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Soil Physical Properties in Agricultural Systems: Structure, Water Movement, Compaction, and Implications for Crop Productivity: A Review

Ruwaida Khalid Sabber
Department of Soil Science and Water Rescores, Agriculture College, Tikrit University, Tikrit, Iraq

Abstract: Soil physical properties are one of the most important factors that determine the productivity and sustainability of agricultural systems. They determine the ways water can flow and hold, the aeration of the soils, the penetration of the roots into the soil and the physical environment that the plants require to grow. This review was aimed at providing a scientific overview of the major soil physical properties that take place in agricultural soils and the most significant ones which are soil structure, soil texture, soil water movement, soil water retention, soil bulk density, soil porosity and soil compaction. The effect of physical degradation of soils on plant growth and the best management practices that could be used to improve the physical condition of the soils was also discussed. The results indicate that soil texture is the fundamental skeleton of soil and soil structure is the one that mostly dictates the functionality of the soil in an agricultural context. Vanel condition of the soil, destruction of structure and reduction of porosity negatively affect infiltration, root establishment, and crop yield. On the other hand, appropriate management such as less tilling, cover crops, organic amendments and controlled traffic agriculture would improve the physical quality of the soil and sustainability of agriculture on a long run. In general, the physical conditions of soil are crucial in enhancing the performance of crops, water-use efficiency, and the condition of the soil in contemporary agricultural systems.

Keywords: Soil physical properties; Soil structure; Soil texture; Water movement; Water retention; Soil compaction; Porosity; Bulk density.

Introduction

The physical properties of soil are essential to the performance, productivity, and sustainability of agricultural systems since soil is not simply a medium by which plants are anchored, but a dynamic physical environment that controls the storage and movement of water, the exchange of air, penetration of roots, transfer of heat, and degradation resistance. Soil structure, soil texture, soil bulk density, soil porosity, aggregate stability, and infiltration behavior are some of the most prominent physical characteristics that directly influence the establishment of plants and growth of crops. According to the Food and Agriculture Organization (FAO), soil structure influences the aeration, water movement, heat exchange, plant root growth, and soil erosion resistance, which is why it is one of the key determinants of soil functionality in agricultural lands (FAO, n.d.-a).

Agricultural applicability of soil physics is that not only is crop productivity dependent on the chemical sense of soil fertility but also the capability of the soil to sustain a favorable physical environment to the root and soil biota. The water and air balance of the soil is provided by the pore spaces, which are required during respiration of roots, activity of microorganisms and nutrient uptake. Fao recommendations on soil and crop productivity emphasize the fact that physical properties of the soil are strong determinants of plant behaviour in that they affect the water availability, rooting environment and soil susceptibility to crusting, erosion and structural degradation (FAO, n.d.-b). Likewise, soil erosion and any other forms of physical degradation of soil decrease the soil health and agricultural productivity, robbing the latter of the most functional layer (FAO, 2019; FAO, n.d.-c).

One of the greatest physical constraints to agricultural soils is soil compaction because it alters the continuity of pores, heightens the mechanical resistance and restricts the movement of water, air, and roots. According to the USDA Natural Resources Conservation Service, bulk density is a central measure of compaction and high bulk density correlates with low porosity, low available water capacity, shallow rooting, weak aeration and weakened biological activity, which can lead to decreased productivity (USDA-NRCS, 2023; USDA-NRCS, 2019). A review that is more up-to-date also came to the conclusion that the use of machinery compaction can considerably reduce crop yields and affect the soil hydraulic behaviour especially when it comes to repeated traffic and improper field management (Shaheb et al., 2021). Recent systematic reviews highlighted the need to understand modern trends and future challenges in heterogeneous developmental sectors in a holistic analytical approach, by focusing on the interplay between structural conditions and economic determinants and long-term planning (Palani, 2025a; Palani, 2025b).

Another theme in soil physics is water movement in soil as the agronomic value of soil does not just lie in the water holding capacity but also how well water enters, moves and stays in the root zone. One of the most frequently used measures of soil functionality is infiltration because it is an indicator of the capacity of the soil to accept water, retain it and allow its use by plants, reduce runoff and erosion. In USDA-NRCS publications, infiltration is calculated based on the soil texture and structure, organic matter, pore continuity, and surface condition, and the inadequate infiltration rate leads to the danger of runoff, soil erosion, and inefficient water utilization (USDA-NRCS, 2014a, 2014b). The aggregate stability is also vital as stable aggregates promote infiltration, help in maintaining pore networks and minimizing structural breakages during rainfall or other mechanical disturbances (USDA-NRCS, n.d.). Recent studies also indicate that other measures like cover cropping can enhance the soil structure and macroaggregation, which enhances physical strength of agricultural soils (Gentsch et al., 2024).

The physical properties of soil have taken on a new dimension in modern agriculture because the system of cropping is becoming more susceptible to the action of more machinery, pressure of irrigation, soil erosion, and the altering climate pattern. The concept of sustainable soil management therefore entails the necessity to preserve the structure of the soil, minimize compaction, soil porosity and maximize water infiltration and storage to ensure a healthy growth of the roots, efficient use of water and a stable crop yield. In this case, the current review aims to provide a general scientific outlook on the major physical properties of the soil in the agricultural systems, namely, soil structure, water flow, and compaction and its impact on crop productivity and the sustainable use of the land (FAO, n.d.-a; USDA-NRCS, 2023; Shaheb et al., 2021).

Methodology

A structured narrative-review method was used to identify, organize and synthesize the relevant scientific publications on soil physical properties with particular reference to soil structure, water movement, soil compaction and the implication on crop productivity. Although the present paper is not a meta-analysis, the principles of literature-search and reporting were clearly adhered to following the PRISMA 2020 framework to increase the level of clarity, reproducibility, and rational selection of the studies (Page et al., 2021a, 2021b). The PRISMA 2020 is commonly employed to enhance reporting of the review methods and selection process, and Cochrane Handbook is a reputable source of evidence synthesis and methodological soundness in the review writing.

The literature search was done in the major academic databases and the institutional resources that are trustworthy. The search of scientific articles was primarily done using Pubmed, Google scholar, and other academic indexing paths in addition to the fact that official publications of organizations related to soils, agriculture and land management were also accessed to seek technical and conceptual advice. PubMed was added due to the fact that it is a free resource managed by the U.S. National Library of Medicine and has over 40 million citations and abstracts in biomedical and life-science literature, which is beneficial in interdisciplinary issues that bridges soil science, plant growth, and environmental health.

The search strategy was founded on the combination of the keywords describing the area in question of the review, including: soil physical properties, soil structure, soil texture, bulk density, soil porosity, aggregate stability, soil water movement, infiltration, hydraulic conductivity, soil compaction, root growth, crop productivity, soil degradation, and agricultural systems. Search was narrowed down with the help of Boolean operators such as AND and OR in the effort to make the search more relevant. Screening of reference lists of sampled papers manually also assisted to identify other studies that were directly related to the aims of the review. It follows the practice of review, where systematic searching and checking of back references are used to increase the coverage of the literature (Page et al., 2021a; Cochrane, 2024).

Peer-reviewed journal articles, authoritative review articles and official reports or technical documents published by respected scientific or international agencies formed the inclusion criteria. The studies also had to be eligible, in the sense that they were dealing specifically with one or more of the following themes: physical properties of soils in agricultural lands, the effects of soil structure and porosity on crop growth, the interactions between infiltration and soil-water, the bulk density and compaction and the effects of physical degradation of soil on crop growth or sustainable land management. The stress was laid on recent literature to obtain the scientific knowledge available, but all the reference material foundations were retained where they were of the utmost value to the conceptual foundation of soil physics. The final synthesis included only English-language materials.

The exclusion criteria were the presence of duplicate records, poor scientific sources, articles that were not directly pertinent to soil physical behavior in agriculture, and articles that focused only on chemical or biological but not physical behavior of soil. After the first search, titles and abstracts were narrowed down, and possibly relevant articles were then narrowed to a full text reading. Articles that met the needs of relevancy in terms of theme and scientific relevance were stored as part of the review narrative. It is a procedure that is staged and is anchored on the overall logic that is proposed with transparent review reporting as identification, screening and eligibility are evaluated and final inclusion is handled in a transparent order (Page et al., 2021a, 2021b).

The literature chosen was then sorted out to the central areas of the review. These thematic areas were: (1) concept and importance of soil physical properties, (2) soil structure and soil texture, (3) the movement and retention of water in soils, (4) bulk density, porosity, and soil compaction, (5) effects of physical degradation on crop development, and (6) how to improve the physical properties of soils in agricultural systems through management practices. It was this evidence that was later synthesized in a descriptive and critical fashion with the hope of coming up with an integrated scientific picture of the role played by physical soil behaviour on agricultural productivity and sustainability.

No new field sample, lab or meta-analysis of statistics was done since this is a review paper and not an experimental study. Instead, evidence synthesis, comparison of published results, and interpretation of repeated patterns of scientific results across studies was highlighted as the approach. The descriptive synthesis methodology is suitable when review articles aim to synthesize concepts, processes, and practical implications of diverse, albeit not unrelated sources, especially when the literature is both experimental and institutional technical advice (Cochrane, 2024) is used.

Lastly, the review was planned keeping in mind the need to ensure a robust and credible reference base through the entire paper. In that regard, the entire paper will include at least 20-30 valid sources, and most likely, even more of them, in terms of peer-reviewed articles, and other credible institutional sources, to facilitate adequate academic content, balance, and scientific validity.

Soil Physical Properties Concept.

The quantifiable characteristics that describe the physical state of soil and the functioning of soil as the location of plant development, water storage, gas and mechanical support respiration in agriculture are the physical properties of soil. These are features of the texture, structure, bulk density, porosity, aggregate stability, infiltration and water retention and all these features produce the environment in which the roots develop and biomass crops thrive. Their capacity to regulate the movement of water, gases, and heat and influence resistance to soil compaction, soil erosion, and soil degradation under cultivation are what make these properties the key component of the soil quality in modern soil science (Sainju et al., 2022; Shaheb et al., 2021).

Among these properties, the ratio of sand, silt and clay particles in the soil, which is the simplest of these properties, is the soil texture. The water-holding capacity together with the drainage, aeration and penetration ability of the roots in the soil profile are highly influenced by the texture. But texture is not the whole story in the description of soil behavior in the field. Soil structure which is the grouping of the primary particles into aggregates and pore networks is also vital as it dictates the continuity of the pores, the ease at which water penetrates and the physical hindrance that the roots experience. The recent researches and reviews emphasize that the plant growth directly depends on the soil structure, and the alteration in the structure may have a considerable impact on the formation of roots and shoots in relatively similar conditions (Giuliani et al., 2024; Cavalieri-Polizeli et al., 2022).

The concept of porosity as the ratio of the volume of the soil that is occupied by the pores to the solid material is one of the primary aspects of the concept of soil physical properties. These pores are of different sizes and functions: the larger pores are more preferable in terms of aeration and rapid drainage, the smaller ones retain water that may be utilized by the plants. The spatial composition and stability of this pore structure is very important as it controls infiltration, water retention, root development and microbial habitat. Recent survey on pore structure in soil verified that pore networks play a central role in the movement of water, gas and solutes in a soil and are thus central to soil fertility and plant productivity (Wang et al., 2024). Likewise, recent research has shown that porosity is also highly related to aggregate stability and soil structural resilience, especially when grazing or other activities are applied on the soil (Yang et al., 2025).

Another important concept of soil physics that often finds use as indicators of soil compaction and overall structural conditions is the bulk density. Bulk density is the weight of dry soil/volume and is the inverse of total pores in most soils in agriculture. A growth in bulk density beyond critical values will tend to lead to a reduction in porosity, reduction in infiltration, reduction in aeration, increase in mechanical resistance, and low root development of the soil. The existing literature on soil compaction has continuously pointed out that compaction increases soil strength, reduces hydraulic performance, and can cause considerable decreases in crop yields because of the frequent movement of machinery or malpractice (Shaheb et al., 2021). The recent synthesis work also focuses on the fact that bulk density is not a mere descriptive measure, but a macro-scale phenomenon, which correlates the packing behaviour of soils to their agricultural performance and vulnerability to degradation (Robinson et al., 2025).

Aggregate stability is another important aspect of physical quality of the soil because it shows how soil aggregates resist disintegration during rainfall, wetting or tillage or other disturbances. Stable aggregates help in the continuity of pores, reduce crusting, runoff, increase infiltration, and improvement of root zone structural environment. Recent studies have re-established that aggregate stability is directly related to water infiltration, erosion control, and functional quality of agricultural soil and that methodological measurements have also established that it is one of the most informative indicators in soil-health assessment (Rieke et al., 2022; Yost et al., 2024). Furthermore, land use studies have also shown that aggregate stability is a management and soil-property sensitive measure, which confirms its applicability as a structural measure in agricultural environments (Zhang et al., 2024).

Water behavior is one of the most direct linkages between soil physics and crop performance as the physical properties of soil also include how the soil can receive, transmit and retain water. Infiltration, hydraulic conductivity and water retention determine the availability of rainfall or irrigation to plants or its loss as a runoff, deep drainage or evaporation. It has been shown many times that soils with an enhanced structure, which is less compact and with better aggregate stability are more likely to have better infiltration and root-zone hydrology. As an example, dynamic field experiments have demonstrated that aggregate stability variations introduced by management are directly related to the variations in infiltration behavior in the process of crop development (Xu et al., 2024). Similarly, root-soil interaction analysis shows that roots can change the slope of soil water retention and permeability, and thus, physical behaviour of soil and plant development can not work independently, but rather, they rely on each other (Ni et al., 2019).

Physical properties of the soil are not measured independently as far as agriculture is concerned but as a system that determines the capacity of the soil to sustain growth of plants productively under farming conditions. A soil can be sufficient in terms of its chemistry, but still be unsuitable in terms of performance due to degraded soil structure, discontinuity in the pore network or excessive density such that roots are unable to grow normally. This is why, more and more the modern literature talks about soil physical quality as of one of the main elements of the total soil health and agricultural sustainability. Both reviews and field studies suggest that good physical conditions facilitate root development, enhance water utilization, resilience to stress, and more stable yields, but physical degradation impairs productivity and increases erosion and long-term deterioration (Sainju et al., 2022; Shaheb et al., 2021; Khasi et al., 2024).

In conclusion, we can say that soil physical properties may be viewed as a complex of characteristics, which define physical conditions of contact of plant roots, water and air in agricultural soils. They play a crucial role in characterizing the behavior of soils in terms of tillage, machinery traffic, irrigation, rainfall and environmental stress. Therefore, the investigation of physical properties of soil is a fundamental notion in soil physics and agricultural sciences because it is one of the links between the nature of soil as it is and its use in crop production systems and sustainable land management (Giuliani et al., 2024; Wang et al., 2024; Robinson et al., 2025).

Agricultural Lands Soil Structure and Texture.

Two basic physical properties that determine the behavior of agricultural soils are soil texture and soil structure, however they describe different facets of the soil system. The proportion of silt, clay and sand in relation to each other is referred to as the soil texture and hence it is considered as one of the properties which are highly natural. Their organization into aggregates and pore networks instead is referred to as soil structure and is more dynamic in that it also changes with cultivation, compaction, biological activity and how organic matter is handled. The agricultural soils texture varies with the structure to a significant extent to influence water entry, internal drainage, aeration, root penetration, and overall crop performance (Klöffel et al., 2024).

The mineral structure of the soil is given by texture and has a considerable impact on hydraulic and mechanical behavior. The rough-textured soils are more likely to have larger pore spaces and therefore, they drain at a higher rate and lower water-holding capacity, as compared to the fine-textured soils, which have higher water-holding capacity but more vulnerable to dope aeration and mechanical constraint on compacting. Nevertheless, field performance can not be attributed to texture, since soils of similar clay, silt, and sand content can have different behavior in terms of their aggregation and pore continuity. Klöffel et al. (2024) found that the content of clay was one of the most predictive of soil structural variability across agricultural soils, and soil organic carbon, as well as land-use history, were also found to play a role in the nature of that textural structure at work.

Soil structure is a major concern in agricultural land as it directly determines the permanence of pores and therefore, control the infiltration, aeration and root growth. A controlled study conducted by Giuliani et al. (2024) found that even though the bulk density was similar, the difference in root and shoot development was because of a difference in soil structure. They discovered that more heterogeneous the soil structure became, the more complex the pore networks, and that at high density created about 50% of the number of macropores as homogeneous soil that stimulated the growth of the barley and pea roots. This observation is significant in that it demonstrates that structure is not merely an aesthetic quality; it is directly involved in the functioning of plants.

Field scale tillage studies also have the significance of structure. Xu et al. (2024) compared four tillage systems in the Mollisols region of northeast China and discovered that the tillage treatment caused considerable changes in the soil bulk density, porosity, aggregate stability, and infiltration characteristics when growing crops. Certain types of tillage in that work increased capillary porosity and stability of water-stable aggregates, and, increased infiltration rates. These results indicate that soil structure is directly linked to hydraulic performance, and management practices have a positive or negative influence on the structural functioning depending on their effects on pore structure and aggregate stability (Xu et al., 2024).

Repetitive disturbances and deficit of restorative routines can over time wear down framework in prolonged farming uses. The study by Klöffel and other authors (2024) that was based on structural change with compaction and the agricultural intensification process found that the subsoils were the most affected area and that the soil organic carbon percentage when it dropped to about 23 percent the structural began to decrease. This applies best to agricultural systems since it has shown a strong relationship between the quality of the structure and conservation of organic carbon and reduction of excessive mechanical stress. That is, the soil structure is not solely based on the natural soil texture but also on the way land is used in the course of time.

Bulk density is a useful intermediate in the relationship between texture and structure since it indicates the extent to which the soil particles are compacted in a given volume. Although the natural bulk density is varied among the soil textures, elevated values in cropland are likely to be indicative of less pore space and increased structural compression. On average, Panagos et al. (2024) found that the bulk density of the 020 cm layer in croplands was 1.26 g cm -3, which was relatively high compared to 0.83 g cm -3 in woodlands and concluded that the variation in bulk density was largely controlled by land use. This supports the thesis that the field of agriculture is prone to structural stress in the soils, and especially in the regions with significant traffic and disturbance (Panagos et al., 2024).

As a rule, the notions of soil texture and soil structure should be regarded as complementary, rather than as dissimilar features of arable soils. The basic mineral structure and the majority of the base hydraulic tendencies of the soil is determined by the texture, yet whether or not that skeleton is energized to propagate water movement, aeration, and root growth, is through structure. The current research demonstrates that the management can implement dramatic changes in the soil structure but the direction and character of these changes significantly depends on the textural environment underlying it, the organic carbon state of the soil, and the level of agricultural perturbation. Therefore, in order to determine physical constraints and construct sustainable soil-management strategies in agroecosystems, knowledge of texture and structure would be essential (Klöffel et al., 2024; Giuliani et al., 2024; Xu et al., 2024; Panagos et al., 2024).

Movement and Retention of Water in Soil.

Among the most significant processes in soil physics is the movement of water and water retention which determine whether or not the rainfall or irrigation water is available to crops or is lost to run off, evaporation or deep percolation. The interactions between pore-size distribution, aggregate stability, bulk density, organic matter, and soil management control these processes in agricultural soils. Consequently, the hydraulic properties of soil cannot be explained by the texture per se; they are highly dependent on continuity and functionality of the pore system formed by soil structure and its history (Vlček et al., 2022; Xu et al., 2024).

The movement of water in soil normally starts with infiltration, which is the process of water getting into the surface of the soil. Once it has entered a profile, water flow under the effects of gravitational and matric forces also occurs, and is generally characterized by hydraulic conductivity and associated flow characteristics. Infiltration is of particular concern to agricultural practice, as it determines the runoff, risk of erosion, water retention and irrigation efficiency. An experiment of maize plots with varying tillage regimes revealed that low tillage had higher saturated hydraulic conductivity and had better water retention than the conventional tillage, suggesting a decreased propensity to form overland flows (Vlček et al., 2022). Likewise, Xu et al. (2024) found that the Mollisols tillage treatments had significant effects on initial, stable, and average infiltration rates during crop growth, which confirmed that infiltration is very sensitive to changes in management-induced structural changes.

Soil water retention is the ability of soil to withstand the pull of gravity and retain some of this water to be used by plants. The volume of pores as well as the size affects this property. Big pores drain fast following rain or irrigation, medium and small ones store water longer and are more directly involved in the supply of water to the plants. Due to this there may be a wide variation in the agricultural value of soils of similar water content based on the degree to which the water is bound and the potential of roots to reach the water. Vlček et al. (2022) noticed that saturated hydraulic conductivity and water retention were higher when tilled lightly compared to when tilled with conventional methods, and cover crops in traditionally tilled fields yielded significant improvements in each of these characteristics. The findings indicate that water retention needs to be regarded alongside infiltration as a productive soil should be able not only to receive water but also to store a sufficient amount of it in the root zone.

Soil structure is particularly important in the behavior of water, particularly in terms of aggregate stability and pore continuity. Stable aggregates aid in the preservation of linked macropores and mesopores, which enhance infiltration and the redistribution of water internally. Yang et al. (2024) conducted a study of the black-soil region of northeast China in 2024 and discovered that aggregate stability was significantly enhanced, and that the average infiltration rate was greatly increased by 41.8 to 78.3 percent in comparison to the control, whereas the stable infiltration rate was increased 109.2 to 165.9 percent. The authors also noted that there were strong correlations between aggregate properties and infiltration performance, with improved aggregate organization leading to improved soil and water conservation. This proves that not only the mineral composition of soil is important in hydraulic functioning, but also the physical integrity of aggregates and related pore system.

The water movement and water retention can thus be altered through management practices by restructuring soil. Xu et al. (2024) also showed that tillage systems changed the bulk density, capillary porosity, and aggregate stability throughout the crop-growth phase, which were translated into infiltration performance. Similarly, Vlček et al. (2022) found that low tillage, thin sowing rows, and cover crop increased saturated hydraulic conductivity and water retention in maize fields. Collectively, these studies demonstrate that water movement and retention are not inherent soil characteristics but dynamic characteristics that are responsive to land management. Realistically, agricultural systems that maintain porosity and aggregate stability have higher chances of enhancing water-use efficiency and lowering erosion and drought stress probabilities.

The second significant factor of soil-water relations is the interaction between the hydraulic behavior and roots. Roots do not just steal water out of soil, but also alter the geometry of pores and consequently affect water retention and permeability. Ni et al. (2019) demonstrated that the root growth and decay may change the soil water retention curve and saturated permeability, which means that the development of plants and hydraulic behavior of soil affect each other. The significance of this in agricultural systems lies in the fact that root activity may slowly modify the physical environment of the root zone, which in effect may modify preferential flow paths in some instances as well as influencing the distribution of retained water.

Agronomically the ratio of water movement to water retention is indispensable. When the infiltration is too low, the rainfall and irrigation water will be lost as run off and this enhances erosion and decreases the recharge of the root zone. Excessive runoff can cause crops to experience short-term drought despite irrigation or rain. Conversely, when the soil holds excessive water under poorly aerated situations, the respiration of roots and microbial activities might be hampered. The reason is that the most productive agricultural soils are not always those with the highest total water content, but those that have a good equilibrium between a fast rate of water penetration, satisfactory storage, and an acceptable level of aeration. The overall results of new field research show that this balance is most probable in situations where soil structure is highly maintained and the management has reduced compaction and enhanced aggregation (Vlček et al., 2022; Xu et al., 2024; Yang et al., 2024).

To conclude, water flow and water retention in soil are at the heart of agricultural soil performance as they govern the supply of water, the production of runoff, storage of root-zone water, and physical stability of cultivated soil. Recent studies indicate that these properties are extremely affected by the soil structure, aggregate stability, and the management approaches like reduced tillage practices and cover cropping. Thus, the knowledge of soil-water interactions is necessary to enhance irrigation performance, preserve soil moisture, and maintain crop yield in the agricultural systems (Vlček et al., 2022; Xu et al., 2024; Ni et al., 2019; Yang et al., 2024).

Bulk Density of Soil, Porosity, Compaction.

Physical properties that are closely related to each other and are central to the determination of soil functionality and crop productivity in the agricultural system include soil bulk density, porosity, and compaction. Bulk density is the ratio of the weight of a specific volume of dry soil and is commonly used as a measure of soil compaction and integrity. Porosity on the other hand is the ratio of the soil volume that is filled with pores that are vital in holding water, air, and developing roots. The process of soil compaction takes place when there is external pressure on the soil, which causes the soil to be compacted by machinery or trampling by animals and thus the pore volume is lost, resulting in an increase in bulk density and a decrease in porosity. All three of these characteristics constitute the physical environment of the root zone and have a significant impact on the growth of plants and the interplay between soil and water (Shaheb et al., 2021; Panagos et al., 2024).

Bulk density is of special significance since it combines multiple factors on the physical state of soil into one measurable value. Overall, increased bulk density implies that the soil is more compacted and has less pore space particularly the macropores that are very important in aeration and root penetration. Panagos et al. (2024) based on the large-scale LUCAS soil data in Europe, found that bulk density was much higher on croplands than natural ecosystems, with the mean value of 1.26 g cm -3 in agricultural topsoils, and 0.83 g cm -3 in woodlands. The researchers made land use a significant source of bulk density change, showing that agricultural activities can significantly change the packing and structural integrity of the soil over the years (Panagos et al., 2024).

The porosity is directly connected to bulk density, where the growth in bulk density is usually accompanied by the decrease in the total pore space. But the number of pores is not the only important factor but the distribution of the pore size is also of critical importance. The macropores allow quick water, and gaseous exchange, and micropores ensure water retention. Compaction may cause a decrease in macroporosity, which can greatly inhibit oxygen diffusion and limit root growth. The studies have revealed that soil compaction causes a decrease in the connectivity of macropores and pore continuity that subsequently reduces the hydraulic conductivity and increases the resistance to root penetration (Shaheb et al., 2021). Moreover, the scientific evidence of soil structure shows that the porosity is directly connected to the aggregate stability and the soil organic matter, which points to the fact that to keep the pore network stable, good structure and sustainable management are needed (Klöffel et al., 2024).

One of the most common types of physical degradation in agricultural lands is soil compaction. Repeated passages of heavy machines, intensive tillage, and working in wet conditions are the main causes of it. Compaction enhances the strength of the soil, its resistance to penetration and reduces porosity, permeability and aeration. An extensive survey conducted by Shaheb et al. (2021) indicated that soil compaction can greatly decrease crop production by slowing root growth, decreasing water infiltration and hindering nutrient absorption. The authors noted that compaction can impact surface and subsurface layers, but that subsoil compaction is especially problematic as it is more challenging to reverse and may last over time.

Further experimental studies reveal the effects of compaction on the physical behavior of soils. Tian et al. (2022) compared the impacts of various tillage systems on the soil structure and realized that the effects of greater bulk density were related to higher penetration resistance, lower least limiting water range, and worse root-zone conditions. Other techniques employed in the study, including X-ray computed tomography, demonstrated that compaction modulates pore architecture, decreasing connectivity and mechanical limitations to root development (Tian et al., 2022). These results affirm that the compaction process is not only a superficial process but a structural change that extends to the whole profile of the soil.

The connection between compaction and water dynamics are also critical. Compressed soils have lower infiltration rates and higher surface runoff, thereby resulting in erosion and inefficient water utilization. Simultaneously, lower macroporosity decreases the ability to drain and this can lead to waterlogging in some circumstances. Xu et al. (2024) revealed that increasing bulk density and decreasing porosity were positively correlated with lower infiltration rates and decreased aggregate stability, which also testifies to the high interaction between compaction and soil hydraulic performance. This association underscores the need to effectively manage compaction to not only enhance root development but also increase the ability of agricultural systems to utilize water efficiently.

The management practices are important in the control of bulk density and compaction. It has been demonstrated that reduced tillage, controlled traffic farming, organic amendments, and cover cropping will enhance the soil structure and diminish the effects of compaction. Klöffel et al. (2024) established that soil organic carbon is critical in ensuring structural resilience, whose threshold is about 23 percent below which the soil structure starts to decline. This implies that organic matter is necessary in keeping porosity intact and in minimizing the chances of compaction. Equally, research has revealed that conservation-based activities have the potential to enhance pore continuity, decrease bulk density, and improve the overall physical quality of the soil (Xu et al., 2024).

On the agricultural standpoint, the porosity versus bulk density is very important. Although high bulk density limits the growth of the roots and water flow, the inverse is also true, and high bulk density can be a sign of poor structure and stability. Thus, the best soil conditions are when there is enough pore space to allow air and water to travel, and because the soil should not be degraded by time. Studies repeatedly prove that soils with moderate bulk density, fixed aggregates, and interconnected pore structures offer the most desirable environment to crop productiveness and long-term viability (Shaheb et al., 2021; Panagos et al., 2024; Tian et al., 2022).

Overall in conclusion, the bulk density, porosity and compaction of the soil are important measurements of the physical quality of soil in the agricultural systems. They are tightly related to each other and collectively define the effectiveness of the movement of water, growth of roots, aeration, and the productivity of soil in general. These properties can be greatly affected by agricultural practices that may increase or decrease soil performance. Accordingly, the goals of effective soil management should be to reduce compaction, ensure a sufficient porosity, and ensure a structural integrity to ensure sustainable crop production and soil health (Palani et al.,2019:Shaheb et al., 2021; Kloffel et al., 2024; Xu et al., 2024).

Physical Environment Management and Improvement of Soil.

The physical properties of the soil are crucial to the sustenance of crop productivity because the desirable soil structure, porosity and hydraulic functioning might not be maintained automatically under continuous agricultural use. Recurrent tillage, uncontrolled traffic of machineries, elimination of residues, and decreased returns of organic matter can over time erode the stability of the aggregates, augment bulk density and lower infiltration. This is the reason that the recent research is more inclined on the management systems that can protect the soil structure, lessen compaction, and recover the pore continuity with the help of biological and organic processes rather than mechanical loosening in a short-term (Kabato et al., 2025; Shaheb et al., 2021).

One of the most prevalent practices that are explored is reduced or conservation tillage. Compared to recurring mouldboard ploughing, reduction of the tillage often leads to reduced soil disturbance, which helps to maintain aggregates and possibly increase soil organic matter near the surface. Comparing contrasting tillage systems in the field, Crittenden et al. (2015) observed that non-inversion tillage enhanced soil organic matter and aggregate stability and in one field, it enhanced soil water retention, without incurring any yield penalty in most instances. Though decreased tillage can occasionally enhance penetration resistance or reduce field-saturated hydraulic conductivity in certain situations, the study still found that it could be an effective substitute in situations where the goal is to maintain or enhance soil physical quality. Similarly, Alvarez and Steinbach (2009) have reviewed tillage systems and gave a report that the benefits of no-till in minimizing compaction risk and enhancing the quality of the structural form are likely to manifest in the long run.

Cover crop is another important strategy which enhances physical properties of the soil by the way of root activity, returning of residues and covering of the soil surface. A critical review by Koudahe et al. (2022) revealed that integrating cover crops into conventional crop production systems may reduce the bulk density of soil, improve the soil structure and hydraulic properties of the soil, enabling the soil to take up more water. Field evidence supports this: as Xu et al. (2024) have discovered, the same tillage systems that were also associated with improved aggregate stability also enhanced the infiltration during crop growth, and recent findings on cover crops and tillage in Luvisols have shown that the management option confers positive impacts on the selected physical and water-retention characteristics (Gajewski et al., 2025). Cover crops are also slowly evolving to be one of the most reasonable solutions to improve the physical characteristics of soil in the context of modern agriculture because they contribute to organic contributions and formation of biological pores (Koudahe et al., 2022).

The other management alternative that has been found to be most relevant is controlled traffic farming as it concentrates the machine loads into fixed traffic lanes and makes the crop area to be subjected to compaction only once. Da Luz et al. (2023) in a Geoderma study observed that the uncontrolled traffic enhanced the bulk density and penetration resistance and decreased the total porosity but did not affect the soil physical functionality as compared to the controlled traffic. Previous experimental studies on vegetable production also revealed that controlled traffic treatment had better physical properties of soil and less requirement of tillage activities than the use of traditional traffic systems (McPhee et al., 2015). The findings are especially relevant in the field of mechanized agriculture, where the structural degradation is mostly due to compaction as a result of traffic.

Another method that has been proven to have a positive effect on the physical properties of the soil is introduction of organic amendments. Organic materials like compost, manure, crop residues, and biochar could enhance the stability of the aggregates, reduce bulk density and enhance the ability of the soil to retain water by increasing soil organic matter and promoting aggregation. Tejada et al. (2008) showed that the two organic waste amendments reduced the aggregate instability and bulk density and soil loss during simulated rainfall. Detection of recent reviews also indicates that the soils that are treated with organic materials are known to have low bulk density, high pore volume, enhanced infiltration, and augmented water-retaining capability

(Xu et al., 2025). Furthermore, biochar research indicates that it is likely to reduce bulk density and can improve the aggregate stability and infiltration, especially when applied in combination with compost or manure (Blanco-Canqui, 2017; Premalatha et al., 2023).

The preservation of soil organic carbon is also a critical consideration in enhancing the physical properties of soil, as organic carbon is directly connected with aggregation, stability of pores and compaction resistance. Klöffel et al. (2024) determined a critical point of soil organic carbon of about 23 percent in soils that was below which the soil structure in agricultural soils started to decline. It means that the practices that build up carbon such as retention of residues, rotations diversified, cover cropping, and organic amendments are not only beneficial, but also the physical restoration is built on the practices that accumulate carbon. In this feeling, physical quality management of soil is highly associated with the long-term carbon management and is not associated with short-term mechanical intervention.

Another reason is that physical improvements of soil frequently demand combined management, rather than one practice. Kabato et al. (2025) stress the importance of soil-health management to achieve climate resiliency and crop productivity and combine soil amendments, diverse cropping systems, conservation agriculture, and context-specific practices. This conforms with the literature in general that shows that optimum functioning is usually at a lower disturbance with the incorporation of the biological cover and organic strength. That is, soil physical quality can best be enhanced when it is managed to encompass compaction, aggregation, organic matter, and water movement instead of each property being addressed individually.

To sum it up, the preservation of the soil structure, reduction of compaction, and strengthening of the biological and organic foundation of soil can help to manage the physical conditions of the soils in the agricultural systems. The use of reduced tillage, cover crops, controlled traffic farming and organic amendments are well supported in the literature on the effectiveness of each of these strategies to reduce bulk density and improve the aggregate stability, infiltration and favored root environment. This results in the necessity to develop sustainable soil management based on integrated practices that would not only help to avoid physical damage to the soil but also enhance the long-term resilience and productivity of the soil (Crittenden et al., 2015; Koudahe et al., 2022; da Luz et al., 2023; Kabato et al., 2025).

Future Projections and challenges of Soil physics as a solution to sustainable agriculture.

The fact that the structure of the soil of agricultural land is affected by nature as well as long-term management are one of the most important questions in soil physics, and it is difficult to predict and reverse the degradation. The recent research on the temperate-boreal agricultural soils made it clear that the soil structure changes over time in relation to the interaction of soil properties, climate, site, time and management as well as that agricultural intensification can lead to soil structural degradation particularly when soil organic carbon gets to the critical levels. It shows that the physical quality of the soil cannot be under the control of a few operations in the field and that the protection of the structure and carbon condition should be carried out on a long-term basis (Klöffel et al., 2024).

The second significant risk is climate variability. Weakly structured soils with low infiltration or high compaction will be less resilient with greater variability in rainfall and more frequent droughts and floods. In recent criticisms, the fact that the improved knowledge of soil health is now central to climate resilience because of physical health improvements, water retention, infiltration, and crop strength to environmental stress is highlighted (Kabato et al., 2025).

The second challenge in the future is the need to change towards the use of simple indicators to more integrated measures of physical quality of soils. Bulk density is quite convenient, and does not give a complete indication of pore continuity, aggregate structure and functional soil behaviour. Recent changes in the study of soil-structure stipulate the necessity to strengthen the links between the indicators that are measurable and actual field performance, particularly the root development, water movement, and performance when subjected to farming (Klöffel et al., 2024).

Sustainable agriculture and soil physics will probably see the future as relying on integrated management systems as opposed to the isolated practices. The reviews that are in place are slowly getting some traction to conserve tillage, retain residues, cover crops, organic amendments and traffic control in such a way that the structure, porosity and water relations are improved not separately but together. This bigger systems perspective has now been viewed as crucial to climate-wise, and productivity-focused agriculture (Kabato et al., 2025; Al-Shammary et al., 2025).

In conclusion, soil physics in agriculture has a future of protecting the soil structure, enhancing soil resilience to climate stress and adopting integrated management that uses better monitoring equipment. The quality of soil physical constraints diagnosis, prevention, and correction will be more dependent on the sustainability of the agriculture over the years (Klöffel et al., 2024; Kabato et al., 2025).

Conclusion

In summation, physical characteristics of soil are the key factors to the agricultural productivity as they determine the flow of water, aeration, root development and the entire functioning of the soil. This review shows that soil texture, structure, bulk density, porosity and water retention are all intertwined and have a significant influence on crop growth and soil functioning.

It is also evident that the physical degradation of soil, compaction and structural degradation have adverse effects on the plant growth due to low penetration of roots, low infiltration and low interaction of soil- water. On the other hand, good physical condition of soils provides good environment to roots and guarantees constant production of crops.

On the whole, sustainable agriculture requires the restoration of physical conditions of soil by adequate management. Maintaining soil structure, compaction, and increasing water-use efficiency are great steps toward ensuring healthiness of soil, and long-term crop production.

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