



A Review on Depth Wise Nutrients Status in Punjab's Soils

Md. Junaid Hashmi ^{a+++*}, Yadvendra Pal Singh ^a
and Animesh Ghosh ^a

^a Department of Soil science and Agriculture Chemistry, Lovely Professional University, Phagwara, Punjab, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: <https://doi.org/10.9734/ijpss/2024/v36i94950>

Open Peer Review History:

This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: <https://www.sdiarticle5.com/review-history/121395>

Received: 08/06/2024

Accepted: 10/08/2024

Published: 23/08/2024

Review Article

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. Several agricultural zones provided soil samples, which were then examined for important macronutrients (N, P, and K) and micronutrients (Zn, Fe, Mn, and Cu). Recent article contains status of soil nutrients of Punjab emphasizing mostly deficits elements that may hinder crop growth. It was also reflected by the researchers that because of intensive farming methods and insufficient replenishing, nitrogen levels become low with time. Analyzing the data published by the research papers it was observed that potassium and phosphorus levels were moderate, although significant deficits were found in several locations. Micronutrient investigation revealed that iron and manganese levels were comparatively adequate, but there was a general shortage in zinc in this

⁺⁺ M.Sc Student;

*Corresponding author: E-mail: jaavi7788@gmail.com;

Cite as: Hashmi, Md. Junaid, Yadvendra Pal Singh, and Animesh Ghosh. 2024. "A Review on Depth Wise Nutrients Status in Punjab's Soils". *International Journal of Plant & Soil Science* 36 (9):38-54. <https://doi.org/10.9734/ijpss/2024/v36i94950>.

region. The review emphasizes that in order to maximize soil fertility and increase crop yields, region-specific nutrient management practices are necessary. The application of organic amendments, balanced fertilization techniques, and routine soil testing to identify and correct nutrient imbalances are among the recommendations. In order to maximize fertilizer applications, improve nutrient use efficiency, and guarantee Punjab's long-term agricultural productivity and environmental sustainability, these variations must be taken into consideration. This review emphasizes how crucial it is to implement customized soil management plans in order to prevent nutrient depletion and maintain the area's agricultural future.

Keywords: Nutrients; soil depths; nitrogen; phosphorus; potassium.

1. INTRODUCTION

Food production is now self-sufficient thanks to the Green Revolution, meeting the needs of an expanding population. However, as nutrients are being drawn out of soil reserves, this has also resulted in a decrease in the amount of nutrients in the soil [1]. 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 [2,3]. Due to the use of high-yielding cultivars, extensive cropping, increased crop yield, increased use of high-analysis fertilizers, and decreased use of crop residues, animal manures, and composts, micronutrient shortages in crops are receiving more attention. Micronutrient deficiencies significantly hampered crop performance in terms of food grain output, which had an effect on the food chain. However, the regional and worldwide variations in micronutrient deficits are leading to significant dietary limitations that impact over 2 billion people. Micronutrient availability varied greatly in distinct orders of soils with variable soil textures, cropping sequences, geomorphologies, and farming techniques [4]. The variation in topography, climate, and soil development factors and processes that modify soil pH, organic matter content in soils, complexation with natural organic chelates, and redox reactions in soils, which affect nutrient availability in soils, are the main factors directing the distribution of micronutrients. In a similar vein, topographical locations, soil development rates, and climate of the region are factors that affect soil micronutrient availability [5].

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 [6]. A balanced application of organics, fertilizers, and biofertilizers is essential for long-term soil fertility maintenance [7].

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 [2]. 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. In order to minimize nutrient depletion, assure sustainable resource use, and improve agricultural practices through optimal fertilizer applications and better nutrient use efficiency, the article emphasizes the necessity for personalized soil management strategies. It also provides information to help agricultural stakeholders and policymakers create plans and policies for preserving Punjab's soil fertility and advancing sustainable agricultural productivity.

Applying fertilizer more precisely and effectively is made possible by depth wise analysis, which offers a thorough understanding of nutrient distribution at different soil depths [1]. 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 [8,9]. These methods 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 [10]. 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.

So, in this review article, soil data published by researchers from 2010 to 2023 has been analyzed based on their fertility status (N, P, K) and other relevant parameters like pH, EC, BD etc for Punjab agricultural belt. Moreover, emphasis has been given on depth-wise fertility status of specific districts for adapting site specific nutrient management strategies.

2. 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 [11]. 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 [12,13,14,15,16]. 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.

3. 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 [17,18]. The four main types of soil that are found in Punjab are clayey, sandy, loamy, and alluvial soils [19]. Different types of crops have different properties that influence things like water retention, availability of nutrients, and crop suitability:

- **Alluvial Soils:** The most common type of soil in Punjab is alluvial, especially in the fertile plains of the area. (Amritsar, Beas, Hari Ke) These soils are created by rivers, mainly the Indus and its tributaries, depositing silt, sand, and clay [20]. Because of their high nutrient content and excellent water-holding capacity, alluvial soils are extremely fertile [21,22]. A wide range of crops, such as wheat, rice, corn, sugarcane, and cotton, can be grown there with success. Both Kharif and Rabi crops thrive in the ideal soil texture, which varies from sandy loam to clay loam.
- **Loamy Soils:** A balanced combination of sand, silt, and clay characterizes loamy soils, which provide ideal growing conditions for plants. These soils have a reputation for having high fertility, moderate water-holding capacity, and good drainage [23]. Loamy soils are particularly good for growing crops like wheat, barley, and pulses and are typically found in Punjab's central regions (Ludhiana). Their design facilitates effective nutrient absorption and robust root development.
- **Sandy Soils:** Parts of southwest Punjab, including the districts of Bathinda and Ferozepur, have sandy soils that are primarily made up of sand particles [19,24]. These soils can quickly drain and leach nutrients because of their high permeability and low water-holding capacity. As a result, regular fertilization and irrigation are needed to support crop growth in sandy soils [25]. These obstacles notwithstanding, they are appropriate for

crops that do well in well-drained environments, such as millets, watermelons, and groundnuts.

- **Clay Soils:** Clayey soils are heavy and dense due to the high percentage of clay particles in them. Although these soils have good nutrient retention, they have poor drainage, which can cause problems with waterlogging [26]. Clayey soils, which are found in places like Jalandhar and Ludhiana, are ideal for crops that require a lot of water, like rice [19,27]. Aerating the soil and using suitable irrigation techniques are crucial for managing clayey soils in a way that maximizes productivity.
- **Calcareous Soils:** Some regions of Punjab (Patiala) are home to calcareous soils, which are high in calcium carbonate [28]. Due to their typical alkaline nature, these soils can be difficult to access nutrients in, especially for micronutrients like zinc and iron [29]. For the best crop growth, calcareous soils need to be carefully managed to maintain balanced nutrient supplies and pH levels.
- **Desert Soils:** Desert soils can be found on Punjab's southwest (Sri Muktsar Sahib, Abohar, Fazilka) edge, which borders Rajasthan. These are sandy soils with a low level of organic matter and a restricted ability to hold water [30,31]. Because of their susceptibility to erosion, agriculture depends heavily on irrigation and soil preservation techniques. Hardy crops like pearl millet, sorghum, and some vegetables can be successfully grown in spite of these restrictions.

4. 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.

4.1 Jalandhar District

In the Jalandhar area, the 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 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 [32,33]. 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 [34].

4.2 Ludhiana District

In the Ludhiana district, soil nutrient levels were characterized by the following standard deviations: nitrogen (N) at 416.31, phosphorus (P) at 254.36, and potassium (K) at 241.78. 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 [35]. 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 [36]. 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.

4.3 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 [37].

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 [38]. 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.

4.4 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 [39]. 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.

4.5 Hoshiarpur 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 [40,41]. 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.

4.6 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 [42]. 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.

4.7 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 [19]. 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 [43,44]. 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.

4.8 Fazilka District

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 [45]. 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 [46]. 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 [47]. 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 [48].

4.9 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 [2]. 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 [23]. Phosphorus levels

vary but often tend to be medium to low. Continuous cropping without adequate replenishment can lead to phosphorus depletion [49]. 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 [50].

4.10 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 [51]. 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 [51]. 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 [52]. 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⁻¹. The majority of soil samples (84%) fall in the normal range (loamy sand (23%) > loam (17%) > silt loam (1%) > sand (1%).

4.11 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 [53]. Potassium levels are typically sufficient but can be marginal in some areas. Farmers use potassium chloride (muriate of potash) to ensure adequate potassium supply [52].

4.12 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 [54]. 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 [55]. 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 [52].

4.13 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 [27].

5. 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 [56]. Because of a number of variables, such as soil texture, organic matter content, microbial activity, and root activity, nutrient distribution changes with soil depth [57]. 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 [58,59]. 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., [60]; Ali et al., [61]. 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 [62,63]. 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 [64]. 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 [65]. A reduced amount of organic matter inhibits microbial activity and the natural resupply of nutrients [66]. 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 [67].

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 [68], 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 [69]. 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 [70]. 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 [71]. In sugarcane-growing areas, nitrogen availability ranges from 194.4-301.0 kg/ha [43]. Agroforestry sites have an average nitrogen level of 145.5 kg/ha, while intensive rice-wheat cultivation areas average 106.60 kg/ha [72].

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 [73]. 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 [72]. In Bathinda, phosphorus availability ranges between 17.5 to 21.5 kg/ha [2]. 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 [71]. 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 [74].

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 [68]. The remaining 8% of the area has less than 113 kg/ha [73]. 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 [72]. In the submontane regions of Punjab under rainfed land use, available potassium ranges from 10.3 to 21.3 kg/ha [70]. 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 [69]. 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 [74]. Overall, the ample availability of potassium in Punjab soils supports robust agricultural productivity in various cropping systems across the region.

6. 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 [75,76]. 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 [77]. 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 [78,79,80,81]. The soil's capacity to retain and exchange vital nutrients, or CEC, is a crucial component that affects the nutrients' availability to plants. Table 1 contains influencing factors of pH in the said region and problems associated with it.

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 [19]. In Bathinda, soil pH ranges from 8.27 to 8.52 [2, 69], 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 [71]. 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 [72,68].

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 [82,83]. Larger particle sizes in sandy soils cause them to have high permeability and low water-holding capacity [84,122,123]. 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 [85,86]. However, they may have inadequate drainage and aeration, which can result in nutrient imbalances and decreased availability because

of wet conditions [116-119]. 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 [87,88]. 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 [85,56,89]. Therefore, controlling soil fertility and maximizing nutrient management techniques require an understanding of soil texture [120,121].

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 [90,91]. 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 [92]. 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 [75,93]. Extreme salinity levels either prevent or favor salt-tolerant microbial populations, which influences nutrient cycling processes [94]. Soil EC also affects microbial activity [95,96,97,98]. 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 [68]. 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 [70]. Intensively cultivated soils show EC values ranging from 0.31 to 0.98 dS/m [73]. In southwestern Punjab, EC values are between 0.32 and 0.46 dS/m [71]. 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 [72].

Table 1. Factors influencing the nutrient availability in soils

Factor	Influencing factors	Problems associated	References
Soil pH	Affects nutrient solubility and microbial activity.	Acidic soils may lead to aluminum toxicity, limiting phosphorus availability.	[108,109]
Soil Texture	Influences water retention, aeration, and nutrient-holding capacity.	Sandy soils have low nutrient retention; clay soils can suffer from poor drainage.	[110]
Organic Matter Content	Provides a nutrient reservoir and enhances soil structure.	High organic matter improves nutrient retention and microbial activity.	[4]
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.	[111]
Soil Moisture	Affects nutrient solubility and plant uptake rates.	Excessively wet or dry conditions can limit nutrient availability.	[73]
Soil Temperature	Influences microbial activity and nutrient cycling rates.	Warmer temperatures generally increase microbial activity and nutrient release.	[112]
Microbial Activity	Plays a crucial role in nutrient mineralization and cycling.	Mycorrhizal fungi enhance phosphorus uptake; nitrogen-fixing bacteria increase nitrogen availability.	[113]
Soil Aeration	Affects root growth and microbial activity.	Poorly aerated soils may limit nutrient uptake by roots.	[108]
Soil Erosion	Reduces soil fertility by removing nutrient-rich topsoil.	Erosion can lead to nutrient deficiencies in exposed areas.	[114]
Fertilizer Application	Determines nutrient availability based on type and timing.	Balanced fertilizer use ensures adequate nutrient supply to crops.	[115]

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 [99,99,100]. 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 [19,101,102]. 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 [103,104,105]. 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 [20,106,107]. 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 [124,125].

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 [73]. 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% [69].

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%) [73]. 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 [71]. In major sugarcane-growing areas, organic carbon ranges from 0.23% to 0.94% [43]. In Bathinda, it ranges from 3.2 to 8.7 g/kg, averaging 4.9 g/kg [2]. In the rice-wheat system, organic carbon content ranges from 0.74% to 1.05%, with a mean of 0.87% [71]. Agroforestry sites have a mean organic carbon content of 0.27%, while intensive rice-wheat cultivation sites average 0.24% [72]. All the factors influencing nutrient availability are also tabulated below along with problem associated with it for Punjab region (Table 1).

7. 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.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Dhaliwal SS, Sharma V, Shukla AK, Kaur J, Gupta RK, Verma V, Singh P. Interactive effect of land use systems on depth-wise soil properties and micronutrients minerals in North-Western, India. *Heliyon*. 2023; 9(2).
2. Yadav BK, Sidhu AS, Thaman Sudhir. Soil fertility status of Punjab Agricultural University seed farm, Chak Ruldu Singh Wala, Sangat, Bathinda, Punjab. *Annals of Plant and Soil Research*. 2016;18(3):226-231.
3. Shukla AK, Behera SK, Chaudhari SK, Singh G. Fertilizer use in Indian agriculture and its impact on human health and environment. *Indian J Fertil*. 2022;18(3): 218-37.
4. Dhaliwal SS, Sharma S, Sharma V, Shukla AK, Walia SS, Alhomrani M, Hossain A. Long-term integrated nutrient management in the maize-wheat cropping system in alluvial soils of North-Western India: Influence on soil organic carbon, microbial activity and nutrient status. *Agronomy*. 2021;11(11):2258.
5. Shakeri S, Saffari M. The status of chemical forms of iron and manganese in various orders of calcareous soils and their relationship with some physicochemical and mineralogical properties. *Communications in Soil Science and Plant Analysis*. 2020;51(15):2054-2068.
6. Bhattacharyya R, Ghosh BN, Mishra PK, Mandal B, Rao CS, Sarkar D, Franzluebbbers AJ. Soil degradation in India: Challenges and potential solutions. *Sustainability*. 2015;7(4):3528-3570.
7. Bhatt BP, Mondal S, Saurabh K, Naik SK, Rao KK, Ahmed A. Soil health and fertilizer use in india. in *soil and fertilizers*. CRC Press. 2020;183-207.
8. Singh L, Bansal S, Sharma I. Sustainability of agriculture systems: A case study of Punjab. *Indian Journal of Economics and Development*. 2020;16(2s):225-231.
9. Kuldeep S. Agricultural sustainability in Punjab: Issues and challenges. *Indian Journal of Economics and Development*. 2021;17(1):136-142.
10. Das D, Sahoo J, Raza MB, Barman M, Das R. Ongoing soil potassium depletion under intensive cropping in India and probable mitigation strategies. A review. *Agronomy for Sustainable Development*. 2022;42(1):4.
11. Yang Y, Wu J, Zhao S, Mao Y, Zhang J, Pan X, Van der Ploeg M. Impact of long-term sub-soiling tillage on soil porosity and soil physical properties in the soil profile. *Land Degradation and Development*. 2021;32(10):2892-2905.
12. Ozlu E, Kumar S. Response of soil organic carbon, pH, electrical conductivity, and

- water stable aggregates to long-term annual manure and inorganic fertilizer. *Soil Science Society of America Journal*. 2018;82(5):1243-1251.
13. Bhatt MK, Labanya R, Joshi HC. Influence of long-term chemical fertilizers and organic manures on soil fertility-A review. *Universal Journal of Agricultural Research*. 2019;7(5):177-188.
 14. Yadav SK, Benbi DK, Prasad R. Effect of continuous application of organic and inorganic sources of nutrients on chemical properties of soil. *International Journal of Current Microbiology and Applied Sciences*. 2019;8(4):2455-63.
 15. Kwiatkowski CA, Harasim E. Chemical properties of soil in four-field crop rotations under organic and conventional farming systems. *Agronomy*. 2020;10(7):1045.
 16. Niemiec M, Chowaniak M, Sikora J, Szeląg-Sikora A, Gródek-Szostak Z, Komorowska M. Selected properties of soils for long-term use in organic farming. *Sustainability*. 2020;12(6):2509.
 17. Sidhu BS, Sharda R, Singh S. A study of availability and utilization of water resources in Punjab. *Current World Environment*. 2020;15(3):544-559.
 18. Vatta K, Budhiraja P. Agriculture in Indian Punjab. *Sustainable Development in India: Groundwater Irrigation, Energy Use, and Food Production*; 2020.
 19. Singh H, Gill KS, Jha JN. Punjab. In *Geotechnical characteristics of soils and rocks of India*. CRC Press. 2021;537-556.
 20. Dhaliwal SS, Naresh RK, Mandal A, Singh R, Dhaliwal MK. Dynamics and transformations of micronutrients in agricultural soils as influenced by organic matter build-up: A review. *Environmental and Sustainability Indicators*. 2019;1: 100007.
 21. Halder TK, Dolui AK, Saha D. Monitoring of nutrient status in an alluvial soil amended with different inorganic and organic fertilizers. *Int. J. Curr. Microbiol. App. Sci*. 2020;9(5):3465-3473.
 22. Garg N, Choudhary OP, Thaman S, Sharma V, Singh H, Vashistha M, Dhaliwal MS. Effects of irrigation water quality and NPK-fertigation levels on plant growth, yield and tuber size of potatoes in a sandy loam alluvial soil of semi-arid region of Indian Punjab. *Agricultural Water Management*. 2022;266: 107604.
 23. Meena RS, Das A, Yadav GS, Lal R. (Eds.). *Legumes for soil health and sustainable management*; 2018.
 24. Krishan G, Rao MS, Ghosh NC. Groundwater Resources in Punjab and Bist-Doab Area: An Appraisal and Overview. In *Riverine Systems: Understanding the Hydrological, Hydrosocial and Hydro-heritage Dynamics*. Cham: Springer International Publishing. 2022;187-213.
 25. Zade S, Gourkhede PH, Vaidya PH, Singh RS, Sinha SK, Kumar A, Kumar V. *Problem Soils and Their Management Practices*; 2021.
 26. Ahada CP, Suthar S. Assessing groundwater hydrochemistry of Malwa Punjab, India. *Arabian Journal of Geosciences*. 2018;11:1-15.
 27. Cons IJS. *Soil Conservation*. *Indian J. Soil Cons*. 2023;51(2)
 28. Monga AK, Kumar R. Geospatial mapping of minerals identified using x-ray diffraction in the soils of Punjab state in the north-west of Indian subcontinent. *Journal of the Indian Society of Remote Sensing*. 2022;50(3):549-562.
 29. Kumar S, Kumar D, Sekhon KS, Choudhary OP. Influence of levels and methods of boron application on the yield and uptake of boron by cotton in a calcareous soil of Punjab. *Communications in Soil Science and Plant Analysis*. 2018;49(4):499-514.
 30. Prakash R, Kumar R, Singh V, Singh VK. Soil microbial and nutrient dynamics influenced by irrigation-induced salinity and sewage sludge incorporation in sandy-loam textured soil. *International Agrophysics*. 2020;34(4).
 31. Hadda MS, Arora S, Singh DP. Assessment of soil physical characteristics as affected by soil conservation treatments under a semiarid tropical environment. *Journal of Natural Resource Conservation and Management*. 2023;4(1):92-99.
 32. Sahu H, Kumar U, Mariappan S, Mishra AP, Kumar S. Impact of organic and inorganic farming on soil quality and crop productivity for agricultural fields: A comparative assessment. *Environmental Challenges*. 2024;15:100903.
 33. Sharma J, Kumar P, Dua VK, Sharma V, Kumar D, Kumar S, Khan MA. Status of micronutrients in intensively cultivated potato growing soils of Punjab. *Potato Journal*. 2017;44(1).

34. Jaihoon Rafie JR, Raj Kumar RK, Kuldip Singh KS. Soil fertility mapping of the Experimental Farm of School of Agriculture in Lovely Professional University, Phagwara (Punjab); 2019.
35. Kanojia AK, Sreekesh S. Status of soil nutritional health in rice (*Oryza sativa*) fields: A study of Ludhiana district in Punjab; 2022.
36. Dwivedi BS, Singh VK, Shekhawat K, Meena MC, Dey A. Enhancing use efficiency of phosphorus and potassium under different cropping systems of India. *Indian J. Fertil.* 2017;13(8):20-41.
37. Vaisnow B, Sengar SS, Jatav GK, Patel T, Bhagat RK. Soil fertility status of major nutrient in vertisol of Dhamtari block. *Journal of Plant Development Sciences.* 2014;6(4):587- 591.
38. Sharma T, Sharma A, Kaur I, Mahajan RK, Litoria PK, Sahoo SK, Bajwa BS. Uranium distribution in groundwater and assessment of age dependent radiation dose in Amritsar, Gurdaspur and Pathankot districts of Punjab, India. *Chemosphere.* 2019;219:607-616.
39. Verma G, Dhaliwal SS, Sharma V, Singh J, Dhillon BS, Randhawa HS. Soil fertility assessment of pau regional research station, Gurdaspur, Punjab. *Agricultural Research Journal.* 2023;60(5).
40. Sunita MSB, Singh A. Evaluation of soil fertility status of adopted villages in Hoshiarpur district of Punjab; 2020.
41. Shikha D, Dadwal V, Kapil C, Singha G, Mehta V, Acharya R. Assessment of Macronutrients and Physicochemical Parameters of Agricultural Soils in Nawanshahr-Hoshiarpur Districts of Punjab; 2023.
42. Singh H, Singh J. Soil fertility status as influenced by cropping system in submountain zone of lower Shiwalik hills in Punjab. *Journal of Krishi Vigyan.* 2017;6(1):197-199.
43. Verma RR, Srivastava TK, Singh KP. Fertility status of major sugarcane growing soils of Punjab, India. *Journal of the Indian Society of Soil Science.* 2016;64(4):427-431.
44. Kumar S, Sharma P, Kumar R. Assessing agricultural practices and plant protection methods in Rupnagar District, Punjab, India. *Asian Journal of Agricultural and Horticultural Research.* 2023;10(4):594-606.
45. Kaur, Navdeep, Vipan Kumar Rampal. Irrigation water use pattern and constraints faced by the farmers in Punjab. *Indian Journal of Extension Education.* 2022;58(3):77–82.
46. Sandhu, Randhir Singh, Simerpreet Kaur Sehgal, Kumar Amrit, Navdeep Singh, Didar Singh. Environmental monitoring to assess ground water quality and its impact on soils in Southwestern India. *Acta Geophysica.* 2022;70(1):349–60.
47. Srivastava AK. Nutrient management in citrus orchards of Himalayan mid-hill regions of India. *Balanced Fertilization for Sustaining Crop Productivity;* 2006.
48. Sangeet, Ranguwal, Raj Kumar. *Handbook of Solid Waste Management: Sustainability through Circular Economy.* 2020;1–32.
49. Yadav BK, Jagdish Grover, Sukhwinder Singh. Effect of soil calcium carbonate on growth, yield and nutrient content in cotton crop under semi-arid region of Punjab. *Journal of the Indian Society of Soil Science.* 2023;71(4):421–27.
50. Yadav BR, Sidhu AS, Deepak Kumar Deepak Kumar. Distribution and Indexation of Plant Available Nutrients in Bathinda District of South-West. Punjab, India; 2018.
51. Dhaliwal NS, Karamjit Sharma, Sandhu GS. Status of different varieties and fertilizer use in Wheat (*Triticum Aestivum L.*) in Sri Muktsar Sahib District of Punjab. *Journal of Krishi Vigyan.* 2018;7(1):192–96.
52. Thind, Surinder, Kumar JS. Package of practices for cultivation of fruits. Additional Director of Communication for Punjab Agricultural University: Ludhiana. 2021;1–188.
53. Panjgotra S, Sangha GK, Sharma S. The impact of earthworm population and cast properties in the soils of wheat fields in different regions of Punjab. *J Ent. Zool. Stud.* 2019;7(3):857-862.
54. Biratu, Gizachew Kebede, Eyasu Elias, Pheneas Ntawuruhunga, Gudeta W. Sileshi. Cassava response to the integrated use of manure and NPK Fertilizer in Zambia. *Heliyon.* 2018;4(8):e00759.
55. Verma VK, Patel LB, Toor GS, Sharma PK. Spatial distribution of macronutrients in soils of Arid Tract of Punjab, India. *International Journal of Agriculture and Biology.* 2005;7(2):295–97.

56. Havlin JL. Soil: Fertility and nutrient management. In Landscape and land capacity. CRC Press. 2020;251-265.
57. Herrick JE, Wander MM. Relationships between soil organic carbon and soil quality in cropped and rangeland soils: The importance of distribution, composition, and soil biological activity. In Soil processes and the carbon cycle. CRC Press. 2018;405-425.
58. Loide V, Saue T, Võsa T, Tamm K. The effect of acidified slurry on crop uptake and leaching of nutrients from a loamy topsoil. *Acta Agriculturae Scandinavica, Section B—Soil and Plant Science*. 2020;70(1):31-38.
59. Han E, Li F, Perkons U, Küpper PM, Bauke SL, Athmann M, Köpke U. Can precrops uplift subsoil nutrients to topsoil? *Plant and Soil*. 2021;463:329-345.
60. Meyer N, Welp G, Rodionov A, Borchard N, Martius C, Amelung W. Nitrogen and phosphorus supply controls soil organic carbon mineralization in tropical topsoil and subsoil. *Soil Biology and Biochemistry*. 2018;119:152-161.
61. Ali S, Liu K, Ahmed W, Jing H, Qaswar M, Kofi Anthonio C, Zhang H. Nitrogen mineralization, soil microbial biomass and extracellular enzyme activities regulated by long-term N fertilizer inputs: A comparison study from upland and paddy soils in a red soil region of China. *Agronomy*. 2021;11(10):2057.
62. Liang Z, Olesen JE, Jensen JL, Elsgaard L. Nutrient availability affects carbon turnover and microbial physiology differently in topsoil and subsoil under a temperate grassland. *Geoderma*. 2019; 336:22-30.
63. Young KE, Ferrenberg S, Reibold R, Reed SC, Swenson T, Northen T, Darrouzet-Nardi A. Vertical movement of soluble carbon and nutrients from biocrusts to subsurface mineral soils. *Geoderma*. 2022;405:115495.
64. Amirhajloo S, Gheysari M, Shayannejad M, Shirvani M. Selection of the best nitrogen fertilizer management scenario in wheat based on Palmer drought severity index with an environmental perspective. *European Journal of Agronomy*. 2023;151: 126980.
65. Marschner P, Rengel Z. Nutrient availability in soils. In Marschner's Mineral Nutrition of Plants. Academic press. 2023;499-522.
66. Naylor D, McClure R, Jansson J. Trends in microbial community composition and function by soil depth. *Microorganisms*. 2022;10(3):540.
67. Germon A, Laclau JP, Robin A, Jourdan C. Tamm Review: Deep fine roots in forest ecosystems: Why dig deeper? *Forest Ecology and Management*. 2020;466:118135.
68. Mahesh V. A review of the evaluation of soil fertility status of Punjab state of India. *The Pharma Innovation*. 2022;12(2):3701-3706.
69. Vashisht BB, Maharjan B, Sharma S, Kaur S. Soil quality and its potential indicators under different land use systems in the Shivaliks of Indian Punjab. *Sustainability*. 2020;12(8):3490.
70. Maini A, Sharma V, Sharma S. Assessment of soil biochemical properties and soil quality index under rainfed land use systems in submontane Punjab, India; 2022.
71. Mandal A, Toor AS, Dhaliwal SS. Effect of land-uses on physico-chemical properties and nutrient status of surface (0–15 cm) and sub-surface (15–30 cm) layers in soils of South-Western Punjab, India. *Int. J Curr. Microbiol. Appl. Sci*. 2018;7:2659-2671.
72. Dhaliwal SS, Naresh RK, Walia MK, Gupta RK, Mandal A, Singh R. Long-term effects of intensive rice–wheat and agroforestry based cropping systems on build-up of nutrients and budgets in alluvial soils of Punjab, India. *Archives of Agronomy and Soil Science*. 2020;66(3):330-342.
73. Sharma BD, Raj-Kumar, Manchanda JS, Dhaliwal SS, Thind HS, Yadvinder-Singh. Mapping of chemical characteristics and fertility status of intensively cultivated soils of Punjab, India. *Communications in Soil Science and Plant Analysis*. 2016;47(15): 1813-1827.
74. Bhole BS, Sharma S. Seasonal variation of rhizospheric soil properties under different land use systems at lower Shivalik foothills of Punjab, India. *Agroforestry Systems*. 2020;94:1959-1976.
75. Penn CJ, Camberato JJ. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture*. 2019;9(6):120.
76. Neina D. The role of soil pH in plant nutrition and soil remediation. *Applied and Environmental Soil Science*. 2019;2019(1): 5794869.

77. Alam SI, Hammuda H, Khan F, Al Enazi R, Goktepe I. Electrical conductivity, pH, organic matter and texture of selected soils around the Qatar university campus. *Research in Agriculture Livestock and Fisheries*. 2020;7(3):403-409.
78. Usharani KV, Roopashree KM, Naik D. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *Journal of Pharmacognosy and Phytochemistry*. 2019;8(5):1256-1267.
79. Solly EF, Weber V, Zimmermann S, Walthert L, Hagedorn F, Schmidt MW. Is the content and potential preservation of soil organic carbon reflected by cation exchange capacity? A case study in Swiss forest soils. *Biogeosciences Discussions*. 2019;1-32.
80. Domingues RR, Sánchez-Monedero MA, Spokas KA, Melo LC, Trugilho PF, Valenciano MN, Silva CA. Enhancing cation exchange capacity of weathered soils using biochar: Feedstock, pyrolysis conditions and addition rate. *Agronomy*. 2020;10(6):824.
81. Ćirić V, Prekop N, Šeremešić S, Vojnov B, Pejić B, Radovanović D, Marinković D. The implication of cation exchange capacity (cec) assessment for soil quality management and improvement. *Agriculture and Forestry/Poljoprivreda i šumarstv*. 2023;69(4).
82. Ge N, Wei X, Wang X, Liu X, Shao M, Jia X, Zhang Q. Soil texture determines the distribution of aggregate-associated carbon, nitrogen and phosphorous under two contrasting land use types in the Loess Plateau. *Catena*. 2019;172:148-157.
83. Ding SJ, Zhang XF, Yang WL, Xin XL, Zhu AN, Huang SM. Soil nutrients and aggregate composition of four soils with contrasting textures in a long-term experiment. *Eurasian Soil Science*. 2021;54:1746-1755.
84. Dhiman G, Bhattacharya J, Roy S. Soil textures and nutrients estimation using remote sensing data in north India-Punjab region. *Procedia Computer Science*. 2023;218:2041-2048.
85. Kome GK, Enang RK, Tabi FO, Yerima BPK. Influence of clay minerals on some soil fertility attributes: A review. *Open Journal of Soil Science*. 2019;9(9):155-188.
86. Liao W, Thomas SC. Biochar particle size and post-pyrolysis mechanical processing affect soil pH, water retention capacity, and plant performance. *Soil Systems*. 2019;3(1):14.
87. Abuarab ME, El-Mogy MM, Hassan AM, Abdeldaym EA, Abdelkader NH, BI El-Sawy M. The effects of root aeration and different soil conditioners on the nutritional values, yield, and water productivity of potato in clay loam soil. *Agronomy*. 2019;9(8):418.
88. Pandao MR, Thakare AA, Choudhari RJ, Navghare NR, Sirsat DD, Rathod SR. Soil health and nutrient management. *International Journal of Plant and Soil Science*. 2024;36(5):873-883.
89. Bashir O, Ali T, Baba ZA, Rather GH, Bangroo SA, Mukhtar SD, Bhat RA. Soil organic matter and its impact on soil properties and nutrient status. *Microbiota and biofertilizers, Vol 2: Ecofriendly tools for reclamation of degraded soil environs*. 2021;129-159.
90. Corwin DL, Scudiero E. Field-scale apparent soil electrical conductivity. *Soil Science Society of America Journal*. 2020;84(5):1405-1441.
91. Gondek M, Weindorf DC, Thiel C, Kleinheinz G. Soluble salts in compost and their effects on soil and plants: A review. *Compost Science and Utilization*. 2020;28(2):59-75.
92. Wali SU, Gada MA, Umar KJ, Abba A, Umar A. Understanding the causes, effects, and remediation of salinity in irrigated fields: A review. *International Journal of Agriculture and Animal Production (IJAAP) ISSN, 2799-0907*; 2021.
93. Othaman NN, Isa MN, Ismail RC, Ahmad MI, Hui CK. Factors that affect soil electrical conductivity (EC) based system for smart farming application. In *AIP conference proceedings*. AIP Publishing. 2020;2203(1).
94. Zhang C. *Fundamentals of environmental sampling and analysis*. John Wiley and Sons; 2024.
95. Song D, Tang J, Xi X, Zhang S, Liang G, Zhou W, Wang X. Responses of soil nutrients and microbial activities to additions of maize straw biochar and chemical fertilization in a calcareous soil. *European Journal of Soil Biology*. 2018;84:1-10.
96. Zhang WW, Chong WANG, Rui XUE, Wang LJ. Effects of salinity on the soil microbial community and soil fertility.

- Journal of Integrative Agriculture. 2019;18(6):1360-1368.
97. Mhete M, Eze PN, Rahube TO, Akinyemi FO. Soil properties influence bacterial abundance and diversity under different land-use regimes in semi-arid environments. *Scientific African*. 2020;7:e00246.
 98. Karimi A, Moezzi A, Chorom M, Enayatizamir N. Application of biochar changed the status of nutrients and biological activity in a calcareous soil. *Journal of Soil Science and Plant Nutrition*. 2020;20:450-459.
 99. Duiker SW. Soil organic matter and nutrient availability. In *Soil Organic Carbon and Feeding the Future*. CRC Press. 2021;103-136.
 100. Islam MR, Bilkis S, Hoque TS, Uddin S, Jahiruddin M, Rahman MM, Datta R. Mineralization of farm manures and slurries under aerobic and anaerobic conditions for subsequent release of phosphorus and sulphur in soil. *Sustainability*. 2021;13(15):8605.
 101. Antil RS, Narwal RP, Singh BR. Raising soil organic matter to improve productivity and nutritional quality of food crops in India. In *Soil Organic Matter and Feeding the Future*. CRC Press. 2021;235-258.
 102. Virk AL, Yadav GS, Zhao X, Kan ZR, Qi JY, Ahmad N, Zhang HL. Role of legumes in managing soil organic matter and improving crop yield. In *Soil Organic Matter and Feeding the Future*. CRC Press. 2021;259-278.
 103. Brust GE. Management strategies for organic vegetable fertility. In *Safety and practice for organic food*. Academic Press. 2019;193-212.
 104. Mattos Jr D, Kadyampakeni DM, Oliver AQ, Boaretto RM, Morgan KT, Quaggio JA. Soil and nutrition interactions. In *The genus citrus*. Woodhead Publishing. 2020;311-331.
 105. Yahaya SM, Mahmud AA, Abdullahi M, Haruna A. Recent advances in the chemistry of nitrogen, phosphorus and potassium as fertilizers in soil: A review. *Pedosphere*. 2023;33(3):385-406.
 106. Raza T, Qadir MF, Khan KS, Eash NS, Yousuf M, Chatterjee S, Oetting JN. Unrevealing the potential of microbes in decomposition of organic matter and release of carbon in the ecosystem. *Journal of Environmental Management*. 2023;344:118529.
 107. Filipović A, Perčin A, Hadžiabulić A, Mandić A. Transformation of organic matter and impact on the ecosystem. In *Agroforestry for Carbon and Ecosystem Management* Academic Press. 2024;311-329.
 108. Kumar A, Choudhary AK, Pooniya V, Suri VK, Singh U. Soil factors associated with micronutrient acquisition in crops-biofortification perspective. *Biofortification of Food Crops*. 2016;159-176.
 109. Kumar R, Kumar R, Mittal S, Arora M, Babu JN. Role of soil physicochemical characteristics on the present state of arsenic and its adsorption in alluvial soils of two agri-intensive region of Bathinda, Punjab, India. *Journal of Soils and Sediments*. 2016;16:605-620.
 110. Bhattacharyya R, Ghosh BN, Dogra P, Mishra PK, Santra P, Kumar S, Parmar B. Soil conservation issues in India. *Sustainability*. 2016;8(6):565.
 111. Mittal S, Saini SP. Evaluation of nutrient index using manganese as a measure of fertility status of soils under different cropping systems of Punjab in North-Western India. *Journal of the Indian Society of Soil Science*. 2020;68(4):415-422.
 112. Jat ML, Stirling CM, Jat HS, Tatarwal JP, Jat RK, Singh R, Shirsath PB. Soil processes and wheat cropping under emerging climate change scenarios in South Asia. *Advances in Agronomy*. 2018;148:111-171.
 113. Kunal, Sharma S, Gosal SK, Choudhary R, Singh R, Adholeya A. Optical sensing and arbuscular mycorrhizal fungi for improving fertilizer nitrogen and phosphorus use efficiencies in maize. *Journal of Soil Science and Plant Nutrition*. 2020;20:2087-2098.
 114. Kaur T, Sinha AK. Pesticides in agricultural run offs affecting water resources: A study of Punjab (India). *Agricultural Sciences*. 2019;10(10):1381-1395.
 115. Panhwar QA, Ali A, Naher UA, Memon MY. Fertilizer management strategies for enhancing nutrient use efficiency and sustainable wheat production. In *Organic farming*. Woodhead Publishing. 2019;17-39.
 116. Ackerson JP. *Soil sampling guidelines*. Purdue University, Purdue Extension; 2018.
 117. Jones J. *Soil analysis handbook of reference methods*. CRC press; 2018.

118. Kratz S, Vogel C, Adam C. Agronomic performance of P recycling fertilizers and methods to predict it: A review. *Nutrient Cycling in Agroecosystems*. 2019;115:1-39.
119. Lin D, Chen Y, Qiao Y, Qin D, Miao Y, Sheng K, Wang Y. A study on an accurate modeling for distinguishing nitrogen, phosphorous and potassium status in summer maize using in situ canopy hyperspectral data. *Computers and Electronics in Agriculture*. 2024;221:108989.
120. Liu D, Huang Y, An S, Sun H, Bhople P, Chen Z. Soil physicochemical and microbial characteristics of contrasting land-use types along soil depth gradients. *Catena*. 2018;162:345-353.
121. Mukhopadhyay D. Soil analysis: A relook and way forward. *Soil Analysis: Recent Trends and Applications*. 2020;1-18.
122. Singh G, Partap R, Dinesh D, Singh G, Jinger D, Singh G. Assessment of soil fertility status in sub-mountainous area of Rupnagar District, Punjab. *Ann. Agric. Res. New Series Vol. 42 (2)* : 199-208.
123. Singh VK, Malhi GS, Kaur M, Singh G, Jatav HS. Use of organic soil amendments for improving soil ecosystem health and crop productivity. *Ecosystem Services*; 2022.
124. Tyagi N, Upadhyay MK, Majumdar A, Pathak SK, Giri B, Jaiswal MK, Srivastava S. An assessment of various potentially toxic elements and associated health risks in agricultural soil along the middle Gangetic basin, India. *Chemosphere*. 2022;300:134433.
125. Zhang G, Bai J, Zhai Y, Jia J, Zhao Q, Wang W, Hu X. Microbial diversity and functions in saline soils: A review from a biogeochemical perspective. *Journal of Advanced Research*. 2024;59:129-140.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). This publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

© Copyright (2024): Author(s). The licensee is the journal publisher. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Peer-review history:

The peer review history for this paper can be accessed here:

<https://www.sdiarticle5.com/review-history/121395>