PLANT SCIENCE TODAY
ISSN 2348-1900 (online)
Vol 11(sp4): 01–09
https://doi.org/10.14719/pst.5342

HORIZON
e-Publishing Group
HePG

REVIEW ARTICLE

Soil physical health sustenance: strategies and perspectives - A review

Bharathi M[1], Sivakumar K[1*], Gopalakrishnan M[1], Vennila MA[2], Anandham R[3] & Sritharan N[4]

[1]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[2]ICAR - Krishi Vigyan Kendra, Papparapatty, Dharmapuri 636 809, India

[3]Department of Agricultural Microbiology, Tamil Nadu Agricultural University, Coimbatore 641 003, India

[4]Department of Rice, Tamil Nadu Agricultural University, Coimbatore 641 003, India

*Email: sivakumar.k@tnau.ac.in

OPEN ACCESS

ARTICLE HISTORY
Received: 28 September 2024
Accepted: 15 October 2024
Available online
Version 1.0 : 13 December 2024

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

CITE THIS ARTICLE
Bharathi M, Sivakumar K, Gopalakrishnan M, Vennila MA, Anandham R, Sritharan N. Soil physical health sustenance: strategies and perspectives - A review. Plant Science Today.2024;11(sp4):01-09. https://doi.org/10.14719/pst.5342

Abstract

Soil physical health sustenance is vital for ensuring sustainable agricultural output and environmental well-being. This review discusses several tactics and viewpoints targeted at protecting and promoting soil physical health. Soil health comprises its physical, chemical and biological characteristics, defining its capacity to sustain life. Degradation of soil physical health, caused by erosion, nutrient depletion and incorrect management methods, offers difficulties to agricultural sustainability, manifesting as reduced crop output and increased soil erosion. Soil physical qualities, including structure, porosity and water retention, directly influence plant development and ecosystem functioning. Effective soil management techniques, including practices like conservation tillage, covering crops and the use of organic amendments, are essential for preserving ideal soil physical conditions. Furthermore, advancements in technology, such as precision farming and remote sensing, provide innovative solutions for monitoring and managing soil health. However, constraints such as a lack of standardized assessment procedures and inadequate laboratory facilities restrict thorough soil health assessments. Future efforts should focus on multidisciplinary research to clarify the complex relationships among soil features and develop appropriate soil management solutions for varied agroecosystems. This analysis gives insights into soil physical health sustenance strategies and highlights the necessity of holistic soil management for resilient and sustainable agriculture.

Keywords

conservational agriculture; soil degradation; soil health; soil quality indices

Introduction

Soil is a vital natural resource, comparable to air and water, and is a valuable gift to humanity. Soil is a complex system that interconnects various components of the Earth such as the atmosphere, hydrosphere, lithosphere and biosphere. It comprises organic and inorganic minerals, air and water that act as a reserve for plant growth and productivity. Soil functions as a medium for plant growth, but it also plays a significant role in the environment by purifying water, sequestering carbon, recycling nutrients and providing habitats for various organisms (1).

Soil health can be defined as "the continued capacity of a soil to function as a vital, living ecosystem that sustains plants, animals and humans" (2). Soil health includes the physical, chemical and biological characteristics of soil, all of which are essential for maintaining sustained agricultural output. Consequently, soil health primarily emphasizes enhancing or maintaining the diverse activities that the soil is currently capable of performing. Preserving or enhancing soil health is regarded as essential to achieve sustainable agricultural production.

The deterioration of soil health in India is increasing continuously due to factors such as soil erosion, excessive extraction of nutrients, decreased utilization of organics and imbalanced fertilizer application. Consequently, this results in nutrient deficiencies in crop growth and reduces the effectiveness of fertilizers. A healthy soil, considered "fit for purpose," is defined by its cultivability, flexibility, efficient retention of water and nutrients and superior drainage capacity. Such soil conditions facilitate robust root growth and optimal crop establishment (3). In turn, these characteristics can be collectively improved by maintaining the soil's physical health.

The physical health of any soil is determined by the function of climate, time, topography, parent material and vegetation (4). Soil physical and mechanical properties include soil structure, moisture, permeability, temperature, bulk density, texture, porosity and others (5). Among various physical properties of soil, it is mandatory to understand that certain factors affect plant growth directly or indirectly. Soil air, temperature, water and mechanical resistance that hinder the germination of seedlings are the major factors that directly obstruct plant growth whereas soil bulk density, structure, texture and aggregate stability are the properties that show indirect effects on plant growth (6).

This review discusses the impact of several physical soil qualities on crop growth, development and productivity. This review also seeks to elucidate soil physical health, markers of soil physical quality, obstacles in sustaining soil physical health, solutions for improvement and future views for maintaining optimal soil physical health.

Soil physical health

Soil health and soil quality are terms often used to describe the soil's ability to support sustainable production. However, these terms can be used as synonyms for each other except for the limitation that soil health is mainly focused on soil dynamic quality. It is mainly pertained to soil biological characteristics. In contrast, soil quality can be defined as the 'capacity of soil to function within its ecosystem boundary to sustain biological productivity, maintain environmental quality and promote plant and animal health' (2).

A soil that can effectively sustain its inherent or acquired productive capacity/ability and provide ecological benefits is indicated to be in good health. The concepts of soil quality and soil health are discussed in the 14th Edition of the Soil Science textbook, *Nature and Properties of Soils* (7) . The book states that, although both phrases are frequently used interchangeably, they represent two separate concepts. Soil health denotes the self-regulation, stability, resilience and absence of stress indicators within the soil as an ecosystem. Soil quality refers to the biological integrity of the soil community, including the equilibrium among organisms inside the soil and the interactions between soil organisms and their surroundings. The concept of soil health demands the integration of soil's physical, chemical and biological properties together and their role in sustainable production, crop growth and ecological stability (8).

The soil's physical health refers to the capability of the soil to meet the needs of plants and the ecosystem such as aeration, physical strength, water, etc. The physical properties of soil depend on the arrangement, shape, amount, size, shape and mineral composition, organic matter content and pore spaces. Physical properties of soil such as the degree of compaction, aeration, water holding capacity, drainage and soil aggregate stability should be in optimum conditions because they can affect the plant growth adversely (9).

Soil Quality Indicators

The soil quality, or its ability to function, is generally assessed using in-built and dynamic soil properties. They act as indicators of soil function because these properties cannot be measured directly and they may be subjective. These inherent soil properties are formed over thousands of years and alter very little or not at all when managed. These properties are the result of soil-forming factors such as climate, time, biota, parent material and landscape. Examples of soil inherent properties include the type of clay, soil texture, drainage class and depth of bedrock. The soil quality indicators are generally classified as physical, chemical and biological indicators depending upon how the soil function gets affected but this classification is not clearly defined because any single soil property or indicator influences the many soil functions (10).

Physical indicators, used for evaluating the soil quality, rationale for selection, their functions in soil characteristics and issues caused by them due to improper maintenance are listed in Table 1.

These soil quality indicators determine how effectively water and roots can move or penetrate the soil and how resilient the soil resource is to the effects of climate change. Features like soil color, topsoil thickness, subsoil exposure, soil structure and sediment deposits are considered visual examples of physical indicators (10). This represents another category of soil quality indicators, distinct from physical, chemical and biological indicators, currently referred to as visual indicators. These can be observed directly or interpreted from photographs. Examples of potential visual indicators include subsoil exposure, soil color changes, plant responses, ephemeral gullies, runoff, blowing soil, weed species, ponding and sediment deposition. Such visual signs indicate clearly that the quality of the soil is either changing or under threat (11) (Fig.1).

Challenges in Soil Physical Health Management

While numerous soil health indicators have been suggested, there is still no globally accepted and standardized method for assessing soil health (5). Physical parameters of soil health, such as bulk density, water retention, soil texture (proportions of sand, silt and clay) and water holding capacity, are recognized as important indicators for maintaining soil health. However, many soil health cards fail to include these parameters. Estimation of soil physical properties is mostly laborious and many of the soil science laboratories lack facilities to carry over these experiments so they cannot be measured (12). For example, the infiltration rate measurement in the field is a time-consuming procedure and also it utilizes about 10 liters of water which becomes challenging when the experiment is to be carried out widely (13).

Table 1. The physical indicators considered for evaluating the soil quality

Physical indicators	Rationale for selection	Soil functions mediated by them	Issues caused due to improper maintenance	References
Soil texture	Water and nutrient retention and transport, modeling use	It determines the soil characteristics affecting crop growth such as water-holding capacity, permeability and workability of soil.	Cannot be readily changed and cannot be easily managed.	(34)
Infiltration rate	Runoff, leaching and erosion potential.	The rapid infiltration rate indicates a good soil structure in clay or silt soil textures but not in soils having sandy textures.	Quick infiltration of water can increase the risk of off-site contamination in the water table. The field method of analysis of infiltration rate is tedious and requires more amount of water.	(35, 13)
Soil penetration	Plant root penetration, water infiltration, soil aeration	Based on the soil types, a little topsoil compaction is advantageous for crop development and root anchorage.	Soil compaction alters the structure of the soil by raising its bulk density and penetration resistance while reducing its porosity, negatively affecting crop growth and development.	(36, 37.38)
Bulk density	Porosity, penetration of crop root, porosity, indicator of soil compaction.	It replicates the ability of soil to function for water and solute movement, structural support and soil aeration.	Increased risk of pollutant transfer occurs.	(35)
Soil crusting	Water penetration, Increased water runoff and soil loss.		Precipitation leads to the breakdown of soil aggregates that leads to soil aggregate breakdown blocking the spoil's pores. This results in the sealing of pores, reducing water penetration and increasing water runoff and soil loss.	(39)
Aggregate stability	Soil structure, crop emergence and erosion resistance which is an early indicators of soil management effects.	The stability of soil macro aggregates is linked to microorganisms that produce adhesive substances, which, together with fungal hyphae and fine roots, help bind the aggregates together.	It does not sufficiently describe the soil habitat, or the soil structure encountered by soil microbes or roots.	(15,40)
Hydraulic conductivity	Indication of relative water transmission rate of the soil.	Rainfall retention, water storage and comprehensive soil moisture management.	Dynamic characterization of the soil-plant-atmospheric continuum is determined by hydraulic conductivity.	(19,41,42)
Porosity	Closely associated with bulk density and frequently utilized to assess the extent of compaction.	An increase in porosity decreases the bulk density, soil strength and soil compaction.	Decreased soil porosity is linked to limited root growth, reduced root proliferation, and diminished nutrient availability.	(38,43,44)
Water holding capacity	Good water-holding capacity of the soil is correlated with good soil structure.	It is a fundamental hydraulic property of soil, responsible for the functioning of soil in ecosystems and has a significant impact on soil management.	Soil water movement and retention, crusting and aeration are all influenced by aggregation.	(38,45,46)

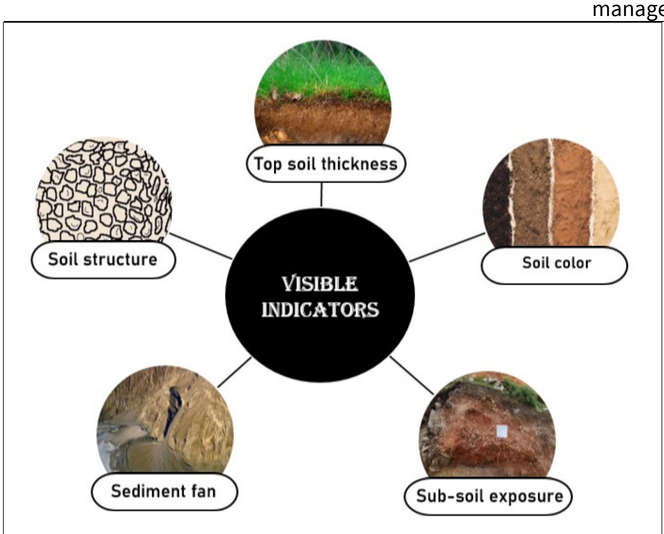

Fig. 1. Visible Soil quality indicators.

A further constraint in preserving soil physical health is the focus on measuring only surface soil parameters rather than the entire profile characteristics (14). Even if the soil physical health analysis is carried out worldwide, the slight variations made in standard methods of analysis used by different laboratories may make it difficult to compare the existing datasets which is challenging (15).

Strategies for the sustenance of soil physical health

Indian soils are naturally low in quality due to the warm climate and the effects of erosion. The conversion of forest land to cropland, along with improper management practices in agriculture, further contributes to the degradation of soil (16). To restore the soil's physical health, several approaches are employed, including regenerative agriculture, the application of organic and inorganic soil amendments and engineered nanoparticles (ENPs). Many practices such as crop rotations, cover crops, crop residue management, mulching, conservational tillage, livestock integration and rotational grazing are associated with regenerative agriculture. These are generally considered 'Good Agricultural Practices' and they remain integral to traditional farming practices (17). Organic amendments consist of materials such as sphagnum peat, straw, wood chips, biosolids, grass clippings, manure, compost, sawdust, wood ash and biochar. In contrast, inorganic amendments include vermiculite, sand, tire chunks, perlite and pea gravel (18). Out of these soil amendments, biochar is being used widely and is creating interest as a potential soil amendment. It results from the incomplete and slow combustion of organic materials, containing a high organic carbon content (60 to 80 %), which can improve various soil properties and be especially beneficial for soils with low organic carbon levels (19). The different effects of these strategies on soil physical health are outlined in the following sections.

Impact of various strategies on soil physical health

Agronomic practices

To maintain good soil physical health, various agronomic practices are carried out and they are collectively termed 'regenerative agriculture'. A compilation of practices related to regenerative agriculture proposed by McGuire (20) and Merfield (21) are depicted in Fig. 2. It is crucial to emphasize that meeting the standards of Regenerative Organic Agriculture requires the exclusion of chemical fertilizers and synthetic pesticides and soil-free cultivation methods are not allowed. While some practices commonly associated with regenerative agriculture, such as crop rotations, crop covers and integration of livestock, have long been recognized as standard agricultural techniques and remain essential in conventional farming, other practices present challenges (22). For example, conservation agriculture can be practiced within an organic system or as a method that depends on genetically modified organisms (GMOs), along with the use of intensive herbicides and fertilizers (17) (Fig.2). A few research findings have been listed in tables (2-7) to support that the above-stated agronomic strategies help improve soil physical health.

Engineered Nanoparticles

Engineered nanoparticles are specifically designed materials with dimensions typically ranging from 1 to 100 nanometers and can take various forms, such as nanowires, spheres, nanotubes and nanorods (23). Research has demonstrated that ENPs like Iron (II,III) oxide (Fe_3O_4), Zinc Oxide (ZnO), Magnesium Oxide (MgO), Silicon Dioxide (SiO_2) and Titanium Dioxide (TiO_2) positively impact on soil physical properties, including enhancing hydraulic conductivity and increasing soil porosity (5,24). In a study by Aggelides (25), the application of MgO ENPs was shown to reduce soil bulk density, an effect not observed to the same extent with Fe_3O_4 ENPs. This reduction in bulk density improved soil aeration and root penetration, potentially due to the smaller particle size of MgO ENPs. However, specific particle dimensions for both ENPs were not detailed. Additionally, MgO ENPs improved soil structure, increased porosity and lower bulk density. On the other hand, Fe_3O_4 ENPs primarily contributed to strengthening soil aggregates by enhancing the bonds between iron and soil particles, thereby increasing the tensile strength of the aggregates. Furthermore, the use of γ-Al_2O_3 and CuO ENPs resulted in reduced swelling and shrinkage stress, as well as decreases in hydraulic conductivity and soil density (25). The application of ENPs for soil remediation has been extensively studied and reviewed, with nanoscale zero-valent iron (nZVI) being one of the most researched materials for environmental remediation over the last two decades (26). Other studies have found that carbon nanofibers (CNFs) act as growth enhancers, improving plants' water uptake abilities. These studies also reported significant increases in germination rates, shoot and root growth and higher levels of chlorophyll and protein content in plants treated with Cu-CNFs (27).

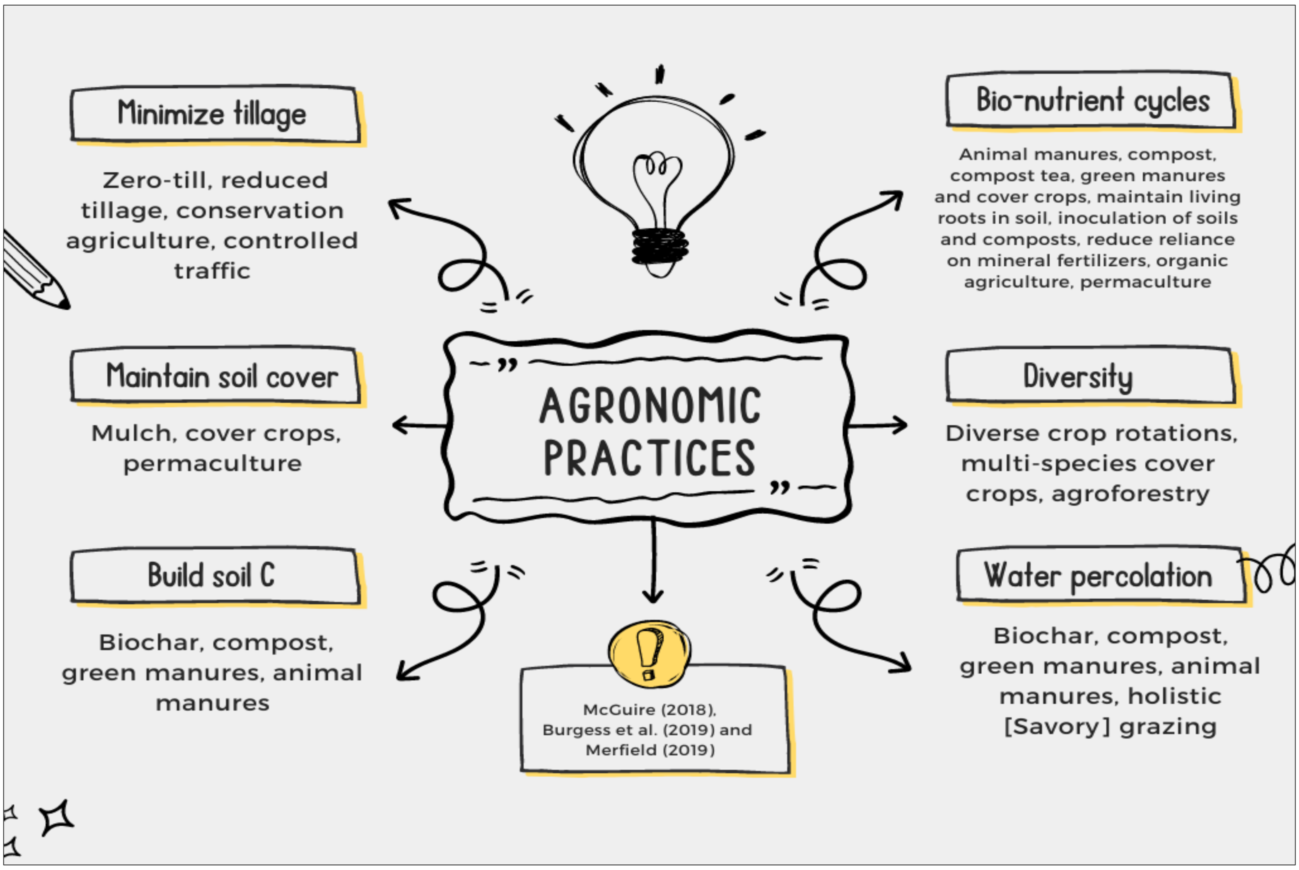

Fig. 2. List of agronomic practices associated with regenerative agriculture.

Table 2. Soil Structure with respect to the various practices

S.No.	Strategy / Practice followed	Results	Reference
1.	Crop rotation	When legume-based crops were included in crop rotations, the labile carbon concentration increased and resulted in soil structure improvement.	(47)
2.	Rotational grazing	Light to moderate grazing significantly improved the soil structure and soil organic carbon (SOC) more than heavy grazing	(48,49)
3.	Biochar application	Biochar application along with animal manure improved the structure of soil by binding soil particles strongly resulting in the formation of soil aggregate and increasing soil's tensile strength, in sandy soils.	(50)
4.	No-tillage	The increase in SOC resulted in higher aggregate stability and maintenance of good soil structure.	(51)

Table 3. Bulk density, Particle density, Porosity of soil

S.No.	Strategy / Practice followed	Results	Reference
1.	Residue retention	Retaining residues on the soil surface improved porosity and soil aggregates.	(52,53,54)
2.	Biochar application	As the amount of biochar applied increased, soil thermal conductivity declined due to a reduction in soil bulk density. The incorporation of biochar was observed to enhance soil porosity by 8.4 % while lowering the bulk density.	(55,56)
3.	Zero tillage	Zero tillage along with residue retention, resulted in a considerable decrease in bulk density in semi-arid regions.	(57)
4.	Organic soil amendment application	Soils amended with *C. pascorum*, *P. biglobosa* and *L. purpereus*, resulted in a 9.6 %, 8.2 % and 6.2 % decrease in bulk density values respectively, in comparison with the non-amended soils.	(46)

Table 4. Soil permeability / Infiltration rate

S.No.	Strategy / Practice followed	Results	Reference
1.	Crop residue retention	Retention of crop residues and surface roughness creation by opting for strategic tillage proved to be a practical option for breaking soil crusts, improving water infiltration and reducing runoff.	(58)
2.	Organic amendment application	An increase in organic matter content and soil microbial activity led to improved water infiltration. This was particularly noticeable when 120 t/ha of household waste and manure were applied, resulting in higher water infiltration rates (549.25 cm and 596.46 cm, respectively) compared to the control, which measured around 332.16 cm.	(59)
3.	Zero tillage	Zero tillage along with mulch resulted in a significant reduction in bulk density (BD) and a higher infiltration rate.	(60,61)
4.	Biochar application	The hydrophobic nature of biochar induces water repellency, leading to a reduction in water infiltration and hydraulic conductivity.	(19)

Table 5. Soil temperature

S.No.	Strategy / Practice followed	Results	Reference
1.	Cover crops	Cover crops usage in summer was found to reduce soil compaction and temperature and increase aggregate stability and water content of the soil.	(51)
2.	Residue retention	Surface residue retention was found to control weeds, moderate soil temperature, decrease evaporation and increase biological activity.	(62)
3.	Conservational agriculture	In hot regions, under conservational agriculture systems, the soil temperatures were found to reduce when residues are retained which also helped in plant growth and yield improvement.	(63,64)

Table 6. Water holding capacity

S.No.	Strategy / Practice followed	Results	Reference
1.	Biochar application	The application of biochar has been shown to increase water retention in 17 out of 19 soils, demonstrating that in 90 % of cases, biochar enhances the soil's capacity to retain water.	(19)
2.	Conservational agriculture	Increased soil water storage was identified as one of the outcomes when conservation agriculture and its components were implemented.	(65,66,23)
3.	Conventional tillage	In certain situations, the soil tilled conventionally resulted in a greater infiltration and storage of soil water than conservational agriculture by loosening the surface of the soil and destroying soil crusts.	(24,67)
4.	Compost application	Compost, when applied to loamy and clay soils in different concentrations, the water retention capacity of the soils increased when a higher amount of compost was applied.	(25)

Table 7. Penetration resistance

S.No.	Strategy / Practice followed	Results	Reference
1.	Conservational agriculture	When conservation agriculture is followed, a decrease in subsurface compaction was noted, particularly it was evident in the 15-30 cm layer where soil penetration resistance significantly decreased. This reduction likely enhanced root structure, resulting in increased crop yields.	(26)
2.	No-tillage	The implementation of no-tillage practices alongside permanent raised beds, in contrast to conventional tilling, led to a 15.9 % and 30.7 % decrease in penetration resistance in maize.	(27)
3.	Compost application	Bulk density and penetration resistance decreased with the use of composts made from municipal waste and sewage sludge, with the reduction being more significant in loamy soil compared to clay soil.	(25)

Crop simulation modeling for soil physical health management

Crop modeling has been utilized in agriculture since the 1970s, and various models are now more readily accessible to users with varying degrees of experience and knowledge. The science field is attaining greater heights from being a neophyte science to date, with lots of evolution supported and backed up by improved languages, software, computer facilities and development tools. Despite being cultivated through scientific methods, the fundamental basis remains rooted in the knowledge gained from crop physiology, soil science, agro-meteorology and other relevant agricultural disciplines. The crop system simulators use empirical equations to model carbon, water and nitrogen balance processes and these equations are calculated daily or hourly by a computer program to forecast crop growth, nutrient absorption, water usage, final yield and other plant characteristics (28).

The crop models may be empirical/mathematical, mechanistic, static and dynamic, deterministic and stochastic, simulation and optimizing models. The majority of crop models that are used to predict crop production are in these categories and they offer a variety of low-cost management alternatives and tactics (29). In early models, where solar radiation and temperature were only the driving variables, they were focused exclusively on crop carbon balance under optimum conditions (28). Using the leaf-level parameters for simulation of crop photosynthesis along with prediction of crop development throughout their stages of growth and scrutinizing policies for reproductive yield increase were the primary focus (30, 31). The following advances made in models were oriented to field decision making such as irrigation scheduling, pest and disease management (32, 33). Some of the crop simulation models used to assess soil physical health are given in Table 8.

Conclusion and Future Perspectives

Maintaining the physical health of the soil is essential for ensuring sustainable agricultural productivity and environmental resilience over the long term. This review highlights various strategies and viewpoints aimed at preserving and enhancing soil physical health. Essential soil management techniques, including conservation tillage, cover cropping, crop rotation and the application of organic amendments, are vital for preserving soil structure, enhancing water infiltration and reducing erosion. Soil organic matter is a vital measure of soil physical health, influencing soil structure, water retention and nutrient availability. Practices that focus on increasing soil organic matter, such as the application of compost and the management of agricultural residues, are vital for sustaining soil physical health. Soil compaction presents a major threat, as it limits root growth, impedes water infiltration and hampers nutrient uptake. The use of appropriate soil conservation methods, such as controlled

Table 8. Crop simulation models are used to assess soil physical health

Simulation models	Reference	Time & scale	Summary of functions
DSSAT (Decision Support System for Agrotechnology Transfer)	(68)	Day Field	It features simulation models for over 42 crops, as per version 4.8.2 and includes modules for simulating soil water movement, nutrient dynamics, runoff, percolation and crop growth responses to soil physical properties.
APSIM (Agricultural Production Systems sIMulator)	(69)	Day Field	A comprehensive model designed to simulate biophysical processes in agricultural systems, including crop growth, soil processes and management practices. It provides detailed representations of soil physical characteristics, such as water infiltration, moisture retention and the dynamic behavior of soil structure.
STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard)	(70)	Day Field	This is a process-based crop model designed to simulate the growth of various crops under diverse management practices and environmental conditions. The model is now adapted for nearly 20 crop species. It comprises components for replicating soil's physical characteristics like moisture levels, temperature and compaction.
CROPSYST (Cropping SYSTems simulator)	(71)	Day Plot	It is a process-driven crop model created to simulate the growth of multiple crops under varying management practices and environmental conditions. It includes modules for simulating the physical properties of soil such as soil temperature, soil water content and soil compaction.
SALUS (System Approach to Land Use Sustainability)	(72)	Day Field	It is a dynamic modeling framework for simulating agricultural systems at various spatial and temporal scales. It includes modules for simulating soil physical properties such as soil temperature, soil water dynamics and soil compaction.

traffic farming and subsoiling, can mitigate the negative effects of soil compaction. Technological advancements, such as precision agriculture and remote sensing, offer promising opportunities to monitor soil physical health and implement site-specific management practices to address soil degradation.

Additional research is required to enhance our understanding of the intricate interactions between soil's physical, chemical and biological properties and their influence on overall soil health. Since laboratory analyses of various soils' physical properties can be time-consuming, combining experimental studies, field observations and modeling techniques will be beneficial for understanding these interactions. Developing new soil management strategies tailored to different agroecosystems and environmental conditions is necessary to promote sustainable soil physical health. Adopting regenerative agricultural practices that focus on enhancing soil resilience and ecosystem services will contribute to the long-term sustainability of soil health. Initiatives aimed at educating and communicating the significance of soil health can enhance social involvement and backing for soil conservation endeavors. Utilizing emerging technologies, such as Artificial Intelligence (AI) and machine learning, for assessing and monitoring soil health can offer valuable insights into soil physical processes and support targeted efforts to enhance soil health. Addressing global challenges like climate change and food security requires an integrated approach that incorporates soil health considerations into agricultural planning and management strategies.

Authors' contributions

BM carried out the works such as collection of literature, structuring the manuscript, preparation and drafting of the manuscript. SK contributed to the manuscript through his guidance, preparation of the framework, correction and revision of the manuscript. GM, VMA, AR and SN were involved in correcting and revising the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used ChatGPT to edit the language and improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

1. Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, De Goede R, et al. Soil quality-A critical review. Soil Biol Biochem. 2018;120:105-25. https://doi.org/10.1016/j.soilbio.2018.01.030
2. Doran JW, Parkin TB. Defining and assessing soil quality. In: Doran W, Coleman DC, Bezdicek DF, Stewart BA, editors. Defining soil quality for a sustainable environment. SSSA Special Publications. 1994;35:1-21. https://doi.org/10.2136/sssaspecpub35.c1
3. Mankotia R, Sharma R, Sepehya S, Saini R, Kumar A. Soil Health Assessment and Its Sustenance. Int J Curr Microbiol Appl Sci . 2019;8 (8):1978-87.
4. McVay K, Budde J, Fabrizzi K, Mikha M, Rice C, Schlegel AJ, et al. Management effects on soil physical properties in long-term tillage studies in Kansas. Soil Sci Soc Am J. 2006;70(2):434-8. https://doi.org/10.2136/sssaj2005.0249
5. Bayat H, Kolahchi Z, Valaey S, Rastgou M, Mahdavi S. Iron and magnesium nano-oxide effects on some physical and mechanical properties of a loamy Hypocalcic Cambisol. Geoderma. 2019;335:57-68. https://doi.org/10.1016/j.geoderma.2018.08.007
6. Roberts TL, Stewart JWB, Bettany JR. The influence of topography on the distribution of organic and inorganic soil phosphorus across a narrow environmental gradient. Canadian Journal of Soil Science. 1985;65(4):651-65. https://doi.org/10.4141/cjss85-071
7. Brady NC, Weil RR. Nature and Properties of Soils.14th ed. Pearson Education;2013.
8. Katyal J, Datta S, Golui D. Global review on state of soil health.In: Katyal JC, Chaudhuri SK, Dwivedi BS, Biswa DR, Rattan RK, Majumdar K, editors.Soil Health: Concept, Status and Monitoring. Indian Society of Soil Science New Delhi. 2016:1-33.
9. Mounissamy VC, Parihar RS, Dwivedi AK, Saha JK, Rajendiran S, et al. Effects of Co-composting of municipal solid waste and pigeon pea biochar on heavy metal mobility in soil and translocation to leafy vegetable spinach. Bull Environ Contam Toxicol. 2021;106:536-44. https://doi.org/10.1007/s00128-020-03096-1
10. Veum K, Kremer R, Sudduth K, Kitchen N, Lerch R, Baffaut C, et al. Conservation effects on soil quality indicators in the Missouri Salt River Basin. J Soil Water Conserv. 2015;70(4):232-46. https://doi.org/10.2489/jswc.70.4.232
11. Kumar R, Jha K, Sharma S, Kumar V, Li C, Rajkumar S, et al. Effect of particle size and weight fraction of SiC on the mechanical, tribological, morphological, and structural properties of Al-5.6 Zn-2.2 Mg-1.3 Cu composites using RSM: fabrication, characterization, and modelling. Heliyon. 2022;8(9):e10602. https://doi.org/10.1016/j.heliyon.2022.e10602.
12. Aher SB, Lakaria BL, Singh AB, Kaleshananda S. Soil aggregation and aggregate associated carbon in a Vertisol under conventional, organic and biodynamic agriculture in Semi-Arid Tropics of Central India. J Indian Soc Soil Sci. 2019;67(2):183-91.
13. Griffiths BS, Faber J, Bloem J. Applying soil health indicators to encourage sustainable soil use: The transition from scientific study to practical application. Sustainability. 2018;10(9):3021. https://doi.org/10.3390/su10093021
14. Sparling G, Schipper L, Bettjeman W, Hill R. Soil quality monitoring in New Zealand: practical lessons from a 6-year trial. Agric Ecosyst Environ. 2004;104(3):523-34. https://doi.org/10.1016/j.agee.2004.01.021
15. Stott D.Soil health technical note No. 450-03.Recommended soil health indicators and associated laboratory procedures [Internet]. United States Department of Agriculture. Natural Resources and Conservation Service. 2019. Available from: https://www.naptprogram.org/files/napt/publications/method-papers/2019-nrcs-technote-450-03.pdf
16. De P, Deb S, Deb D, Chakraborty S, Santra P, Dutta P, et al. Soil quality under different land uses in eastern India: Evaluation by using soil indicators and quality index. Plos one. 2022;17 (9):e0275062. https://doi.org/10.1371/journal.pone.0275062
17. Giller KE, Andersson JA, Corbeels M, Kirkegaard J, Mortensen D, Erenstein O, et al. Beyond conservation agriculture. Front Plant Sci. 2015;6:870. https://doi.org/10.3389/fpls.2015.00870

18. Schoenau J, Davis J. Optimizing soil and plant responses to land-applied manure nutrients in the Great Plains of North America. Can J Soil Sci. 2006;86(4):587-95. https://doi.org/10.4141/S05-115

19. Blanco-Canqui H. Biochar and soil physical properties. Soil Sci Soc Am J. 2017;81(4):687-711. https://doi.org/10.2136/sssaj2017.01.0017

20. McGuire KM. Salt retention in wetland soils and effects on dissolved organic carbon export. Master's Theses and Doctoral Dissertations [Thesis] : Eastern Michigan University; 2018.

21. Merfield CN, Winder L, Stilwell SA, Hofmann RW, Bennett JR, Wargent JJ, et al. Mesh crop covers improve potato yield and inhibit tomato potato psyllid and blight: The roles of mesh pore size and ultraviolet radiation. Ann Appl Biol. 2019;174(2):223-37. https://doi.org/10.1111/aab.12489

22. Page KL, Dang YP, Dalal RC. The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. Front Sustain Food Syst. 2020;4:31. https://doi.org/10.3389/fsufs.2020.00031

23. Verhulst N, Nelissen V, Jespers N, Haven H, Sayre KD, Raes D, et al. Soil water content, maize yield and its stability as affected by tillage and crop residue management in rainfed semi-arid highlands. Plant Soil. 2011;344:73-85. https://doi.org/10.1007/s11104-011-0728-8

24. Jones O, Hauser V, Popham T. No-tillage effects on infiltration, runoff, and water conservation on dryland. Trans ASAE. 1994;37(2):473-9.

25. Aggelides S, Londra P. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. Bioresour Technol. 2000;71(3):253-9. https://doi.org/10.1016/S0960-8524(99)00074-7

26. Mondal S, Das T, Thomas P, Mishra A, Bandyopadhyay K, Aggarwal P, et al. Effect of conservation agriculture on soil hydro-physical properties, total and particulate organic carbon and root morphology in wheat (Triticum aestivum) under rice (Oryza sativa)-wheat system. Indian J Agric Sci. 2019;89(1):46-55. https://doi.org/10.56093/ijas.v89i1.86126

27. Parihar CM, Yadav MR, Jat SL, Singh A, Kumar B, Pradhan S, et al. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. Soil Till Res. 2016;161:116-28. https://doi.org/10.1016/j.still.2016.04.001

28. Boote KJ, Jones JW, Hoogenboom G, White JW. The role of crop systems simulation in agriculture and environment. Int J Agric Environ Inf Syst. 2010;1(1):41-54. https://doi.org/10.4018/jaeis.2010101303

29. Jones JW, Hoogenboom G, Porter CH, Boote KJ, Batchelor WD, et al. The DSSAT cropping system model. Eur J Agron. 2003;18(3-4):235-65. https://doi.org/10.1016/S1161-0301(02)00107-7

30. DeWit C. Photosynthesis ofleafcanopies (Agr. Res. Rep. 663). Pudoc, Wageningen. 1965.

31. Duncan W. Leaf angles, leaf area and canopy photosynthesis 1. Crop Sci. 1971;11(4):482-5. https://doi.org/10.2135/cropsci1971.0011183X001100040006x

32. Wilkerson G, Jones J, Boote K, Ingram K, Mishoe J. Modeling soybean growth for crop management. Trans ASAE. 1983;26(1):63-0073.

33. Swaney D, Sherman D, Howarth R. Modeling water, sediment and organic carbon discharges in the Hudson-Mohawk basin: Coupling to terrestrial sources. Estuaries. 1996;19:833-47. https://doi.org/10.2307/1352301

34. Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC. The concept and future prospects of soil health. Nat Rev Earth Environ. 2020;1(10):544-53.

35. Martlew J, Otten W, Morris N, De Baets S, Deeks LK. Long-term impacts of repeated cover cropping and cultivation approaches on subsoil physical properties. Soil Till Res. 2023;232:105761. https://doi.org/10.1016/j.still.2023.105761

36. Bouwman L, Arts W. Effects of soil compaction on the relationships between nematodes, grass production and soil physical properties. Appl Soil Ecol. 2000;14(3):213-22. https://doi.org/10.1016/S0929-1393(00)00055-X

37. Hamza M, Anderson WK. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Till Res. 2005;82(2):121-45. https://doi.org/10.1016/j.still.2004.08.009

38. Shaheb MR, Venkatesh R, Shearer SA. A review on the effect of soil compaction and its management for sustainable crop production. J Biosyst Eng. 2021:1-23. https://doi.org/10.1007/s42853-021-00117-7

39. Gucci R, Caruso G, Bertolla C, Urbani S, Taticchi A, Esposto S, et al. Changes of soil properties and tree performance induced by soil management in a high-density olive orchard. Eur J Agron. 2012;41:18-27. https://doi.org/10.1016/j.eja.2012.03.002

40. Young IM, Crawford JW, Rappoldt C. New methods and models for characterising structural heterogeneity of soil. Soil Till Res. 2001;61(1-2):33-45. https://doi.org/10.1016/S0167-1987(01)00188-X

41. Hussain N, Hassan G, Arshadullah M, Mujeeb F. Evaluation of amendments for the improvement of physical properties of sodic soil. Int J Agric Biol. 2001;3(3):319-22.

42. Bonfante A, Terribile F, Bouma J. Refining physical aspects of soil quality and soil health when exploring the effects of soil degradation and climate change on biomass production: an Italian case study. Soil. 2019;5(1):1-14. https://doi.org/10.5194/soil-5-1-2019

43. Dexter A. Soil physical quality: Part I. Theory, effects of soil texture, density and organic matter, and effects on root growth. Geoderma. 2004;120(3-4):201-14. https://doi.org/10.1016/j.geoderma.2003.09.004

44. Nawaz MF, Bourrie G, Trolard F. Soil compaction impact and modelling. A review. Agron Sustain Dev. 2013;33:291-309. https://doi.org/10.1007/s13593-011-0071-8

45. Rawls WJ, Pachepsky YA. Using field topographic descriptors to estimate soil water retention. Soil Sci. 2002;167(7):423-35.

46. Ogunwole JO, Iwuafor EN, Eche NM, Diels J. Effect of organic and inorganic soil amendments on soil physical and chemical properties in a West Africa Savanna agroecosystem. Trop Subtrop Agroecosystems. 2010;12(2):247-55.

47. Blair N, Crocker G. Crop rotation effects on soil carbon and physical fertility of two Australian soils. Soil Res. 2000;38(1):71-84. https://doi.org/10.1071/SR99064

48. Hiernaux P, Bielders CL, Valentin C, Bationo A, Fernandez-Rivera S. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. J Arid Environ. 1999;41(3):231-45.

49. Reeder Jd, Schuman GE. Influence of livestock grazing on C sequestration in semi-arid mixed-grass and short-grass rangelands. Environ Pollut. 2002;116(3):457-63. https://doi.org/10.1016/S0269-7491(01)00223-8

50. Khademalrasoul A, Naveed M, Heckrath G, Kumari K, de Jonge LW, Elsgaard L, et al. Biochar effects on soil aggregate properties under no-till maize. Soil Sci. 2014;179(6):273-83. https://doi.org/10.1097/SS.0000000000000069

51. Blanco-Canqui H, Ruis SJ. No-tillage and soil physical environment. Geoderma. 2018;326:164-200. https://doi.org/10.1016/j.geoderma.2018.03.011

52. Dahlgreen J, Parr A. The Impact on Greenhouse Gas Emissions of Rice Cultivation under Alternate Wetting and Drying and the System of Rice Intensification. 2023.

53. De Vries FT, Thébault E, Liiri M, Birkhofer K, Tsiafouli MA, Bjørnlund L, et al. Soil food web properties explain ecosystem services across

European land use systems. Proc Natl Acad Sci. 2013;110(35):14296-301. https://doi.org/10.1073/pnas.1305198110

54. Lehmann A, Zheng W, Rillig MC. Soil biota contributions to soil aggregation. Nat Ecol Evol. 2017;1(12):1828-35. https://doi.org/10.1038/s41559-017-0344-y
55. Bian R, Chen D, Liu X, Cui L, Li L, Pan G, et al. Biochar soil amendment as a solution to prevent Cd-tainted rice from China: results from a cross-site field experiment. Ecol Eng. 2013;58:378-83. https://doi.org/10.1016/j.ecoleng.2013.07.031
56. Omondi MO, Xia X, Nahayo A, Liu X, Korai PK, Pan G. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma. 2016;274:28-34. https://doi.org/10.1016/j.geoderma.2016.03.029
57. Bautista S, Bellot J, Vallejo VR. Mulching treatment for postfire soil conservation in a semiarid ecosystem. Arid Land Res Manag. 1996;10(3):235-42. https://doi.org/10.1080/15324989609381438
58. Dang Y, Seymour NP, Walker S, Bell M, Freebairn D. Strategic tillage in no-till farming systems in Australia's northern grains-growing regions: I. Drivers and implementation. Soil Till Res. 2015;152:104-14. https://doi.org/10.1016/j.still.2015.03.009
59. DIEHL R. Agriculture générale. 2 e édition. J. B Baillière. 1975;19. (Reference needs cross verification based on the link: http://203.189.134.20:90/cgi-bin/koha/opac-detail.pl?biblionumber=21461&shelfbrowse_itemnumber=93441)
60. Shaver T, Peterson G, Ahuja L, Westfall D, Sherrod L, Dunn G. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci Soc Am J. 2002;66(4):1296-303. https://doi.org/10.2136/sssaj2002.1296
61. Sauer T, Clothier B, Daniel T. Surface measurements of the hydraulic properties of a tilled and untilled soil. Soil Tillage Res. 1990;15(4):359-69. https://doi.org/10.1016/0167-1987(90)90109-Q
62. Gathala MK, Ladha J, Saharawat YS, Kumar V, Kumar V, Sharma PK. Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice- wheat rotation. Soil Sci Soc Am J. 2011;75(5):1851-62. https://doi.org/10.2136/sssaj2010.0362
63. Zhang J, Lü F, Shao L, He P. The use of biochar-amended composting to improve the humification and degradation of sewage sludge. Bioresour Technol. 2014;168:252-8. https://doi.org/10.1016/j.biortech.2014.02.080
64. Steward PR, Dougill AJ, Thierfelder C, Pittelkow CM, Stringer LC, Kudzala M, et al. The adaptive capacity of maize-based conservation agriculture systems to climate stress in tropical and subtropical environments: A meta-regression of yields. Agric Ecosyst Environ. 2018;251:194-202. https://doi.org/10.1016/j.agee.2017.09.019
65. Lampurlanés J, Plaza-Bonilla D, Álvaro-Fuentes J, Cantero-Martínez C. Long-term analysis of soil water conservation and crop yield under different tillage systems in Mediterranean rainfed conditions. Field Crops Res. 2016;189:59-67. https://doi.org/10.1016/j.fcr.2016.02.010
66. Pheap S, Lefevre C, Thoumazeau A, Leng V, Boulakia S, Koy R, et al. Multi-functional assessment of soil health under Conservation Agriculture in Cambodia. Soil Tillage Res. 2019;194:104349. https://doi.org/10.1016/j.still.2019.104349
67. Hamblin A. The effect of tillage on soil surface properties and the water balance of a xeralfic alfisol. Soil Tillage Res. 1984;4(6):543-59. https://doi.org/10.1016/0167-1987(84)90004-7
68. Hoogenboom G, Porter C, Shelia V, Boote K, Singh U, White J, et al. Decision support system for agrotechnology transfer (DSSAT) version 4.8 (DSSAT. net). DSSAT Foundation, Gainesville. 2021.
69. Holzworth DP, Huth NI, deVoil PG, Zurcher EJ, Herrmann NI, McLean G, et al. APSIM-evolution towards a new generation of agricultural systems simulation. Environ Model Softw. 2014;62:327-50. https://doi.org/10.1016/j.envsoft.2014.07.009
70. Beaudoin N, Lecharpentier P, Ripoche-Wachter D, Strullu L, Mary B, Léonard J, et al. STICS soil-crop model: conceptual framework, equations and uses: éditions Quae. 2023.
71. Stöckle CO, Donatelli M, Nelson R. CropSyst, a cropping systems simulation model. Eur J Agron. 2003;18(3-4):289-307. https://doi.org/10.1016/S1161-0301(02)00109-0
72. Basso B, Ritchie JT. Simulating crop growth and biogeochemical fluxes in response to land management using the SALUS model: Oxford University Press New York, NY, USA. 2015.