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Soil Texture: Unlocking Fertility and Productivity for Better Crops

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ABSTRACT

The soil texture has a significant impact on crop yield and soil fertility because it controls root penetration, nutrient availability, and water retention—all of which are essential for plant growth and development. This meta-analysis synthesizes data from several agroecosystems to provide a thorough knowledge of the interactions between soil textural classes (sand, silt, and clay proportions) and their effects on agronomic results. Sandy soils, which are distinguished by their coarse particles, have a low capacity to hold nutrients and drain water quickly, making frequent fertilization and irrigation necessary. On the other hand, clayey soils, which have fine particles, are more fertile and retain more moisture, but they also present problems, including inadequate aeration and drainage, which can impede root development and cause waterlogging. The correct ratio of sand, silt, and clay in balanced loamy soils frequently promotes maximum productivity because of their advantageous physical and chemical characteristics. A key challenge of the study was the variability in soil classification, measurement methods, and agroclimatic conditions across datasets, requiring careful standardization and interpretation. Despite these challenges, the study identifies consistent soil texture-yield patterns and offers practical, soil-specific management strategies. It underscores how understanding soil texture can boost yields, enhance fertilizer efficiency, and promote sustainable agriculture amid climate challenges.

Keywords: *Sand, Silt, Clay, Nitrogen, Crop production, Soil Texture, Soil fertility, Sustainable agriculture.*

Introduction

Soil particles can be classified into three primary types, namely sand, silt, and clay, based on their size. These particles are the fundamental components that make up soil minerals. The distribution of soil particles within each size range serves as the foundation for soil classification. The particle size distribution provides essential information regarding the mechanical composition of the soil [39]. Among the various classification criteria, soil texture is considered one of the most important [82]. Numerous soil texture classification schemes have emerged as a consequence of the fact that many nations and organizations have varied criteria for defining the size and texture of soil particles. The International Society of Soil Science system (ISSS system) and the system developed by the United States Department of Agriculture (USDA), the "Kachinsky system", are the widely used soil texture categorization standards worldwide [100]. The USDA system is the one that is applied the most commonly in relevant research by more than 80 countries and regions. In China, for instance, the USDA system is utilized in 62.86 percent of soil texture-related research publications [108].

The USDA classifies sand into five distinct categories: extremely fine, fine, medium, moderate, and coarse. Additionally, it defines the size boundaries of 2 µm, 50 µm, and 2000 µm for the clay, silt, and sand [10]. The USDA system divides the texture of soil into four categories: sand, loam, clay loam, and clay. Furthermore, soil texture is sub-divided into twelve textural classes based on variations in the physicochemical and mineralogical features of soil particles of varying sizes [100] [108].

Soil texture significantly influences the physical characteristics of the soil, including its permeability, specific surface area, and water-holding capacity. Changes in the soil microenvironment, particularly in microbial activity, lead to variations in nutrient cycling in the soil [17] [84]. Numerous studies have attempted to establish a correlation between the concentrations of clay and silt, total nitrogen (N) content, and organic matter content in soil [48] [61] [62]. Clay particles, due to their large specific surface area and colloidal properties, strongly adsorb organic molecules in the soil, as stated by Six et al. [97] and Kumari and Mohan [46]. Clay content in the soil is the critical factor in determining the stability of soil organic matter [24] [80]. According to Rakhsh et al. [75], an increase in the soil's clay concentration results in a large increase in the cation exchange capacity, microbial N content, and soil mineral N. Recent studies have demonstrated a relationship between soil nutrient indicators and the soil texture [44] [27]. For example, Wang et al. [104] investigated nutrient distribution in small-scale river

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basins and found that silt and sand content were the main factors influencing soil organic matter, total N and phosphorus levels. In contrast, other studies have reported minimal or no correlation between soil texture and organic matter content [40] [59] [87]. There is no clear correlation between soil texture and available nutrient content, as soil clay can partially inhibit the decomposition of organic matter while simultaneously adsorbing and stabilizing organic molecules.

As demonstrated by Franzluebbers et al., soil clay particles can simultaneously inhibit the decomposition of organic matter and stabilize organic molecules through adsorption, thereby fulfilling dual functions that complicate the relationship between soil texture and nutrient availability [22]. Nutrient availability in the upper soil profile plays a critical role in crop production and overall land productivity [20] [102]. However, long-term, high-intensity anthropogenic disturbances such as tillage, planting, irrigation, drainage, and fertilization, have significantly altered soil structure, particularly by disrupting macro-aggregates, breaking them into smaller particles. This phenomenon is especially pronounced in puddled transplanted rice systems, where puddling operations degrade macroparticles into fine individual particles. As a result, the N cycling dynamics and distribution in paddy soils differ substantially from those in other soil types [23] [49]. These processes contribute to the distinct physicochemical and biological characteristics that define paddy soils.

Nutrient content of the soil is a crucial indicator of the fertility of paddy soil, which significantly influences rice production [32] [109] [111]. Rice plants obtain a significant portion of their nutrients from the soil. However, the methods used for soil classification are primarily based on the diagnostic horizons, parent material [33] [50] [113] or the local traditional nomenclature [37] [78], which makes it difficult to translate such classification into a quantifiable factor for analysis. In addition to categorising soils according to their physicochemical properties, soil texture also offers a quantitative explanation of the criteria that influence soil texture, which further affects nutrient availabilities. These parameters include the amount of sand, silt, and clay that is present in the soil.

Soil separates

Size-classified soil separates are mineral particles. The main soil divisions are sand (0.05-2.0 mm), silt (0.002-0.05 mm), and clay (<0.002 mm) [95]. Sand improves aeration and drainage, silt retains water, while clay's high surface area and cation exchange capability contain nutrients. The proportion of these components affects soil texture, water retention, permeability, fertility, and workability. Effective soil management requires understanding soil components to maximize land use and agricultural techniques for soil qualities and crop needs [73]. To get more detailed information regarding soil separates and their importance in agriculture, a brief discussion is provided below:

Sand

Sand, a major component of soil, consists of mineral particles ranging in size from 0.05 to 2.0 mm. Due to its coarse texture and large particle size, sand imparts distinctive physical properties to the soil, such as enhanced drainage and improved aeration, both of which are critical for microbial activity and root respiration. Sandy soils are particularly beneficial for crops that require well-drained conditions, including root vegetables and horticultural plants, as they warm up more quickly during the growing season, promoting early crop establishment and effective water movement [13].

However, the inherent limitations of sandy soils include a low surface area and reduced CEC, which contribute to poor nutrient retention and low water-holding capacity. As a result, sandy soils are naturally less fertile and more prone to nutrient leaching. These limitations can be mitigated through sustainable techniques such as mulching, balanced fertilisation, and the integration of organic matter [47].

Beyond traditional agriculture, sand is also used in specialized systems where proper drainage is crucial, like turfgrass systems, nurseries, and greenhouse production. Furthermore, when soil is blended with finer particles like silt and clay to form loamy soils, it helps combine aeration with improved water and nutrient retention, thereby increases agricultural production [31]. The integration of sand with other soil components and amendments serves as the cornerstone of sustainable soil management.

Silt

Silt, a soil component with particle sizes ranging from 0.002 to 0.05 mm, plays a crucial role in assessing soil fertility and agricultural output. Due to its intermediate particle size, silt soils have special qualities that improve plant-available water, nutrient retention, and water-holding capacity [13]. The smooth texture of silt maintains a balance between permeability and water retention, facilitating easy tillage and good aeration. Silt particles improve root penetration and lower the danger of erosion by promoting soil aggregation and structural integrity. A variety of crops, such as cereals, legumes, and horticultural plants, can be grown in silt-rich soils since they are quite fertile. However, silt is susceptible to crusting and compaction, particularly when heavy gear or intensive farming methods are used. The necessity of sustainable soil management techniques is highlighted by the fact that these circumstances may prevent root development and water infiltration [47]. In loamy soils, where silt combines with sand and clay, it contributes significantly to creating an ideal growing medium for plants. The addition of organic matter to silt-rich soils can improve aggregation, stimulate microbial activity, and enhance nutrient availability, thereby mitigating compaction and erosion susceptibility [31]. Because of its ability to promote plant growth and healthy soil activities, silt is an essential part of soil systems that enhances agricultural production and environmental sustainability.

Clay

Clay, the finest soil fraction with particle sizes less than 0.002 mm, plays a crucial role in sustainable agriculture due to its distinct physico-chemical properties, which significantly influence soil fertility, structure, and water dynamics. Predominantly composed of secondary minerals such as kaolinite, montmorillonite, and illite, clay particles have a specific surface area, contributing to their exceptional capacity for nutrient and water retention [13]. Their inherent negative charge enables the absorption of essential plant nutrients, including potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), thereby enhancing soil CEC and nutrient availability.

Clay acts as a natural binding agent, promoting soil aggregation, improving root penetration, and enhancing aeration. Its high buffering capacity helps stabilize soil pH, mitigating abrupt fluctuations caused by fertiliser applications, thereby supporting consistent growing conditions [31].

Moreover, clay provides a slow-release mechanism for nutrients, reducing leaching losses and supporting crop nutrition [47].

Clay-rich soils are particularly valuable in arid and semi-arid regions due to their high water-holding capacity. However, if not managed properly, this characteristic can lead to waterlogging, compaction, and reduced aeration, which may restrict root development [67]. These limitations can be addressed through sustainable practices such as reduced tillage and the incorporation of organic matter, which enhances microbial activity, improves aggregate stability, and supports nutrient cycling [38] [106].

Despite certain management challenges, the multifunctional benefits of clay, ranging from enhanced fertility and water regulation to ecological resilience, underscore its essential role in advancing sustainable agriculture. Implementing appropriate soil management strategies can maximize the advantages of clay-rich soils, ensuring long-term agricultural productivity and environmental sustainability.

Soil textural triangle

The soil textural diagram, illustrating the proportions of sand, silt, and clay in soil, is fundamental to understanding soil fertility and crop production [92]. Soil texture directly affects key soil properties, including water retention, drainage, aeration, and nutrient availability, which are crucial for plant growth. Sandy soils, dominated by coarse particles, offer excellent drainage and aeration but struggle to retain water and nutrients, often requiring frequent irrigation and fertilisation. In contrast, clay soils have fine particles that enhance water and nutrient retention but can lead to poor aeration and waterlogging, challenging root development.

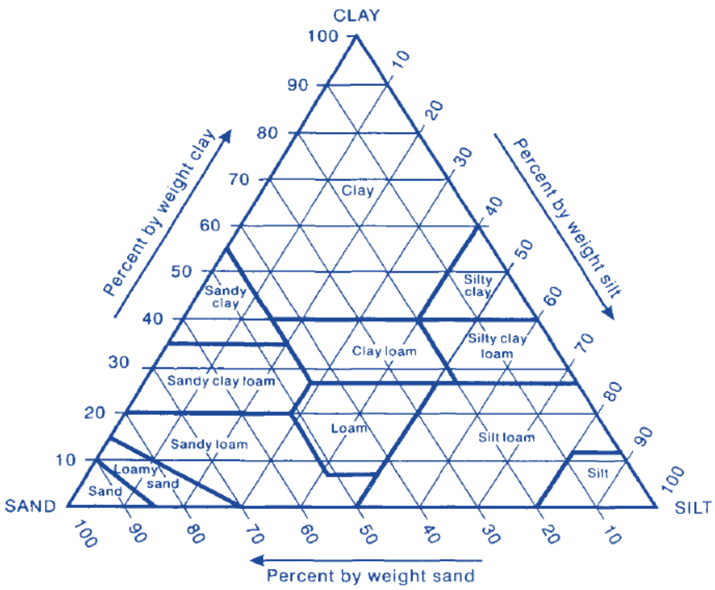

Fig 1: Soil textural diagram showing texturally divergent soil as per soil separates weightage [31]

Loamy soils, with a balanced mix of sand, silt, and clay, typically provide optimal conditions for most crops, combining good drainage with adequate fertility and moisture retention. The soil textural diagram aids in classifying soils like sandy loam, clay loam, or silty clay, helping farmers and agronomists design tailored management practices [28]. For instance, crops with shallow roots or high-water requirements thrive better in loamy soils, while deep-rooted crops may adapt to sandy soils with irrigation adjustments [103]. Furthermore, soil texture influences nutrient cycling and microbial activity. Coarser textures may lead to nutrient leaching, while finer textures immobilize nutrients, making them less available to plants [19] [94]. This knowledge guides the selection of fertilisers and irrigation strategies, optimising resource use. Hence, the soil textural diagram is an indispensable tool in agriculture, enabling sustainable land management and enhancing crop productivity by aligning soil characteristics with crop needs.

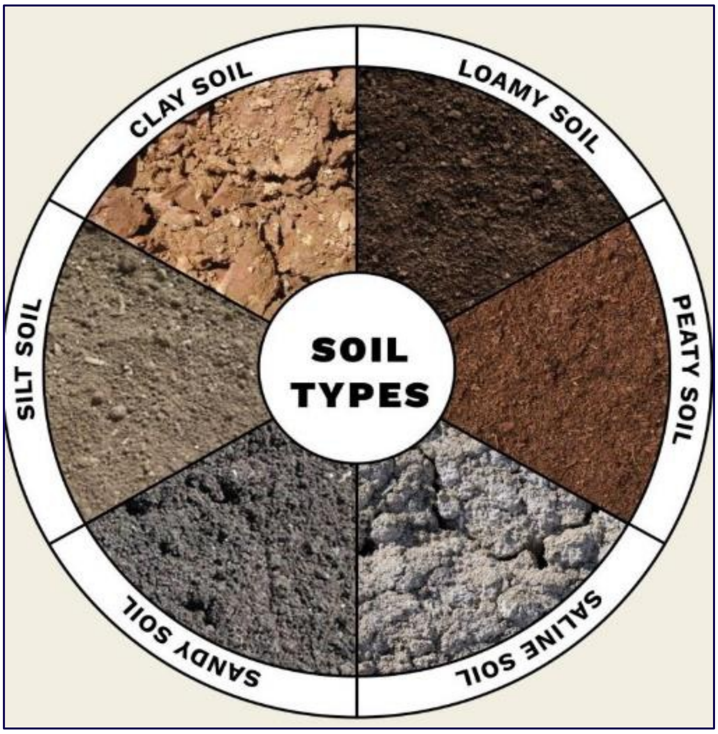

Fig. 2 Different soil textural classification

As depicted in Fig. 1 and Fig. 2, distinct grades are given to soils with varying amounts of sand, silt, and clay. Let's say that a soil has 50% sand, 20% silt, and 30% clay in order to demonstrate how to use the textural diagram in Fig. 1. Keep in mind that the triangle's right side denotes 0% sand and its bottom left apex symbolises 100% sand. Locate the 50% sand point on the diagram's lower edge, then follow the diagonally leftward line that rises from there and runs parallel to the sand zero line. Next, locate the 20% silt line, which is parallel to the silt zero line and represents the diagram's left edge. We are looking for the intersection of the two lines (where they meet the 30% line for clay). This specific instance falls under the category of "sandy clay loam." Observe that a certain class of soil holds a central position within the textural diagram. It describes a soil that has a "balanced" mixture of fine and coarse particles with characteristics halfway between those of clay, silt, and sand. Because of this, loam is frequently regarded as the best soil for agriculture and plant growth. It has a better ability to hold water and nutrients than sand, and it has better tillage, drainage, and aeration qualities than clay. However, this generalization is not always true. Sand or clay may be more appropriate than loam for many plant species under different environmental circumstances.

Particle size distribution

Dividing a continuous range of particle sizes into discrete fractions is arbitrary, and classifying soils into distinct textural groups is even more subjective [112]. Although this method is widely applied, a more informative approach involves measuring and presenting the entire spectrum of particle sizes.

Such a continuous representation of soil texture is commonly employed in engineering disciplines.

Fig. 3 illustrates typical particle size distribution curves, where the ordinates indicate the cumulative fraction of soil particles smaller than the corresponding particle diameter on the abscissa. Using a logarithmic scale on the X-axis enables effective visualisation of fine particles and accommodates multiple orders of magnitude in particle size. It is important to note that this graph represents integral or cumulative data. To create the particle size distribution curve, connect n points, each representing the cumulative fraction of particles finer than the measured diameters (F1, F2,..., Fn).

Fi = (Ms-∑Mi) ……………………………………………………………(1)

M_s

Ms represents the soil sample's total mass, while ∑Mi represents the cumulative mass of particles smaller than the observed diameter. The particle size distribution representation provides information on the largest grain diameter and grading pattern, indicating whether the soil has distinct groups of uniform-sized particles or a continuous array of particle sizes. Poorly graded soils have the majority of particles of one or more unique sizes, showing a step-like distribution curve. Well-graded soils have a smooth, flat distribution curve with no noticeable discontinuities.

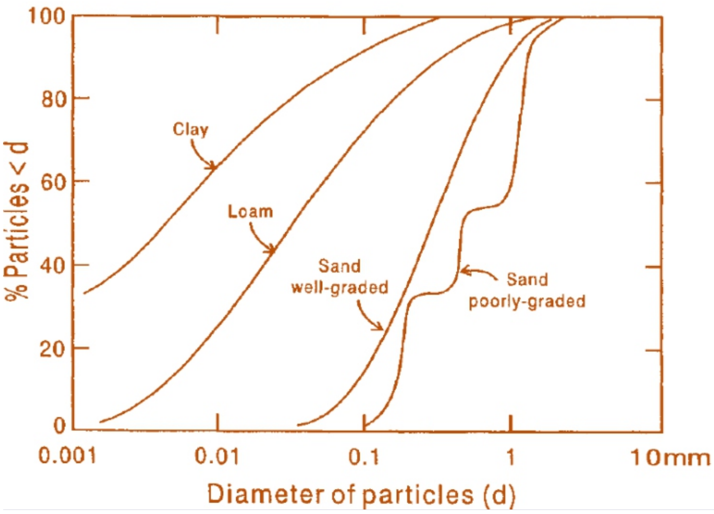

Fig 3: Particle size distribution curves for different soil separates [31]

The so-called definition of this aspect of the particle size distribution is the ratio of the larger diameter d_{60}, which contains 60% of the particles, to the smaller diameter dl0, which contains 10% of the particles (Fig. 3). If there existed a soil material made completely of particles of the same size, *Iu* would be unity. The homogeneity index of some sand deposits could be less than 10. Conversely, some well-graded soils have *IL* values higher than 1000. It is also possible to graphically differentiate the particle size distribution curve to produce a frequency distribution curve for grain sizes, where the most common grain size is shown by a peak. Correlations between this index and the harmonic mean diameter of the grains and other soil characteristics, such as permeability, have been attempted.

Texturally divergent soils *viz-a-viz* nutrient availability

The influence of soil texture on nutrient availability is mostly attributed to alterations in environmental parameters, such as hydraulic properties, water retention capacity, pore structure, and spatial distribution.

These changes influence the composition, activity, and function of the soil microbial system, which subsequently influences nutrient cycling [53] [72] [110]. Parton et al. [69] and Rakhsh et al. [76] determined that the ratio of silt to clay influences the stability of insoluble organic matter, with soil texture being the primary determinant of organic matter mineralisation and immobilisation. Rastetter et al. [81] established a connection between soil texture and moisture content, identifying the latter as the primary determinant of microbial activity and nutrient cycling. Moreover, Raich et al. [74] proposed that alterations in soil texture might affect the nutritional status of soil by changing microbial functionality. In addition to influencing the soil's chemical cycle and regulating soil fertility, soil texture is the primary determinant of plant root development and soil biodiversity [76] [93]. The correlation between the physicochemical properties of the land and its texture is contingent upon the degree of soil disturbance and the duration of soil recovery [90]. The impact of soil texture on various nutrient indices was observed to differ in rice fields that experienced frequent soil disturbances. Jian et al. [37] investigated the nutrient mineralisation and immobilisation capabilities of four diverse paddy soil types and found no significant differences in phosphorus immobilisation capacity among them. The highest N sequestration potential was observed in purple clayey soil, while the lowest capacity was observed in granitic sandy soil. Variation in nutrient availability across soils with different textural characteristics may attributed to the distinct adsorption and desorption conditions of the available nutrients. Moreover, an increase in clay content correspondd with a rise in CEC, aligning with findings from previous studies [58] [77] [89].

Soil particle size *viz-a-viz* nutrient contents/availability

Due to the colloidal nature and large surface area, secondary minerals contained in the clay particles have been shown to significantly influence soil nutrient dynamics. Specifically, clay content exhibits a strong positive correlation with total N, available N, and organic matter content in soil [16]. Similar correlation has been reported across diverse ecosystems [24] [29]. The large surface area of clay particles enhances the adsorption and retention of organic matter and N, thereby contributing to improved soil fertility.

In contrast, it was found that the phosphorus (P) cycle in the soil was independent of the organic carbon and N cycles. This could be attributed to differences in the microbial mineralisation and immobilisation pathways, as well as differences in the microbial regulation of carbon, N, and P homeostasis and immobilisation [12] [14]. Notably, clay content has been negatively correlated with soil P availability. Prior studies have reported that sandy soils typically exhibit higher available P levels than loamy soils, indicating a positive correlation between sand content and available P levels [104] [107] [115].

With respect to potassium (K), both silt and clay play a significant role in its supply, especially in loess-derived soils rich in mica [64]. Zubillaga et al. [116] demonstrated that silt particles can contribute up to 52 percent of the total K content in certain soils. Furthermore, Li et al. [52] reported a significant negative correlation between soil silt and total K, alongside a significant positive correlation with available K. This may be due to reduced diffusion and migration of nutrients, leading to their accumulation, particularly under high moisture conditions such as found in paddy soil [64] [101].

In addition, the CEC of the tillage layer soil was found to have a positive correlation with the soil clay and silt content. This observation was in line with the previous research, where higher clay content enhances the specific surface area of soil colloids and increases surface charge density [70] [72] [78]. These properties, in turn, enhance the soil's ability to adsorb and retain essential nutrient ions.

Table 1: Macro- and micronutrient retention capacities and leaching losses across various soil texture classes

Soil Texture Class	Macro Nutrient Retention (mg/kg)	Micro Nutrient Retention (mg/kg)	Leaching Losses (kg/ha)	References
Sandy	N: 5-10, P: 3-7, K: 20-30	Fe: 0.5, Zn: 0.3, Mn: 0.2	High (10-15)	[96]
Loamy sand	N: 45.79, P:11.53, K:23.07	-	-	[110]
Sandy loam	N: 65.80, P:45.39, K:82.35	-	-	[110]
Loamy	N: 4.6, P:63, K:482	Zn: 6.2, Mn: 45, Cu: 11.4	-	[68]
Silty loam	N: 110.73, P:34.42, K:135.09	-	-	[110]
Silt	N: 83.45, P:26.97, K:143.32	-	-	[110]
Sandy clay loam	N: 3.6, P:84, K:467	Zn: 8.1, Mn: 66, Cu: 15.6	-	[68]
Clay loam	N: 4.8, P:60, K:519	Zn: 5.3, Mn: 38, Cu: 10.3	-	[68]
Silty clay loam	N: 5, P:62, K:524	Zn: 5.9, Mn: 45, Cu: 10.6	-	[68]
Clayey	-	Fe: 30.3, Zn: 0.56, Mn: 2.82, Cu: 0.11	-	[43]
Sandy loam	-	Fe: 59.1, Zn: 0.40, Mn: 1.80, Cu: 0.18	-	[43]

Table 1 illustrates the leaching and nutrient retention characteristics of different soil texture classes, offering information on their management and agricultural applicability. Due to the coarse texture and limited CEC, sandy soils have poor retention of macronutrients (N: 5–10 mg/kg, P: 3–7 mg/kg, K: 20–30 mg/kg) and micronutrients (Fe: 0.5 mg/kg, Zn: 0.3 mg/kg, Mn: 0.2 mg/kg). These soils are less suitable for crops that do not receive regular watering and fertilisation due to their substantial leaching losses (10–15 kg/ha) [66] [96].

Nutrient retention varies significantly across soil types, with sandy loam and loamy sand soils exhibiting better macronutrient retention capacities. Among these, sandy loam tends to retain higher amounts of macronutrients, with recorded values such as N at 65.8 mg/kg, P at 45.4 mg/kg, and K at 82.3 mg/kg [110]. However, there remains a lack of detailed data concerning the retention of specific micronutrients in these soils. Depending on management, loamy soils provide balanced macronutrient retention. Reported N levels in loamy soils range from 4.6-15 mg/kg, reflecting variability across datasets. Micronutrients such as iron (1.0 mg/kg), zinc (6.2 mg/kg), and manganese (45 mg/kg) are generally better retained in loamy soils [68]. Silty loam and silt retain large levels of macronutrients – N at 110.73 mg/kg and K at 143.32 mg/kg. They are nutrient-rich and appropriate for crops that require a lot of nutrients [110]. The higher nutrient retention (K: up to 524 mg/kg, Mn: 66 mg/kg) and the lowest leaching losses (2–5 kg/ha) are found in clayey soils (clay loam and silty clay loam). Although these soils are perfect for intensive farming, waterlogging must be controlled by adequate drainage [43]. This analysis emphasises how crucial it is to modify soil management techniques to suit particular textures in order to maximise crop output and fertiliser utilisation.

Soil texture *viz-a-viz* moisture retention

The texture of the soil affects agricultural water availability, determines soil management techniques, and is crucial for moisture retention [103]. Clayey soils require careful drainage management, whereas sandy soils need regular watering and organic inputs. Loamy and silty soils are perfect for agriculture because they offer a balanced environment for plant growth [86].

In order to maximise water utilization, increase crop yields, and advance sustainable agriculture, farmers must comprehend and manage soil texture in relation to moisture retention. Sandy soils hold less moisture due to larger particle size, resulting in water leaching, thereby reducing the chance of waterlogging [71]. This increases vulnerability to drought stress and requires more frequent irrigation. To boost moisture retention and water-holding ability, farmers frequently add organic matter to sandy soils. Nonetheless, loamy soils, which are sometimes regarded as the best soil for agriculture, provide a well-balanced texture with a combination of clay, silt, and sand. The ratio of macropores (for drainage) to micropores (for moisture retention) is favourable in loamy soils. They are appropriate for a wide range of crops because they retain enough moisture for plant growth without becoming soggy. Additionally, the moderate retention lowers the frequency of watering, which improves water efficiency [65].

Silty soils have a smooth feel because their particles are larger than clay but smaller than sandy soils. Because of their larger surface area and smaller pores, these soils hold moisture better than sandy soils. For plants that are sensitive to moisture, silty soils are perfect because they are frequently fertile and give crops enough water. They may, however, compress, which could prevent root penetration and drainage. This limitation can be overcome with organic additives and proper tillage.

Among all soil textures, clayey soils have the highest potential to hold water due to their tiny particles and large surface area. Clay soil's tiny pores hold water in place, reducing the amount of water that plants may access. Although clay soils are excellent at holding onto moisture, their poor drainage makes them vulnerable to waterlogging [42] [63]. Furthermore, clayey soils are difficult to deal with in both wet and dry conditions, and careful handling is required to keep aeration and avoid compaction. Root development, nutrient uptake, and general plant health are all directly impacted by moisture availability. While clayey soils may impede root oxygenation because of waterlogging, sandy soils frequently need frequent irrigation to meet plant water needs. The best moisture conditions are found in loamy and silty soils, which promote balanced growth and nutrient transmission [4].

Table 2: Field capacity, permanent wilting point, and available water content across various soil texture classes

Soil Texture Class	Field Capacity (%)	Permanent Wilting Point (%)	Available Water Content (%)	References
Sandy	5-10	1-5	4-9	[98]
Loamy sand	14.9	8.4	6.5	[83]
Sandy loam	32.4	16.4	16.0	[83]
Silt loam	31.0	11.0	20.0	[85]
Silt loam	-	8.38	-	[45]
Silt	30.0	6.0	25.0	[85]
Sandy clay loam	-	11.7	-	[18]
Clay loam	28.8	17.42	-	[41]
Silty clay loam	-	11.63	-	[45]
Silty clay loam	27.07	13.63	-	[41]
Sandy clay	-	12.84	-	[18]
Silty clay	27.0	16.78	-	[41]
Clayey	31.36	20.0	-	[41]

Table 2 and Fig. 4 delineate the correlation between soil texture classifications and their water retention characteristics, encompassing field capacity (the moisture retained by soil post-drainage of excess water), permanent wilting point (the critical moisture threshold at which plants exhibit wilting), and available water content (the variance between field capacity and wilting point). Sandy soils exhibit a low field capacity (5–10%) and a permanent wilting threshold (1–5%), leading to a restricted accessible water content (4–9%). Their substantial particles rapidly expel water, making them less suitable for crops that require regular irrigation [98]. Loamy sand and sandy loam demonstrate enhanced water retention. Loamy sand possesses a field capacity of 14.9% and an available water content of 6.5%, but sandy loam exhibits a greater field capacity of 32.4% and an available water content of 16% [83]. Loamy soils maintain equilibrium, exhibiting a field capacity of 15–25%, a permanent wilting point of 5–10%, and an accessible water content of 10–20%. These characteristics render them adaptable for agricultural purposes. Silt loam and silt have exceptional water retention capabilities, possessing field capacities of 30–31%, low wilting points of 6–11%, and high accessible water content ranging from 20–25%. This renders them optimal for crops that are sensitive to water [45] [85]. Clayey soils, such as silty clay loam and clay loam, possess the highest water retention capacity owing to their fine texture, exhibiting field capacities between 27–50% and available water content of 20–30%. Nonetheless, high wilting points (10–20%) restrict water accessibility for plants [41]. These findings underscore the significance of soil-specific irrigation and management techniques for optimal water utilization and crop yield.

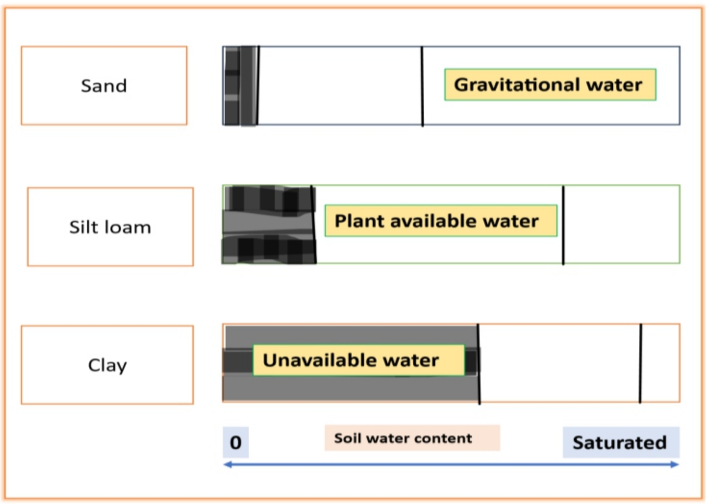

Fig 4. Soil Texture influences water retention

Soil Texture Viz-a-Viz Soil Aeration and Temperature

The proportions of sand, silt, and clay particles determine soil texture, which affects aeration and temperature. Both factors affect root growth, microbial activity, and plant health, affecting the soil's ability to support sustainable agriculture. Air exchange between the soil and the atmosphere facilitates the supply of oxygen to roots and soil microorganisms while enabling the removal of carbon dioxide [30]. Sandy soils, characterized by larger particles and pore spaces, are typically well-aerated. The macropores promote fast gas exchange, promoting root respiration in oxygen-rich environments [15]. However, excessive aeration can cause moisture loss, requiring frequent irrigation.

Loamy soils, with their intermediate texture of sand, silt, and clay particles, provide a balanced combination of aeration and moisture retention. Loamy soils sustain moisture and oxygen availability due to their balanced macropore and micropore distribution [88]. These traits make loamy soils good for most agriculture. Clayey soils, with their tiny particles and high density, lack aeration, causing oxygen deficiency in saturated or compacted states. In poorly drained, waterlogged conditions, root growth and microbial activity may be inhibited due to reduced aeration. However, well-managed clayey soils with adequate drainage can improve aeration and thereby enhance crop development.

Seed germination, root growth, and microbial activity depend on soil temperature. Texture affects soil temperature through heat transfer, water retention, and surface exposure [5]. Sandy soils, with limited water retention and light colour, warm up quickly during the day but cool quickly at night [34]. They are suitable for temperate early-season crops but require careful water management to avoid drought stress. Due to balanced water retention and heat conductivity, loamy soils minimise temperature variations. Stable heat settings encourage root and microbial activity for year-round cultivation. Clayey soils warm and cool more slowly. They are cooler in summer and warmer in winter than sandy soils due to their high water retention ability. In colder climates, their dense nature can prevent root penetration and delay seed germination. Aeration and temperature are controlled by soil texture, affecting crop performance and soil health. Farmers can optimise these characteristics and ensure sustainable agricultural yield by adjusting management strategies to soil textures.

Table 3. Physical properties of soil texture classes: aeration, thermal conductivity, and temperature fluctuations

Soil texture Class	Aeration (Oxygen Diffusion Rate, μg cm^{-2} s^{-1})	Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	Soil Temperature Fluctuations (Seasonal Variability, °C)	References
Sandy	High (60-80)	0.3-0.6	High (10-20)	[26]
Loamy sand	4.8	1.82	-	[3] [21]
Silty clay	3.6	-	-	[21]
Clay loam	-	0.33-0.72	-	[1]
Silty clay loam	-	0.23	-	[55] [56]
Loamy	-	0.15-0.79	-	[25]
Silty clay	-	0.22	-	[56]
Silt loam	-	0.23	13.25	[2] [56]
Sandy	-	0.91	16.0	[2] [3]

Soil aeration, thermal conductivity, and temperature fluctuations, all essential components of soil health and crop productivity, are influenced by soil texture (Table 3). Sandy soils have high aeration rates (60–80 μg cm^{-2} s^{-1}) because of the large pore spaces, which facilitate quick transport of oxygen. Their considerable seasonal temperature variations (10–20°C) are caused by their thermal conductivity, which ranges from 0.3 to 0.6 $W\ m^{-1}\ K^{-1}$. Because of this, they are well-aerated, but they are also susceptible to abrupt temperature changes, which can cause stress to plants [26].

Loamy soils have moderate heat conductivity (0.8–1.2 $W\ m^{-1}K^{-1}$) and aeration (30–50 μg $cm^{-2}s^{-1}$). They are perfect for steady crop growth due to their mild temperature swings (5–10°C). Numerous agricultural applications can benefit greatly from these well-balanced qualities. Clayey soils, due to fine texture, have low aeration (10–20 μg $cm^{-2}s^{-1}$), which restricts oxygen diffusion. However, steady temperatures (3–5°C) are guaranteed by their high thermal conductivity (1.5–2.0 $W\ m^{-1}K^{-1}$). They are susceptible to compaction and waterlogging despite being thermally stable. Other soil types, including loamy sand, exhibit moderate aeration and variable heat conductivity (e.g., 1.82 $W\ m^{-1}\ K^{-1}$) [21]. According to Lu et al. [56], silt loam exhibits moderate temperature variability (~13°C), and silty clay and silt loam have poor thermal conductivity (~0.23 $W\ m^{-1}K^{-1}$). As a result, clayey soils offer thermal stability but struggle with aeration, while sandy soils are excellent at aeration but suffer from significant temperature fluctuations (Table 3).

Soil texture *viz a viz* crop grain yields

Soil nutrient availability and its interaction with rice plant nutrient absorption play a foundational role in determining yield and morphological development of rice crops [35] [57] [109]. As the primary biomass component of the rice crop, rice plants serve as both indicators and beneficiaries of the soil's nutrient supplying capacity. The efficiency with which plants absorb nutrients is influenced by a range of soil physico-chemical properties, which govern nutrient cycling and the release of plant-available nutrients.

Several studies highlight the role of soil texture and composition in modulating nutrient dynamics. For instance, Zheng et al. [114] demonstrated that the roughness of the soil alters the microbial population affects N distribution and accumulation in flue-cured tobacco. Furthermore, Wang et al. [105] showed that a higher clay content in the soil resulted in a significant increase in both maize production and N accumulation under varying irrigation regimes. Conversely, Li et al. [51] observed that loamy soil had a much higher maize yield and N buildup than clay and sandy soil, suggesting that regional differences in climate and cultivation practices may influence these outcomes.

At a broader scale, Chen et al. [16] performed a meta-analysis of global rice–animal co-culture systems and concluded that predicting rice production was significantly influenced by the amount of clay in the soil. Asai et al. [6], who used the Bayesian approach to quantitatively examine the impact of fertiliser on rice yields in Africa, found that clay had a significant effect on the fertiliser efficiency of rice, with high clay soils demonstrating bigger yield increases than low clay soils. The results indicated that clay significantly affected fertilizer effectiveness.

Recent findings further confirm that soils with higher clay fractions, particularly silt loam and silt soils, exhibited the highest levels of N, P, and K accumulation in rice plants, followed by sandy loam and loamy sand soils. As the soil's clay concentration decreased, the dry matter accumulation also decreased in the following order: silt loam > sandy loam > loamy sand > silt soils. Furthermore, the harvest index declined with decreasing clay content, ultimately leading to reduced rice productivity. More than 70 percent of the total nutrient uptake by rice plants was derived from the soil, primarily from readily available nutrients in paddy soils [32] [109] [111]. These insights underscore the critical role of soil texture, especially clay content, in shaping nutrient uptake efficiency, biomass accumulation and rice yield outcomes.

Table 4. Grain yield and cropproductivity index associated with different soil texture classes

Soil texture Class	Average Grain Yield (kg/ha)	Crop Productivity Index	References
Sandy	1,500-2,500	Low (0.2-0.4)	[79]
Clayey	4,500-5,500	High (0.8-1.0)	[60]
Clayey	1400-3630	-	[54]
Loamy sand	1,450 (Soybean)	-	[4]
Sandy loam	2,170 (Soybean)	-	[4]
Sandy loam	850-2800	-	[54]
Sandy clay loam	8,100 (Corn)	-	[9]
Loamy sand	9,100 (Corn)	-	[9]
Silty loam	10,290 (Paddy)	-	[91]
Loamy sand	2,770 (Sunflower)	0.50	[7]
Clay loam	2850-4320	-	[54]
Loamy sand	1,510 (Groundnut)	0.33	[7]
Loamy sand	4,106 (Wheat)	-	[8]
Sandy clay loam	3,810 (Wheat)	-	[11]

Silty clay	4,800 (Rice)	-	[99]
Clay loam	5,760 (Rice)	-	[99]
Loamy sand	5,028 (Maize)	0.5	[36]
Sandy clay loam	3130-4720	-	[54]

Table 4 gives insights into how soil properties affect agricultural results by highlighting the connection between soil texture, average grain yield, and crop productivity index. Sandy soils retain little water and nutrients [79], resulting in low crop yields. Loamy soils are known for their balanced texture and moderate fertility, with a productivity index of 0.5–0.7 and yields of 3,500–4,500 kg/ha. These soils balance nutrient retention, aeration, and drainage, making them good for many crops. Clayey soils retain nutrients well and yield 4,500–5,500 kg/ha and 0.8–1.0 productivity index [60]. They retain nutrients and water for intensive agriculture.

Several studies reveal crop-specific soil performance. Loamy sand soil, being less fertile, supports sunflower (2,770 kg/ha) and soybean (1,450 kg/ha), which have a productivity index of 0.5. Aulakh & Garg [7] found that loamy sand yields 1,510 kg/ha of groundnuts with a productivity index of 0.33. Wheat yields 4,106 kg/ha in loamy sand soils [8]. More productive maize grows on loamy sand, yielding 5,028 kg/ha and 0.5 productivity (Jalota et al., 2010). Maize (8,100 kg/ha) and soybean (2,170 kg/ha) demonstrate the adaptability of sandy loam soils, which offer moderate nutrient retention and drainage. However, crop types and management methods influences the crop yields ranging from 850–2,800 kg/ha [54].

Sandy clay loam yields 8,100 kg/ha corn and 3,810 kg/ha wheat due to its balanced sand and clay properties [9] [11]. A yield range of 3,130–4,720 kg/ha shows its versatility in grain production [54]. Clay loam soils produce 5,760 kg/ha of rice and are ideal for water-intensive crops [99]. Crop yields of 2,850–4,320 kg/ha suggest high productivity under proper management [54]. Silty loam, which retains water and is fertile, yields 10,290 kg/ha of paddy [91]. Silty clay soils support 4,800 kg/ha rice yields [99]. These findings exhibit that soil texture is vital to agricultural productivity. Sandy soils are generally less productive compared to loamy and clayey soils, which are more suitable for supporting a wide variety of crops. These studies underline the need for specific crop-soil combinations and competent management to maximise output.

Conclusions

Crop yield and nutrient uptake are impacted by the soil nutrient dynamics, which are greatly influenced by soil texture. By raising the amount of organic matter and microbial activity, clay-rich soils improve soil fertility, thereby improving nutrient availability and uptake, and in turn boost yield. On the other hand, silt is essential for potassium release, whereas sandy soils have a tendency to change pH and deplete nutrients. Because of their increased cation exchange capacity and improved nutrient retention, fine-textured silt loam soils accumulate more nitrogen and organic matter in the tillage layer. This increased soil fertility maximizes crop output by facilitating effective dry matter partitioning and encouraging nutrient absorption and accumulation. Even though different soil textures have varying capacities for delivering nutrients, applying mineral fertilisers is still necessary to achieve higher yields. However, soil physico-chemical characteristics and external nutrient inputs affect the transport, transformation, and bioavailability of mineral fertilizers, which may limit nutrient uptake and release. Therefore, in order to improve nutrient management techniques in crop production, more research is necessary to clarify the relationships between soil texture and fertiliser efficiency. Future studies should focus on developing texture-specific fertilizer formulations and precision nutrient management strategies that consider soil type, organic matter levels, and microbial communities. Integrating remote sensing and geospatial tools with soil nutrient profiling can also enhance site-specific recommendations, ultimately improving crop productivity and sustainability.

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