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REVIEW ARTICLE

Integrating soil physical property management to foster chemical and biological resilience in sustainable crop systems

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Abstract

The favourable physical (such as texture, structure, bulk density, porosity and water holding capacity), chemical (including pH, cation exchange capacity and EC) and biological (like microbial diversity, soil respiration and enzyme activity) traits are regarded as defining features of healthy soil, which is critical for productive and sustainable crop production. Soil health and quality are significantly influenced by these physical, chemical and biological characteristics. The physical properties of soil, such as texture, structure and bulk density, play a pivotal role in determining water holding capacity, nutrient retention, nutrient cycling, root penetration, aeration, drainage and microbial activity all of which are interconnected for sustainable agriculture. Soil quality can be improved through the application of various soil amendments, which are materials derived from organic, inorganic, or biological sources and are aimed at enhancing soil productivity and overall characteristics. Amendments such as cover crops, farmyard manure, vermicompost and biochar have demonstrated significant effects such as reducing bulk density and increasing porosity in various soil textures, including silt loam, clay loam and sandy loam. Similarly, conservation tillage practices, particularly under organic management systems, have been shown to improve soil physical properties compared to conventional tillage by increasing infiltration rates, reducing penetration resistance and enhancing soil structure stability. These practices also positively impact chemical and biological soil properties such as improving nutrient availability, boosting microbial diversity and enhancing soil organic carbon sequestration. By fostering a supportive environment for plant growth, such integrated soil management approaches lead to higher crop yields while promoting long-term soil sustainability and resilience.

Keywords: nutrient availability; pH regulation; soil physical fertility; sustainable yield

Introduction

As quoted by Daniel Hillel, “The soil physical fertility and chemical fertility are the two sides of soil fertility”. While chemical fertility refers to the chemical status of the soil, physical fertility pertains to its physical status. Together, they form the soil's physical environment for crop production. This concept integrates all the physical properties of the soil in relation to their role in influencing soil usability. Therefore, it is more appropriate to use the term “physical fertility” to represent the overall physical characteristics of the soil (1). Soil is a fundamental component of the terrestrial ecosystem, playing a critical role in supporting plant growth, regulating water flow and maintaining environmental quality. A soil quality indicator can be classified into physical, chemical and biological attributes, with the interaction of these components creating a complex functional state. This makes it essential to define how soil functions in relation to each attribute (2). The capacity of soil to support various forms of life, including plants and animals, while also contributing to human well-being and environmental stability, is known as soil health. This concept is often used interchangeably with soil quality. The soil health is heavily influenced by farming practices and the physical, chemical and biological methods used in both conventional and organic agriculture. Recently, there has been growing awareness of the importance of soil biodiversity and ecology, as the abundance of soil organisms can transform sustainable farming practices and soil health management systems (3). Healthy soils are crucial for producing high-quality food and supporting ecosystem functions. Healthy soil offers many vital services, including water regulation, nutrient supply, gas exchange and carbon sequestration. However, ecosystem health and global food security are being adversely impacted by agroecological practices, crop intensification and alterations to the soil's biological, chemical and physical properties (4).

Soil has physical, chemical and biological properties that differ from one soil to another (4). Soil is considered a living, dynamic ecosystem, where its characteristics are shaped by a diverse array of micro and macro-organisms (5). Soil health is highly vulnerable to damage and degradation caused by climate change, global warming, nutrient depletion, erosion, compaction, contamination, salinization, overgrazing and human activities (6). The restoration or enhancement of soil health requires global attention. It is expected that the evaluation of soil health indicators will lead to an improved understanding of the mechanisms that support sustainable farming practices.

Sustainable agriculture involves farming practices that safeguard the environment, enhance and preserve natural resources and optimize the use of non-renewable resources. This approach aims to balance agricultural productivity with ecological responsibility. Soil health is closely linked to human health, water and air quality, food security and the socio-economic well-being of regions. The expected rapid rise in the global population to 8.9 billion by 2050 will result in increased demand for agricultural products (7). A critical challenge facing us is the need to meet the anticipated demand for healthy and sustainable food production. Boosting crop productivity while reducing the impacts of climate change and protecting agroecosystems is a key objective of sustainable agriculture (8).

Sustainable crop production relies heavily on the ability to manage soil physical properties effectively to maintain soil health, increase resilience to climate variability and improve crop yields. In recent years, the importance of sustainable soil management has gained significant attention due to the growing need to enhance agricultural productivity while minimizing environmental degradation.

This review emphasizes the global importance of improving soil physical properties for soil fertility. It explores how physical properties influence chemical and biological characteristics, affecting nutrient availability and microbial activity. The review highlights the interconnections between soil physical conditions and overall soil health, stressing their impact on sustainable agriculture. The review aims to analyse research findings and management strategies to improve soil physical properties for sustainable crop production.

Soil physical properties: An overview

Soil physical properties play a critical role in agricultural productivity and the sustainable use of soil. The study of these properties is essential for understanding soil health and overall productivity (9). The relationship between soil physical properties and crop production can vary widely (10) and the degradation of soil productivity is often due to issues related to soil structure, erosion and depletion of organic matter (11). Key physical and mechanical characteristics, such as soil structure, texture, temperature, bulk density, particle density, porosity, infiltration rate, hydraulic conductivity and moisture content are vital determinants of soil health (12). These properties influence important soil functions such as root penetration, nutrient availability, microbial activity and water retention, all of which are crucial for sustainable crop production. The physical properties which are necessary for plant growth are shown in Fig. 1.

Soil structure

Soil structure is a crucial factor indicating soil physical quality. The soil structure is the arrangement of sand, silt and clay particles. Aggregate stability serves as a key indicator of soil structure (13). The naturally occurring aggregates or clumps of soil particles are known as ped. Peds of soil structure are classified based on three characteristics: type (shape), class (size) and grade (strength of cohesion) (14). Based on aggregate shape soil structure is classified as platy, prismatic or columnar, angular blocky and subangular blocky (15). Soil structure manages

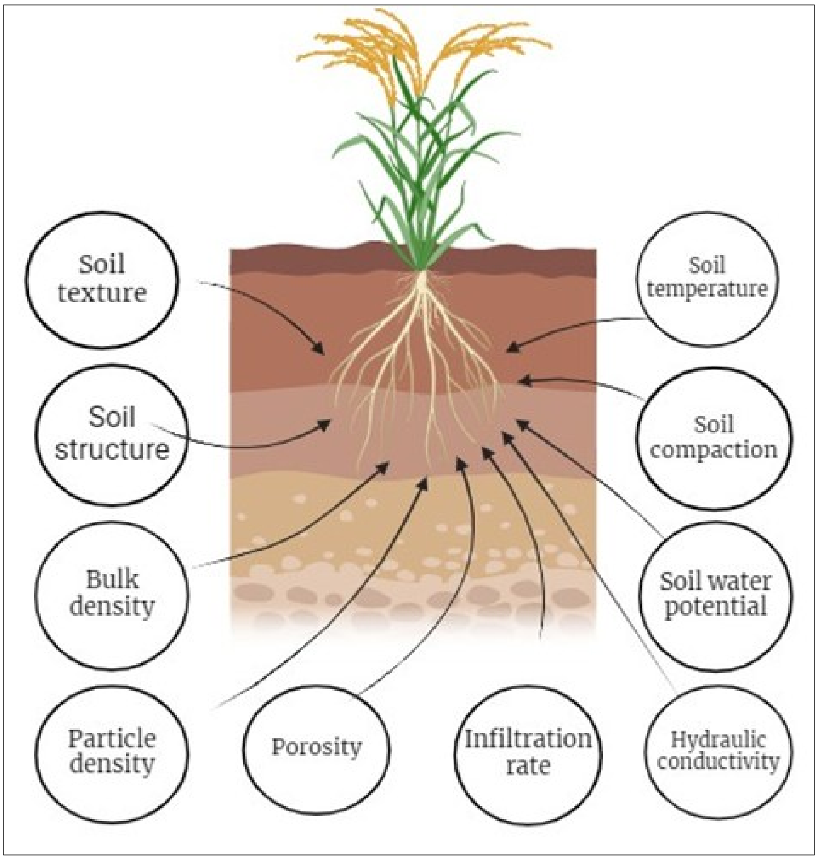

Fig. 1. Physical properties necessary for plant growth.

infiltration and water retention, the dynamics of soil organic matter (SOM) and nutrients, gas exchange, root penetration and vulnerability to erosion (15, 16). The structural aspects of soil are determined by its aggregates, whose "size, shape, composition and stability define various micro-regions in soils, providing structures for microbial growth, as well as controlling the exchange of gas, water, enzymes and nutrients" (17, 18).

A soil with a good structure develops stable aggregates and contains numerous pores of different sizes. This type of soil is easy to cultivate and supports the emergence of seedlings and strong root growth. In contrast, a soil with poor structure lacks stable aggregates and sufficient pore spaces. This can lead to compacted or waterlogged conditions, poor drainage and aeration issues, making it prone to erosion (14). The soil with low bulk density can decrease soil compaction leading to increased aeration, nutrient availability, water holding capacity and infiltration rate can enhance the root and growth of the plant to get a high yield.

Soil texture

Soil texture is fundamentally defined as "a physical property of soil that refers to the different sizes of the mineral particles" (19). Soil texture is classified into three categories according to the USDA system of particle size distribution: fine, medium and coarse. The fine-textured category encompasses clay, clay loam, silty clay, silt and silty clay loam; the medium-textured category consists of loam, sandy loam, silt loam, sandy clay and sandy clay loam and the coarse-textured category includes loamy sand and sand. This term is sometimes used interchangeably with the mechanical composition of soil and is a relatively stable characteristic that influences many other soil properties (20).

It serves as "an important index that reflects the potential productivity of the soil" and is "significantly related to soil moisture, nutrient content, pH, salt content and aeration as well as farming difficulty" (21, 22). Soil physical characteristics have far-reaching effects, as "the mechanical resistance, particle composition and porosity of soil of different textures vary." This variation in texture "changes the water, air, heat and nutrition status of the soil", which consequently affects "the growth and development of crop roots, above ground parts as well as the species and quantity of microorganisms in the soil" (23, 24). Soil texture influences numerous processes, such as infiltration, drainage (both water and air distribution), erosion, chemical interactions and biological activities. Soil textural aspects are broadly discussed in Table 1.

Bulk Density (BD) and compaction

BD is crucial in assessing soil quality, productivity, compaction and porosity. Research has shown that increases in BD lead to reductions in root length density, root diameter and root mass (25). Nevertheless, the functions of soil BD vary based on soil type, particularly soil texture and the amount of soil organic matter (SOM) present (15). It serves as an indicator of the pore space within individual soil horizons, being inversely proportional to pore space. It is useful for evaluating soil compaction levels.

Soil compaction negatively impacts soil's physical properties and fertility, particularly its ability to store and supply water and nutrients. It leads to higher soil BD, reduced porosity, increased soil strength and diminished water infiltration and holding capacity. These changes lower fertilizer efficiency and crop yields, while also increasing risks of waterlogging, runoff and soil erosion, which can contribute to environmental pollution issues (26). The weight of agricultural machinery compacts the soil, leading to increased soil BD, reduced porosity and lower crop yields (27).

Research indicates that higher compaction levels correlate negatively with organic carbon and essential nutrients, such as nitrogen, phosphorus and potassium, across various soil textures (26). This decline in organic matter and nutrient availability can adversely impact soil microbial communities, which are crucial for ecosystem functions (28). Furthermore, while some studies have documented the resilience of microbial communities' post-compaction, the recovery rates vary significantly depending on agricultural management practices (28). Thus, understanding the interplay between soil compaction and biological properties is essential for effective soil management and reclamation strategies.

Hydraulic conductivity and Infiltration

Hydraulic conductivity is one of the properties closely related to soil structure and water movement in the soil. It determines how water moves in soil, with horizontal movement dominant in saturated conditions and vertical flow preferred in non-saturated conditions, based on interlinked pores and pore size (29). The saturated hydraulic (K_{sat}) conductivity is a very sensitive estimation for the movement of water in the soil that changes spatially and temporally due to paedogenic (soil texture and parent material) and anthropogenic factors (crop management practices) (30).

Infiltration rate refers to the speed at which water enters the soil. The amount of soil infiltration is reduced due to excess rainfall leads to runoff (31). Soil permeability is a key physical characteristic that influences the rate at which water infiltrates the soil. The primary indicators of soil permeability are the initial infiltration rate and the steady-state infiltration rate. Factors such as soil bulk density, total porosity, capillary porosity, organic matter content and root characteristics play significant roles in determining soil infiltration rates. Soil infiltration properties are crucial indicators of soil quality and fertility, influenced by various factors such as soil type, land use and management practices (32).

Table 1. Soil textural aspects

Texture	Structural development	Infiltration rates	Drainage	Water holding capacity	Chemical and biological processing	Effect
Sand	Limited	Rapid	Rapid	Low	Reduced compared to high clay content	Leaching of minerals and organic material
Silt	Poor	Moderate	Well drained	Moderate	Moderate	Easily eroded and compacted
Clay	High	Slow	Poorly drained	High	High when not compacted or saturated	Easily compacted
Loam	Good	Well drained	Well drained	Good	Chemically and biologically diverse and active	A mixture of sand, silt and clay

Soil aeration

The physical characteristics of soil, such as its texture, structure and porosity, have a significant impact on the ability of air to move through the soil. This soil aeration is a critical factor that influences the growth and development of plants, the cycling and availability of nutrients and the release of greenhouse gases from the soil into the atmosphere (33). Factors such as soil texture, structure, density, porosity and colour significantly impact soil aeration by influencing oxygen availability, root penetration, moisture retention and nutrient availability for plants (34). Moreover, when soil becomes compacted, it reduces the amount of pore space available for air movement as well as the overall pore volume within the soil. This decreased soil aeration hinders the transport of gases that are critical for plant respiration and the activities of microorganisms living in the soil. Compacted soils with limited aeration can negatively impact plant health and microbial activity (35). Overall, the physical properties of soil have a significant impact on microbial activity and soil aeration, highlighting the importance of understanding and managing these factors for sustainable soil health and productivity.

Impacts of physical property management on chemical and biological properties

Soil is a dynamic system and its physical, chemical and biological properties are intricately interconnected. Managing the physical properties of soil such as texture, structure, porosity and water retention, profoundly influences its chemical and biological characteristics. This interplay is critical for optimizing soil health, enhancing agricultural productivity and maintaining ecosystem sustainability. Physical property management practices such as tillage, compaction control and organic matter incorporation significantly influence soil's aeration, water movement and aggregation. These changes impact chemical processes, including nutrient availability, pH balance and ionic exchange capacity. Favourable physical conditions also support microbial activity, promoting nutrient cycling and organic matter decomposition. Thus, the interplay between physical, chemical and biological properties is crucial for maintaining soil health, as shown in Fig. 2. Integrated management strategies are essential to ensure sustainable productivity and ecosystem stability.

Effect of physical properties on soil chemical properties

Influence of soil texture on nutrient availability and retention

Soil texture plays a crucial role in nutrient availability and retention, directly influencing agricultural productivity. The physical and chemical properties of soils vary with texture, shaping nutrient dynamics and ultimately affecting crop performance, water use efficiency (WUE) and nitrogen use efficiency (NUE). Studies have shown that finer-textured soils, such as loamy and clay soils, tend to outperform sandy soils in crop productivity. For example, maize yields were significantly higher in loamy clay soils (11440 kg ha^{-1}) compared to sandy loam soils (8257 kg ha^{-1}), attributed to better water and nitrogen retention in the loamy soils (36). Similarly, a study on irrigated crops found that loam-textured soils yielded 23.9 % more maize and retained nitrogen more effectively than sandy soils (37). Cucumber yields also favoured clay loam over sandy loam due to superior NUE and WUE (38). Wheat yields varied by texture, with silt loam producing the highest yields under freshwater irrigation conditions (39). In Northwest China, nitrogen leaching in sandy soils was observed to be 1.65 times higher than in loam-textured soils (40).

Finer-textured soils, such as silty loams, demonstrate greater nutrient retention due to their higher cation exchange capacity (CEC) and organic matter content, which enhance nutrient availability for crops (41). In contrast, coarse-textured soils like sandy soils, typically exhibit lower nutrient retention, leading to greater leaching losses and reduced nutrient availability (40). As a result, sandy soils often produce lower yields due to their poor nutrient and water retention capacity, necessitating the adoption of improved management practices (40).

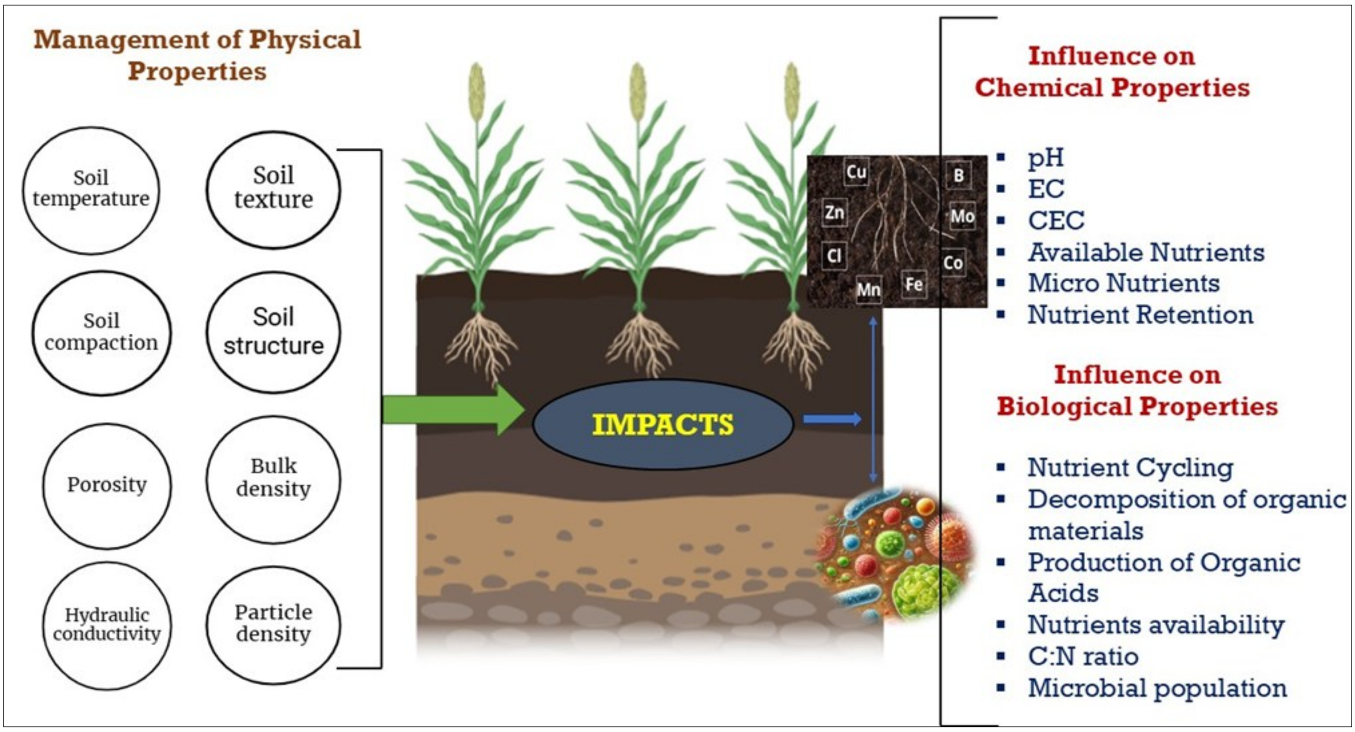

Fig. 2. Interplay between physical, chemical and biological properties in maintaining soil health.

Soil texture also impacts microbial activity, which is vital for nutrient cycling. Finer-textured soils tend to support more stable microbial communities, promoting sustained nutrient availability over time (42). Meanwhile, biochar amendments in sandy soils have been shown to boost microbial biomass and activity, improving nutrient availability (43). While loamy and clay soils generally support higher crop yields, sandy soils can still be made productive through proper management, such as adding organic matter to enhance water retention and nutrient availability.

Role of soil structure in chemical reactions and pH regulation

Soil structure plays a crucial role in regulating pH through mechanisms such as buffering capacity, microbial activity and physical properties. The interaction between soil pH and structural characteristics significantly influences microbial communities and their functions, which are essential for maintaining soil health and nutrient cycling. Soil structure affects proton distribution in the soil solution, a key factor in determining soil pH and nutrient availability (44). Structural changes, such as increased microporosity can enhance microbial respiration rates, especially under acidic conditions (45). The arrangement of soil pores determines the accessibility of nutrients and organic matter, which impacts microbial activity and chemical reactions (46).

Soil pH has a direct effect on microbial community composition and enzyme activities that drive organic matter decomposition (47). Tropical soils are more sensitive to acidification compared to temperate soils, highlighting the importance of soil structure in pH regulation (48). For example, forest soils generally exhibit higher pH buffering capacities than agricultural soils, indicating complex interactions between land use and soil structure (49). However, anthropogenic activities such as fertilizer use can disrupt these natural processes, leading to soil degradation and reduced agricultural productivity (50). Overall, soil physical properties strongly influence microbial dynamics and aeration, underscoring the need for informed management to maintain soil health and long-term productivity.

Soil physical properties and its influence on biological functions

Soil texture

Soil physical properties play a critical role in shaping biological functions by influencing the habitat and resources available to soil organisms. These properties affect nutrient cycling, organic matter decomposition and overall soil fertility. For instance, soil texture has a significant impact on moisture distribution and particulate organic matter availability, which are crucial for microbial access to substrates and subsequent organic matter mineralization (27, 51). Finer-textured soils, such as silt loam, are more effective in retaining moisture, which promotes higher rates of particulate organic matter mineralization. In contrast, coarser soils like loamy sand, while retaining some moisture, influence microbial community dynamics and nutrient cycling differently due to their texture. These variations highlight the significant role of soil texture in organic matter mineralization and nutrient supply (27). The interplay between soil texture and biological functions underscores the importance of fine and coarse soil fractions in supporting microbial activity. Management practices that consider soil texture can help optimize organic matter turnover and sustain soil fertility.

Porosity

The physical properties of soil, including porosity are crucial for root growth and overall plant health, which in turn affects soil biological properties (52). Porosity plays a vital role in creating habitats for microorganisms, as it fosters greater diversity and abundance. Increased soil porosity promotes higher microbial biomass carbon (MBC), nitrogen (MBN) and phosphorus (MBP) levels, enhancing nutrient cycling (53). Studies have shown that incorporating biochar into soil can increase total porosity and pore volume, positively influencing the structure of microbial communities. The size of pores is particularly important, as larger pores (> 5 µm) support a wide range of bacterial genera, whereas smaller pores (< 5 µm) are associated with anaerobic microbial populations (54). Conversely, while increased porosity generally benefits biological properties, excessive porosity can lead to nutrient leaching and reduced water retention, potentially harming soil health. Thus, a balance is essential for optimal soil management.

Bulk density

BD and porosity play a critical role in hydrological conditions, affecting soil moisture and biological processes like peat mineralization (55). Beneficial bacteria such as *Paenibacillus polymyxa* aid in phosphorus absorption in potato farming, illustrating the connection between soil microbial health and density (56). Lower BD increases pore space within the soil, promoting the proliferation of bacteria like *Pseudomonas fluorescens*. Research indicates that soils with a BD of 1.3 g/cm^3 support higher bacterial densities compared to those with a BD of 1.5 g/cm^3, highlighting the importance of reduced compaction for microbial activity (57). However, while reduced BD generally enhances microbial functions, it is important to avoid excessive soil loosening as this can lead to erosion and nutrient leaching, potentially negating the benefits of increased microbial activity. SOM significantly influences BD and porosity. Higher SOM content typically leads to lower BD and increased porosity, facilitating better water retention and nutrient cycling (58, 59).

Soil moisture

Soils with finer textures generally support enhanced biological activity but can also be more susceptible to extreme weather events like droughts and floods. These conditions can disrupt microbial communities and carbon cycling processes (51). Drought stress significantly reduces microbial populations and enzymatic activity, adversely affecting nutrient cycling in agricultural soils (60). While extreme moisture levels generally harm microbial and faunal communities, some microbial groups may adapt over time, potentially increasing their resilience to future climate variability. Fungi tend to be more drought-tolerant than bacteria, reflecting their greater resilience to changes in moisture levels (61). Additionally, the interaction between soil moisture and litter nutrient diversity suggests that nutrient-rich habitats may be particularly vulnerable to the effects of climate change (62). This underscores the need for managing soil physical properties, such as texture and moisture, to enhance microbial resilience and nutrient cycling, aligning with strategies for sustainable crop systems.

Soil physical fertility management practices

Soil quality can be enhanced through the application of soil amendments, which are materials derived from various sources aimed at boosting soil productivity and improving soil characteristics. These amendments fall into two broad categories: organic and inorganic. Organic amendments include substances such as biochar, straw, fruit/vegetable waste residues, animal manure, sawdust and composted organic matter. Inorganic amendments comprise materials such as sand, gypsum, vermiculite, zeolite and lignite. Both organic and inorganic soil amendments play a crucial role in improving the physical and biological properties of soil. They contribute to increased carbon sequestration in the soil, aid in the remediation of saline and contaminated soils and ultimately lead to higher crop yields and more efficient utilization of fertilizers. By incorporating suitable soil amendments, farmers and land managers can enhance the overall quality and fertility of their soils, promoting sustainable agricultural practices (63-65). The amendments and their impacts both above and belowground are shown in Fig. 3.

Effect of tillage practices for improving soil physical properties in different textures

Different tillage practices have varying impacts on soil physical properties across different textures. Conservation tillage methods like zero tillage have been shown to improve soil quality by increasing soil microbial biomass carbon and reducing BD (66). Similarly, conservation tillage practices in organic management have been found to enhance soil physical properties compared to conventional tillage, with higher infiltration rates and lower penetration resistances under organic management (67). Additionally, the use of no-till practices has been linked to improved soil moisture conservation, organic matter maintenance and enhanced crop production compared to conventional tillage, especially in dry-land agriculture scenarios (68). Furthermore, the combination of different tillage systems with soil plastic mulching and fertilizer applications can significantly impact soil porosity, water content and aggregate stability, highlighting the importance of integrated management practices for optimizing soil physical properties to achieve sustainable crop production (69). The effects of different tillage practices on various crops for increasing yield and improving soil physical properties are presented in Table 2.

Effect of various organic amendments for improving soil physical properties

Organic amendments like manures, composts, biochar, cover crops and crop residues can improve several important physical properties of soils such as increasing soil organic matter content, improving soil aggregation and aggregate stability, lowering BD, increasing total porosity and improving resistance to surface crusting and compaction. Sandy loam and clay loam soils amended with hay straw at the rate of 6 % can decrease BD and increase porosity, leading to better water retention and nutrient availability for plants (74).

Other organic amendments such as farmyard manure at the rate of 15 t ha^{-1}, poultry manure at 5 t ha^{-1} and vermicompost at 5 t ha^{-1} have significant effects on decreasing BD and increasing soil porosity. These effects, expressed as different percentages, are shown in Fig. 4 (75-77).

Effect of cover crop for improving soil physical properties

Initially, cover crops were cultivated to serve as green manures, providing a protective mulch layer on the soil surface and acting as a soil amendment to improve soil quality. Subsequently, their use evolved and cover crop residues began to be incorporated directly into the soil to enhance soil fertility and nutrient levels (78).

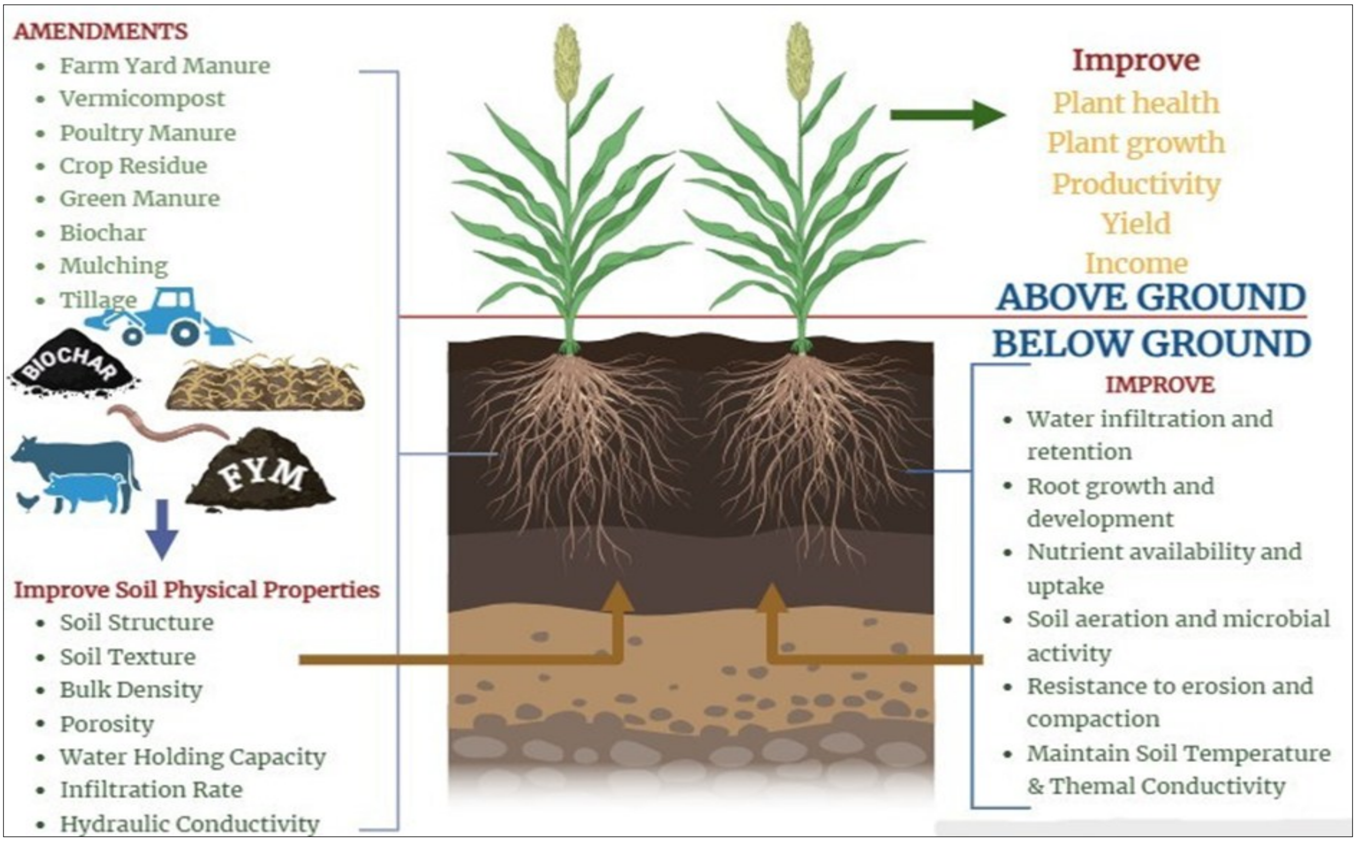

Fig. 3. Amendments and their impacts both above and belowground.

Table 2. Effect of different tillage practices on various crops, yield and soil physical properties

Crops	Soil texture	Tillage	Management strategies	Comparison	Yield increase (%)	Influence on soil physical properties		References
						Physical properties	Percentage increase (%)	
Maize	Sandy clay loam	Deep tillage	1 mould board plough + 2 planking + 2 ploughing	2 planking + 2 ploughing	10.99	Bulk density	5.40	(70)
						Infiltration rate	9.46	
						Porosity	6.05	
Water melon	Clay loam	Conventional tillage	1 mould board plough + 2 passes of disc harrow	2 passes of disc harrow	11.6	Bulk density	4	(71)
						Soil moisture content	6.52	
Wheat	Clayey soil	Conventional tillage	-	No tillage	30	Bulk density	8	(72)
						Soil porosity	10.23	
						Soil moisture content	127	
Bean (*Phaseolus vulgaris* L.)	Clay loam	Conventional tillage	1 disc plough + 2-disc harrow	Chisel plough	12.33	Bulk density	9.5	(73)
						Soil water content	1.2	

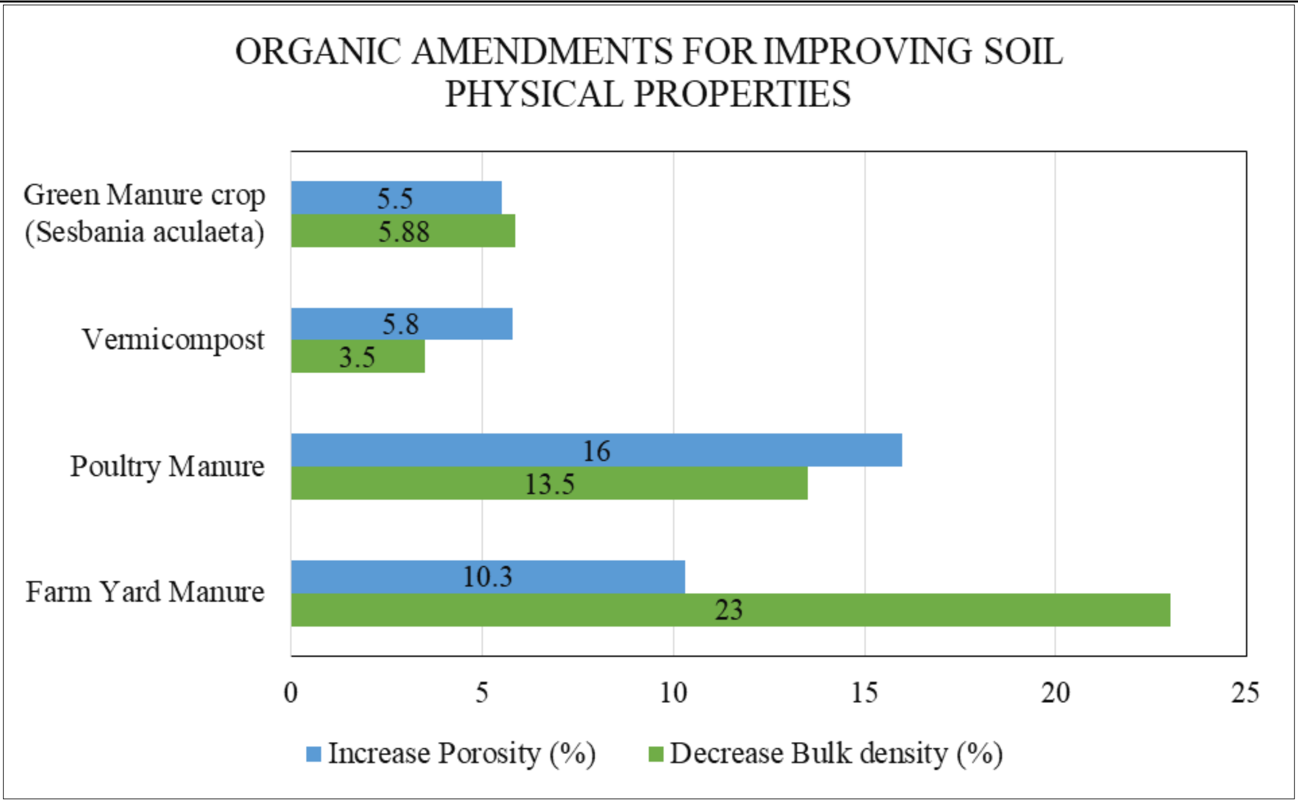

Fig. 4. Organic amendments for improving soil physical properties.

Among the most widely used leguminous cover crops by farmers and researchers are alfalfa (*Medicago sativa*), crimson clover (*Trifolium incarnatum*), hairy vetch (*Vicia villosa*), Austrian winter pea (*Pisum sativum* subsp. *arvense*), sunn hemp (*Crotalaria juncea*) and subterranean clover (*Trifolium subterraneum*). Commonly grown grass cover crops include cereal rye (*Secale cereale*), oat (*Avena sativa*), annual ryegrass (*Lolium multiflorum*) and Sudan grass (*Sorghum* × *drummondi*). Additionally, buckwheat (*Fagopyrum esculentum*), a summer or cool-season annual broadleaf grain and brassicas are other popular cover crop options (79). Table 3 shows the benefits of using cover crops for improving soil physical properties such as BD, hydraulic conductivity and infiltration rate to support better crop production. Table 4 shows the variance in soil temperature resulting from the cultivation of cover crops.

Effect of various biochar for improving soil physical properties

Biochar is a carbon-rich material produced by heating biomass in an oxygen-limited environment through a process called pyrolysis. The feedstock used to create biochar can vary from woody materials to biosolids and is often categorized into three main groups: woody biomass (WB), crop residues (CR) and organic wastes (OW) (91). When these various raw

Table 3. Benefits of cover crops in improving soil physical properties

Texture	Cover crops	Influence on soil physical properties	Increase or decrease	Percentage (%)	References
Silt loam	Sunn hemp	Bulk density	Decrease	4	(80)
Silt loam	Winter wheat	Bulk density	Decrease	12	(81)
Clay loam	Millet	Bulk density	Decrease	24	(82)
Clay loam	Winter wheat	Hydraulic conductivity	Increase	7	(83)
Silt loam	Cereal rye	Hydraulic conductivity	Increase	33	(84)
Silt loam	Rye-hairy vetch	Infiltration rate	Increase	9	(85)

Table 4. Soil temperature variance under cover crops

Texture	Season	Cover crops	Soil temperature		References
			°C	Increase or decrease	
Clay loam	Winter Summer	Crimson clover and white clover mix, hairy vetch and red clover	2.5-5.7 0.1-3	Increase Decrease	(86)
Clayey	Spring (wet)	Roller-crimped + Glyphosate/paraquat	1.7-2.4	Increase	(87)
Sandy	Spring (wet)	Standing rye	0.5	Increase	
Loamy	Winter	Hairy vetch	1.2	Decrease	(88)
Silt loam	Summer	Cereal rye mulch	3.5	Decrease	(89)
Clay loam	Spring	Rolled rye + legume mix	2.1	Increase	(90)

materials are converted into biochar, their carbon content ranges from 40–80 %. Further modifications can be made to alter the cation exchange capacity (CEC) and structure of biochar (92). The impact of biochar on soil physical properties is influenced by several factors, including the type of biomass or feedstock used, the conditions of pyrolysis, the application rate and the environmental conditions (93). Moreover, the effect of biochar on soils of various textures is presented in Table 5.

Conclusion

Soil physical properties play a pivotal role in determining soil health, crop productivity and the overall sustainability of agricultural systems. This review has highlighted the significance of factors such as soil structure, texture, BD, hydraulic conductivity, aeration and temperature in influencing various soil processes and functions. Effective management practices include conservation agriculture, organic amendments, effective tillage practices, cover crops and application of biochar to improve soil health and fertility without harming the environment. By adopting practices that improve soil structure, manage water efficiently, enhance nutrient availability, control erosion and promote soil aeration and microbial activity, farmers can create a more resilient and productive agricultural system. These practices not only contribute to immediate crop yields but also ensure the long-term sustainability of soil resources, supporting the overall health and productivity of agroecosystems.

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Authors' contributions

VSU wrote the manuscript, with guidance from SS. PSP, RA and CSR reviewed the manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare that they have no conflicts of interest.

Ethical issues: None

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Table 5. Effect of biochar on various soil textures

Texture	Biochar	Size of the particle	Biochar rate	Increase or decrease	Influence on soil physical properties	References
Silty loam soil	Willow biochar	> 2 mm	1.5 %	Increase Decrease Increase	Saturated hydraulic conductivity Bulk density Porosity	(94)
Sandy soil	Banana peel ground		2 %	Decrease Decrease	Saturated hydrological conductivity Decrease bulk density	(95)
Yellow-brown loam soil	Maize straw	0.2 mm	3 %	Decrease Increase Increase	Bulk density Water use efficiency Yield of tomato crop	(96)
Clay loam	Woodchips		3 %	Decrease	Bulk density	(97)
Sandy	Sugarcane trash		10 t/ha	Decrease Increase	Bulk density Porosity	(98)
Loam	Rice husk		4 %	Decrease Increase	Bulk density Porosity	(99)

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