and stubble burning (Sharma et al. 2016). Approximately 32% of the state's soils have less than 0.4% organic carbon, 57% contain between 0.4% and 0.75%, and 12% exceed 0.75%. In the Shivalik region, the organic carbon content varies across different land uses: agricultural lands range from 0.03% to 0.75%, forests from 0.03% to 0.45%, afforested areas from 0.12% to 0.33%, and non-arable lands from 0.12% to 0.72% (Vashisht et al. 2020).

In intensively cultivated areas, 31.6% of soils have less than 0.4% organic carbon (averaging 0.32%), 56.6% fall between 0.4% and 0.75% (averaging 0.55%), and 11.8% have more than 0.75% (averaging 0.82%) (Sharma et al. 2016). In southwestern Punjab, organic carbon content is 8.91 g/kg in horticultural land, 5.96 g/kg in cropland, and 3.65 g/kg in uncultivated soils (Mandal et al. 2018). In major sugarcane-growing areas, organic carbon ranges from 0.23% to 0.94% (Verma et al. 2016). In Bathinda, it ranges from 3.2 to 8.7 g/kg, averaging 4.9 g/kg (Yadav et al. 2016). In the rice-wheat system, organic carbon content ranges from 0.74% to 1.05%, with a mean of 0.87% (Mandal et al. 2019). Agroforestry sites have a mean organic carbon content of 0.27%, while intensive rice-wheat cultivation sites average 0.24% (Dhaliwal et al. 2020).

Table 2: Factors influence nutrient availability in soils.

Factor	**Influence on Nutrients**	**Examples**	**References**
Soil pH	Affects nutrient solubility and microbial activity.	Acidic soils may lead to aluminum toxicity, limiting phosphorus availability. Alkaline soils can cause deficiencies in iron, manganese, and zinc, reducing nutrient availability and affecting plant growth.	Kumar *et al.*, 2016
Soil Texture	Influences water retention, aeration, and nutrient-holding capacity.	Sandy soils have low nutrient retention; clay soils can suffer from poor drainage.	Bhattacharyya*et al.*, 2016
Organic Matter Content	Provides a nutrient reservoir and enhances soil structure.	High organic matter improves nutrient retention and microbial activity.	Dhaliwal *et al.*, 2021
Cation Exchange Capacity	Determines soil's ability to retain and exchange cations.	Soils with high CEC can hold onto essential nutrients like potassium and calcium.	Mittal and Saini, 2020
Soil Moisture	Affects nutrient	Excessively wet or	Sharma *et al.*, 2016

	solubility and plant uptake rates.	dry conditions can limit nutrient availability.	
Soil Temperature	Influences microbial activity and nutrient cycling rates.	Warmer temperatures generally increase microbial activity and nutrient release.	Jat *et al.*, 2018
Microbial Activity	Plays a crucial role in nutrient mineralization and cycling.	Mycorrhizal fungi enhance phosphorus uptake; nitrogen-fixing bacteria increase nitrogen availability.	Kunal *et al.*, 2020
Soil Aeration	Affects root growth and microbial activity.	Poorly aerated soils may limit nutrient uptake by roots.	Kumar *et al.*, 2016
Soil Erosion	Reduces soil fertility by removing nutrient-rich topsoil.	Erosion can lead to nutrient deficiencies in exposed areas.	Kaur and Sinha, 2019
Fertilizer Application	Determines nutrient availability based on type and timing.	Balanced fertilizer use ensures adequate nutrient supply to crops.	Panhwar*et al.*, 2019

CONCLUSION

In conclusion, the research on the distribution of nutrients in Punjab various land uses and depths reveals both the difficulties and the possibilities associated with sustainable agriculture. Significant differences have been found in important nutrients such as potassium, phosphorus, nitrogen, and micronutrients, which are influenced by irrigation techniques and intensive farming practices. Adopting focused soil management strategies is essential to preserving soil health and increasing crop yields. These include maximizing irrigation methods, incorporating organic materials, and applying fertilizers more effectively. Punjab can improve soil fertility, prepare for the effects of climate change, and guarantee long-term agricultural sustainability by putting these practices into practice. Sustaining the agricultural future of the region and accomplishing these objectives will require continued research and cooperative efforts.

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