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Unraveling the nexus of organic agriculture and soil health: A review

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Abstract

Organic agriculture is a significant alternative to conventional farming, emphasizing sustainability and soil health. This review explores the intricate relationship between organic agriculture and soil health. Beginning with an introduction to organic agriculture's core principles and objectives, it delves into various practices employed within this system, such as soil and crop management, crop rotation, residue management, and organic manure and biofertilizers. The article examines soil health, encompassing physical, chemical, and biological indicators crucial for evaluating soil quality. It scrutinizes the impact of organic agriculture on soil health across these indicators, highlighting its positive effects on physical structure, chemical composition, and biological diversity. However, challenges and limitations persist, including the availability of organic inputs and managing pests and diseases. Successful organic cropping systems prioritizing soil health are analyzed, underscoring the importance of integrated approaches. In conclusion, the review underscores the pivotal role of organic agriculture in fostering soil health and advocates for further research and adoption of sustainable practices to address existing challenges and promote resilient agricultural systems.

Keywords

challenges; impact; indicators; organic agriculture; practices; soil health; sustainable agriculture

Introduction

Organic agriculture is a sustainable approach that emphasizes enhancing soil fertility by optimally utilizing local resources while avoiding agrochemicals. Genetically modified organisms (GMOs) and various synthetic compounds are commonly employed as food additives. This practice aligns with ecological cycles, intending to decrease the negative environmental impacts of the food production industry, uphold long-term soil sustainability, and minimize reliance on non-renewable resources (1).

Several core objectives underpin sustainable organic agriculture, all promoting environmental health and food security. One primary objective is achieving high crop yields, ensuring that organic farming remains feasible for addressing global food demands while minimizing dependence on harmful synthetic chemicals. A second key goal is harmonizing agriculture with nature by rejuvenating soil through organic inputs such as compost and cover crops, thereby enhancing nutrient cycling that mimics natural ecosystems. Another critical objective is augmenting soil populations of microflora and microfauna, which are essential for maintaining soil fertility, improving nutrient availability, and promoting overall soil health. Additionally, sustainable organic agriculture seeks to enhance soil quality while preserving biodiversity, a crucial factor in boosting ecosystem resilience against pests and diseases. Adopting alternative energy sources is also fundamental to sustainability in organic systems, as it reduces farming operations' carbon footprint. Moreover, balancing crop cultivation with animal husbandry ensures a closed-loop system where animal waste is used as fertilizer, minimizing the need for external inputs. Ensuring that animals are raised in environments closely resembling their natural habitats promotes animal welfare and results in healthier, more productive livestock. Finally, organic farming emphasizes conserving traditional agricultural knowledge, blending time-tested practices with modern innovations to create resilient, sustainable farming systems (2, 3).

Organic farming emerged as a response to the growing environmental and health concerns associated with conventional, chemical-intensive agriculture. Pioneered by figures like Sir Albert Howard in the early 20th century, the movement stressed the importance of soil health and natural nutrient cycling. Following World War II, the widespread adoption of synthetic fertilizers and pesticides raised environmental and public health issues, prompting organic farming to develop as an alternative method. By the 1970s, rising environmental awareness led to the formal establishment of organic certification standards, particularly in the U.S. and Europe. Founded in 1972, the International Federation of Organic Agriculture Movements (IFOAM) aims to offer global leadership and advocate for organic farming practices. Recent developments have focused on increasing market accessibility and improving organic yields through innovative research and sustainable practices (4, 5). These historical milestones highlight the steady progression of organic farming as a sustainable and viable alternative to conventional agriculture. Organic farming is founded on the principle that nature can meet everyone's needs, but not the desires driven by greed (6).

Principles of IFOAM for organic agriculture

Health

The principle of health extends beyond the physical health of crops and livestock to encompass the well-being of the entire ecosystem. Organic farming practices promote soil health through cover crops, crop rotation, and organic fertilizers, which enhance soil organic matter (SOM) and biodiversity. By avoiding synthetic chemicals, organic farming nurtures the microbial communities essential for nutrient cycling, ultimately leading to healthier food systems and communities. Research supports that organic methods can produce higher nutrient content in crops, contributing to human health (2, 7).

Ecology

Organic agriculture aims to work in harmony with natural ecosystems. This is achieved through practices that enhance biodiversity and ecological balance, such as integrating livestock into crop production systems, promoting natural pest control methods, and conserving water resources. By increasing SOM and promoting healthy soil ecosystems, organic practices help maintain the ecological balance, which is vital for sustainable food production (3).

Fairness

The fairness principle emphasizes equitable access to resources and opportunities within the agricultural system. This is practised through community-supported agriculture (CSA) models, fair trade initiatives, and transparent supply chains that ensure farmers receive fair prices for their produce. By prioritizing local food systems and promoting social equity, organic agriculture aims to create inclusive opportunities for all stakeholders involved in the food production process (8).

Care

The principle of care underlines the responsibility of farmers and producers to manage agricultural systems sustainably, considering the health of the environment and future generations. This is reflected in the commitment to sustainable practices, such as reduced reliance on fossil fuels, integrated pest management, and preserving biodiversity. Organic farming encourages stewardship of the land and resources, ensuring that practices today do not compromise the ability of future generations to meet their needs (9) (Fig. 1).

Practices of organic agriculture

Different aspects of organic farming aim to enhance soil structure and effectively manage it to achieve optimal yields. This includes recycling farm waste through composting to generate organic fertilizers, adopting non-chemical and environmentally safe methods for weed management, and utilizing biofertilizers as alternatives to chemical fertilizers (10).

Soil and crop management

Soil fertility depends significantly on soil organic matter, which can be improved through effective agricultural practices (10). Organic farming incorporates strategies like green manuring, crop rotation, and intercropping, each contributing uniquely to soil health and pest management.

Green manuring involves using specific cover crops, such as clover or alfalfa, grown and incorporated into the soil while still green. This practice enhances soil organic matter, improves nutrient availability, and boosts microbial activity. As the green manure decomposes, it releases essential nutrients like nitrogen into the soil, promoting fertility. Additionally, green manuring improves soil structure, enhancing water retention capacity and reducing erosion risk. Its dense growth also suppresses weeds, providing natural weed control (3). Crop rotation, the practice of alternating different crops in a specific sequence across seasons, is vital in breaking pest and disease cycles. Certain pests and pathogens thrive when the same crop is

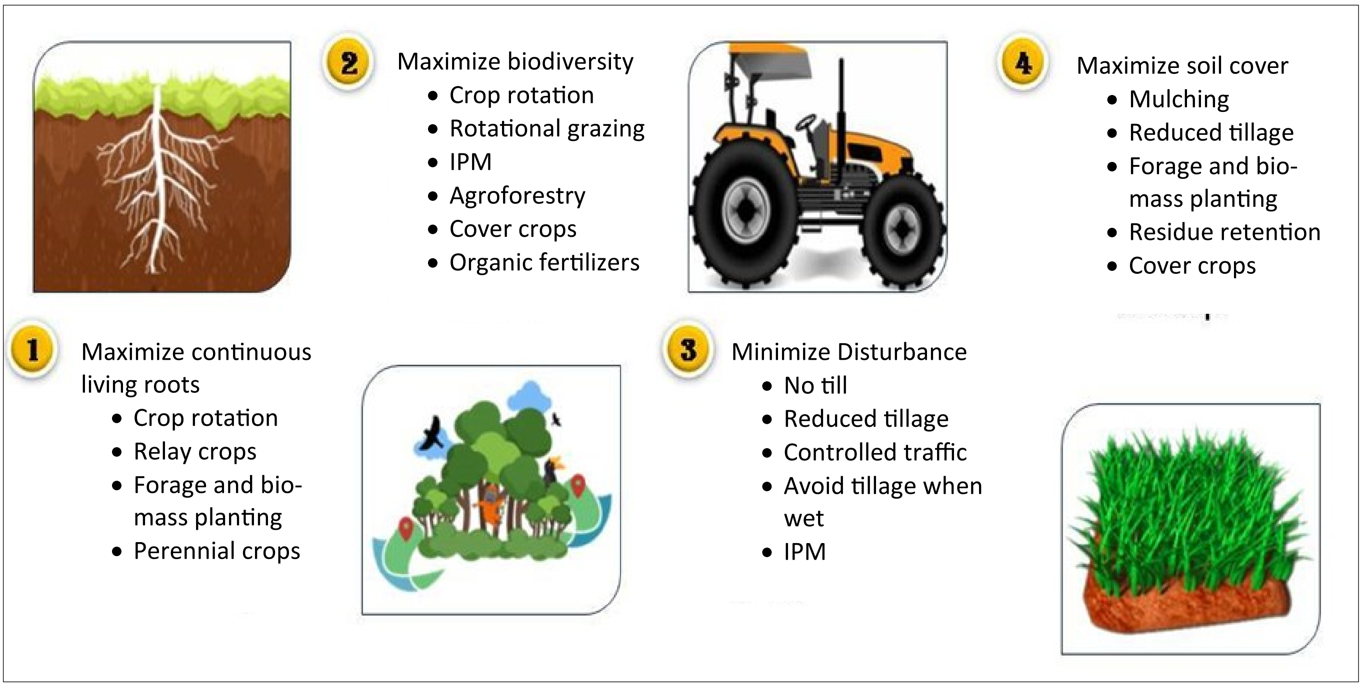

Fig. 1. Principles of organic agriculture.

repeatedly grown, but rotating crops disrupt their life cycles, reducing infestations. Crop rotation also prevents the depletion of specific soil nutrients, as different crops have varying nutrient requirements. For example, leguminous crops in rotation can fix atmospheric nitrogen, enriching the soil for subsequent crops.

This method reduces the need for synthetic fertilizers, contributing to long-term soil health (11). Intercropping, where multiple crops are grown simultaneously in the same field, promotes biodiversity and improves soil fertility. Crops with complementary characteristics can be planted together, with deep-rooted crops loosening the soil and shallow-rooted crops accessing surface nutrients. This system also helps manage pests, as diverse plant species can confuse or repel pests, reducing the likelihood of large-scale infestations. For example, intercropping corn with legumes can enhance nitrogen fixation and provide natural pest control by attracting beneficial insects. The diverse root systems improve soil structure, reduce erosion, and ensure efficient use of available nutrients (12).

Crop rotation and intercropping

Organic farming fundamentally relies on soil biology and soil vitality. Various organic farming techniques, such as crop rotation, mixed cropping, and intercropping, enhance soil life and improve soil properties and biological functions. Crop rotations are assumed to involve switching between crops that enrich the soil and crops grown for profit (13). Rotations may also incorporate rest periods to disrupt weed cycles and work plant matter into the soil. A common organic farming rotation might start with legumes such as alfalfa, clover, or soybeans, which are nitrogen-fixing crops. These legumes enrich the soil by adding nitrogen through symbiosis with nitrogen-fixing bacteria. After the legume phase, a high-nitrogen-demanding crop like corn or broccoli can follow, benefiting from the nitrogen the legumes contribute to the soil. In the next stage, crops with lower nutrient requirements, such as wheat, oats, or barley, might be planted, completing the cycle (13). This approach helps regulate weed growth and facilitates nutrient recycling within the ecosystem (14).

Additionally, intercropping is essential for ecosystem balance in areas with intensive agricultural practices. It involves cultivating different crops with varying requirements within the same field, either by sowing seeds of two different plants concurrently or with a time gap between sowings (10).

Benefits of intercropping

Enhanced biodiversity: By fostering a mix of crops, intercropping enhances plant diversity, creating habitats that attract beneficial insects and microorganisms. This biodiversity supports natural processes like pollination and can aid in pest control by fostering a balanced ecosystem (15).

Pest control: Intercropping disrupts pest life cycles by creating less favorable environments for pests to thrive. Some plant combinations either repel harmful pests or attract their natural predators, reducing reliance on chemical pesticides (15).

Improved soil health

Various crops' different root systems and nutrient needs in an intercropping system lead to better nutrient cycling and soil structure enhancement, improving long-term soil fertility (16).

Resource optimization

Intercropping maximizes using sunlight, water, and soil nutrients, often leading to greater yields per unit area than monoculture farming (17).

Real-life example

A well-known instance is the intercropping of maize with legumes. Legumes fix nitrogen in the soil, improving fertility for subsequent crops, while maize offers structural support to climbing legume plants. This system boosts yields, improves soil health, and helps manage weeds naturally.

By integrating intercropping into farming systems, agriculture can become more sustainable, with increased productivity and improved environmental outcomes (13).

Figure 2 illustrates a crop rotation scheme and an intercropping layout. The crop rotation sequence shows the systematic planting of different crops, including nitrogen-fixing legumes, corn, and wheat, to enhance soil health, control pests, and optimize nutrient use. The intercropping layout displays alternating rows of maize and beans, demonstrating how different crops are strategically positioned to maximize resource efficiency and promote ecosystem balance.

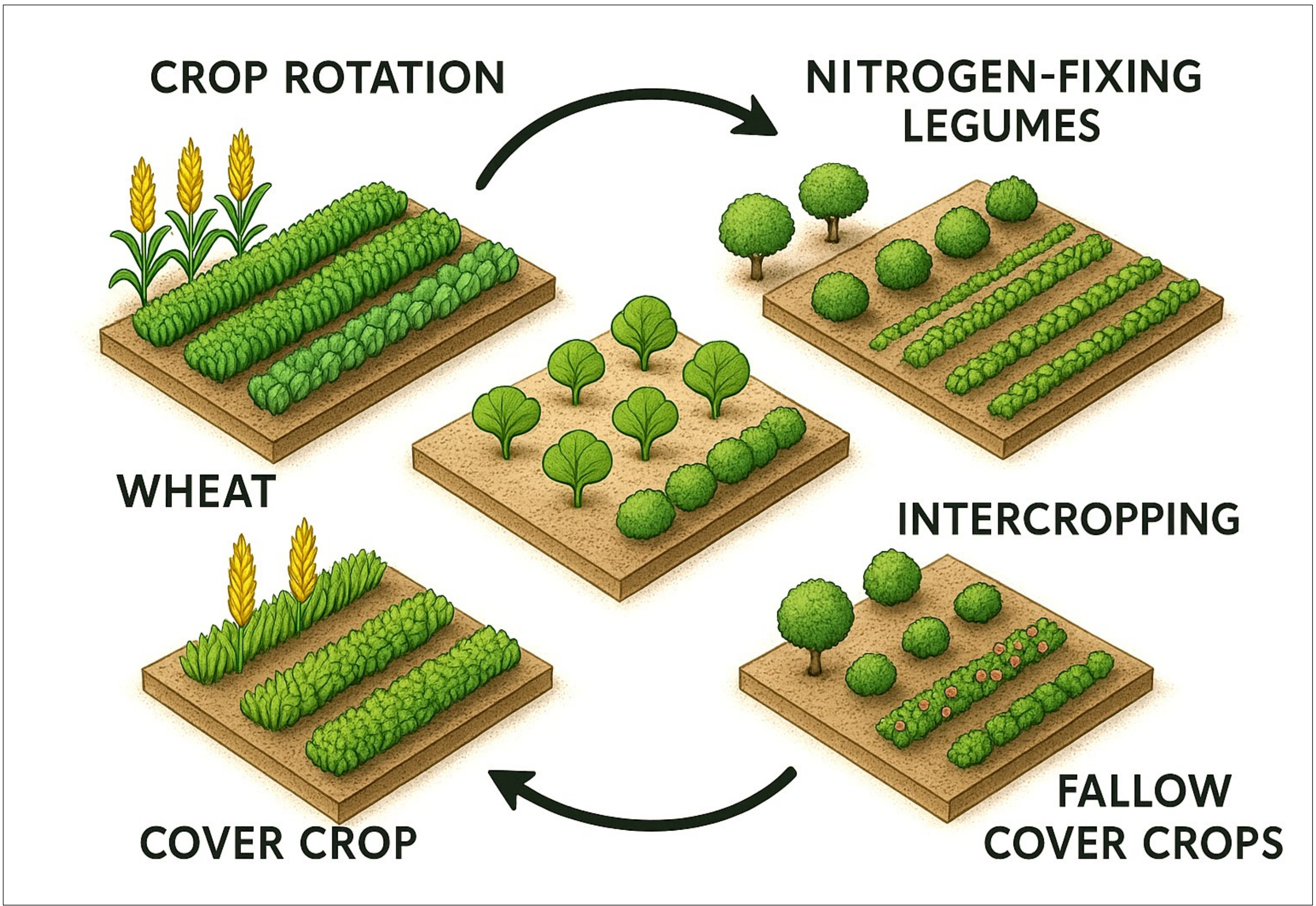

Fig. 2. Illustration depicting a crop rotation scheme and intercropping layout, highlighting the benefits of diverse planting strategies for improving soil health, optimizing resource use, and enhancing pest management.

Crop residue management

In countries like India, vast amounts of crop residues remain unused each year, serving as valuable resources for soil nutrient replenishment. Crop residues encompass a variety of materials such as straws, stalks, bristles, maize cobs, and bean and pea haulms. Additionally, agricultural products like oil cakes, rice husks, peanut shells, and millet remnants are utilized for soil enhancement (10).

Organic manure addition

Organic fertilizers or manures are vital in maintaining soil sustainability and health. They enhance soil quality while preserving the integrity of the ecosystem. Various biological sources, including plant and animal residues, can be utilized for composting to produce organic manure. This organic manure boosts soil biological activity, thereby increasing the availability of inorganic nutrients and promoting humus formation for improved crop yields. The National organic program (NOP) has set out guidelines for the appropriate use of organic fertilizers in conventional agricultural practices. Organic manure is commonly classified into bulky and concentrated forms (18).

Bulky organic fertilizers, called farmyard manures, mainly consist of well-decomposed animal waste such as dung, urine, and other farm residues. This category also includes compost and green manures, crops explicitly grown to improve soil health. Compost, resembling humus, is formed through microbial activity in oxygen-deprived conditions and can come from farm or household refuse. Green manures enhance soil fertility by providing surplus inorganic nutrients and organic matter, promoting microbial growth, and preventing soil erosion, nutrient leaching, and weed growth. These plants, integral to sustainable annual cropping systems, are grown solely to benefit the soil and are not grazed or harvested.

Legumes serve a vital function as green manures by fixing atmospheric nitrogen through symbiotic relationships with nitrogen-fixing bacteria, such as species of rhizobium interactions (19). *Rhizobium*, located in their root nodules. This natural process enhances the soil's nitrogen content, making it more fertile for future crops. Leguminous green manures like dhaincha, cowpea, senji, cluster bean, sun hemp, berseem clover and jantar contribute organic matter and significantly boost soil fertility by increasing nitrogen levels and stimulating microbial activity. In contrast, non-legume plants cannot fix nitrogen, yet they provide unique benefits as green manures. These plants help mitigate nutrient leaching, improve soil structure, and augment soil biomass, contributing to higher crop yields. Examples of such non-legume green manures include jatropha, neem, *Hibiscus viscosa*, and *Vitex negundo* (20, 21).

When comparing nutrient content, bulky organic manures—such as farmyard manure and compost—are abundant in organic matter but usually contain lower concentrations of readily available nutrients. They primarily function as soil conditioners, gradually releasing nutrients and enhancing soil structure. Conversely, concentrated organic manures like blood meal, bone meal, fish fertilizer, horn fertilizer, and hoof meal are characterized by higher nutrient levels, especially nitrogen (N), phosphorus (P), and potassium (K), providing immediate nourishment for plants. This difference illustrates that while bulky manures are ideal for promoting long-term soil health and a steady nutrient supply, concentrated manures are typically utilized to address specific nutrient deficiencies in crops (22).

On-farm waste recycling

On-farm waste recycling is pivotal in promoting sustainable agriculture by diminishing the need for costly and environmentally detrimental chemical fertilizers. Both agricultural and household wastes, such as pruned branches, straw, and discarded fruits and vegetable parts, undergo diverse recycling procedures like composting, anaerobic digestion, and various thermo-chemical treatments (such as catalytic, pyrolytic, and hydrothermal methods) to enhance recycling efficacy. Consequently, there is a reduced reliance on traditional chemical fertilizers and other energy resources. Furthermore, industrial, household, and municipal waste are significant constituents of organic waste management (18).

Biological control of weeds

In environmentally-friendly farming practices, organic farming avoids the reliance on herbicides and chemical treatments for weed control. Instead, it embraces alternative and eco-friendly weed management practices. These methods encompass cultural approaches such as crop alternation, careful selection of crops and cultivars, enhancing crop density through higher seeding rates, and adjusting row spacing to achieve earlier canopy closure (23). Mechanical and physical weed control techniques include tillage, harnessing solar radiation for soil heating, intercropping, implementing stale seedbed techniques, applying mulching, and conducting hand weeding. Additionally, biological weed control methods and the incorporation of biological herbicides are utilized.

For example, using Achenes from *Solanum* species has effectively suppressed *Amaranthus* sp.'s growth in organic vegetable production systems. This practice not only reduces weed competition but also enhances soil biodiversity. Another successful case study involves using *Bacillus thuringiensis* as a biological herbicide, demonstrating effectiveness in controlling specific weed species in organic crops. Moreover, the introduction of beneficial insects, such as the larval stage of the *Cecidomyiidae* family, has been documented to provide natural weed control by targeting certain weed species, further illustrating the effectiveness of biological methods in managing weeds sustainably (8, 24). These examples highlight biological control practices' practical application and effectiveness in organic farming, demonstrating their potential to enhance crop yield and ecological health.

Use of biofertilizers

Excessive reliance on chemical fertilizers degrades soil quality and risks human health through prolonged exposure. Continuous chemical usage disturbs the equilibrium of soil microorganisms, negatively impacting both flora and fauna. Therefore, adopting alternative approaches becomes imperative for the ecosystem's well-being (25). Organic fertilizers, such as biofertilizers, are crucial in promoting sustainable agriculture.

Organic fertilizers are derived from natural sources, contributing to improved soil structure and fertility over time. In contrast, conventional fertilizers, while offering immediate nutrient availability, often lead to soil degradation and environmental issues, such as water pollution and loss of biodiversity. Organic fertilizers enhance soil microbial activity, improving nutrient cycling and increasing crop resilience (26). Table 1 compares organic and conventional fertilizers, highlighting their advantages and disadvantages. Table 2 shows various biofertilizers, the crops

Table 1. The outline of organic and conventional fertilizers

Aspect	Organic fertilizers	Conventional fertilizers
Source	Natural materials (plant, animal, mineral)	Synthetic chemicals
Nutrient release	Slow-release, improves soil health	Fast-release, immediate nutrient availability
Soil impact	Enhances soil structure and microbial activity	It can lead to soil degradation
Environmental effects	Lower risk of water pollution	Higher risk of water and soil contamination
Long-term sustainability	Supports sustainable practices	It may lead to dependency on chemical inputs

Table 2. Various biofertilizers, the crops they benefit, their growth enhancement effects

Biofertilizer	Crop	Growth enhancement effect
Rhizobium spp.	Legumes (e.g., peas, beans)	Nitrogen fixation, improved protein content
Mycorrhizal fungi	Various crops (e.g., corn, wheat)	Enhanced P uptake, improved drought resistance
Azospirillum spp.	Cereals (e.g., rice, wheat)	Increased nitrogen availability, improved root development
Bacillus subtilis	Vegetables (e.g., tomatoes, peppers)	Disease suppression, improved nutrient uptake
Pseudomonas fluorescens	Fruits (e.g., apples, strawberries)	Enhanced plant growth, increased resistance to root pathogens

they benefit, and their growth enhancement effects. Microorganisms significantly impact crop yields by bolstering the availability of micronutrients in the soil and consequently improving soil productivity. Beneficial strains of microbes, including bacteria, fungi, and microalgae, are harnessed as biofertilizers to achieve these goals.

Vermicompost for nutrient management

Vermicompost is produced through vermicomposting, involving specific earthworm species supplied organic waste materials. After digestion, earthworms produce granular cocoons, termed vermicompost. Vermicomposting necessitates moderate environmental conditions conducive to the activity of microorganisms and earthworms. Vermicompost is abundant in micronutrients, macronutrients, phytohormones, and beneficial microflora crucial for plant growth (25).

Pest and disease management using biopesticides

Certified organic growers face more limited choices for plant protection substances than conventional growers. Consequently, they must rely on natural processes and effective ecosystem management to control harmful organisms. Organic farms generally exhibit a greater diversity of arthropod fauna than conventional farms. For instance, an average of around 40 arthropod species was observed in conventional tomato fields. In comparison, organic tomato fields showed an average of approximately 66 species based on five 30-second suction samples per farm. Additionally, organic farms exhibited increased numbers of natural predators and parasitoids.

Moreover, the biodiversity of arthropods, quantified by species richness, is generally one-third higher on organic farms than on conventional farms. Organic farmers often utilize biopesticides, which inhibit the proliferation of nematodes, fungi, insects, and various pests, ultimately leading to their decline. Examples of biopesticides include pyrethrins, nicotine, azadirachtin, margosa, and rotenone (27). These natural alternatives offer effective pest control while aligning with organic farming principles, contributing to the ecosystem's health.

Concepts of soil health

The concept of soil health has arisen as a framework for connecting soil management practices to agronomic productivity and ecosystem functionality (28). In defining the concept of health for soil, soil is considered as a dynamic and living system (29). They have suggested assessing soil health by examining specific fundamental indicators of system functions, drawing parallels to determining human health.

Soil health is defined as the ability of soil to operate as a dynamic living system within the confines of ecosystem and land use limits, supporting the production of plants and animals, improving water and air quality, and fostering the health of plants and animals (30).

Soil health indicators

Optimal indicators should exhibit a robust link with ecosystem activities in the soil. It should also demonstrate a strong association with the functioning of the environment. Furthermore, it must be generally user-friendly and accessible to a diverse array of users, including both specialists and manufacturers. The soil should also adapt to alterations in management methodologies and climatic conditions (31).

Soil health is assessed using a variety of markers, including biological, physical, and chemical aspects. These indicators give important information about the health of the soil system and may be used to monitor and enhance soil quality. Some of the main markers of soil health are:

Physical indicators

Physical soil health indicators typically involve straightforward, rapid, and cost-effective techniques. These indicators, such as texture, bulk density, porosity, and aggregate stability, are associated with hydrological processes such as erosion, aeration, runoff, infiltration rate, and water retention capacity (32). Typically, soil is deemed physically deficient if it exhibits minimal water infiltration, increased surface runoff, inadequate cohesion, limited aeration, root density, and challenges for mechanization (33). Soil texture plays a crucial role in regulating the equilibrium between water and gases and remains relatively constant over time, regardless of soil management practices. Consequently, bulk density and total porosity are more effective indicators for assessing the effects of soil utilization and management on water and air dynamics (34).

Chemical indicators

The chemical characteristics of soil health are linked to its ability to supply nutrients for plants and retain chemical substances or compounds that could be detrimental to the ecosystem and vegetation growth. Soil pH, cation exchange capacity (CEC), organic matter content, and nutrient levels are the primary chemical attributes evaluated in soil health assessments, particularly concerning the soil's capacity to sustain high-yield crops (35). Soil pH is a crucial indicator due to its direct correlation with nutrient availability and solubility while influencing microbial activity. Consequently, evaluating soil pH enables the anticipation of nutrient availability potential within a specific production system (36). Soil organic carbon (SOC) is a fundamental characteristic in assessing soil health, typically showing a direct relationship with crop yield (37). Soil organic carbon influences critical functional processes within soil, such as nutrient storage, particularly nitrogen (N), water retention capability, and the stability of aggregates (38).

Biological indicators

Biological monitoring involves assessing how living organisms respond to changes in their surroundings through measurement (39). Unlike instrumental monitoring, biological indicators offer insight that encompasses a range of environmental factors. A bioindicator refers to an organism, a part of an organism, or a collection of organisms that is used to collect information regarding the state of the environment (40). Various biological indicators have been suggested, each with its benefits and limitations. Table 3 below outlines these biological indicators, detailing their respective advantages, constraints along with relevant references.

Table 3. The outlines of biological indicators detailing their respective advantages, constraints and relevant references

Biological Indicator	Advantages	Limitations	References
Microbial biomass	Indicates the overall health of the soil. Reflects soil organic matter content and nutrient cycling	Sensitive to environmental changes (moisture, temperature)	(30)
Basal and substrate-Induced respiration	Provides insight into microbial activity and metabolic potential. Useful for assessing the availability of organic substrates	Influenced by external factors (moisture, temperature), affecting consistency	(30)
Mineralizable nitrogen	Indicates the potential for plants to have nitrogen availability. Useful for assessing soil fertility	Measurement can be time-consuming and requires specific laboratory techniques; it can vary seasonally	(41)
Enzyme activity	Reflects microbial activity and nutrient cycling processes. Different enzymes can indicate specific nutrient dynamics (e.g., phosphatases for P)	Environmental conditions can influence activity; it may not directly correlate with microbial biomass	(41)
Abundance of microflora	Provides insight into the diversity and health of microbial communities. Important for nutrient cycling and disease suppression	Complex to measure; molecular identification techniques required	(30)
Abundance of soil fauna	Indicates soil structure and aeration; contributes to organic matter breakdown	Variable abundance, labor-intensive identification	(41)
Root diseases	Assesses plant health and yield impact. Identifies the presence of soil pathogens	Focuses only on negative factors like pathogens; extensive testing needed	(30)
Soil biodiversity	Indicates the resilience of soil ecosystems and their ability to respond to changes. Essential for maintaining ecosystem services	Complex to quantify, high biodiversity does not always equate to positive effects on soil health	(41)

Impact of organic agriculture on soil health

Soil health is a key element in organic agriculture, with a particular emphasis on increasing and sustaining SOC (soil organic carbon) levels, which substantially impact soil health and function. Effective management of SOC stocks is critical from agronomic and ecological perspectives to enhance crop production within organic farming systems (42). Adding manure or compost to organic farming practices serves a dual purpose: it prevents excessive release of soluble nutrients like N and P while also providing a crucial C source for the development and function of soil organisms. Moreover, using organic N fertilizers substantially enhances the likelihood of nitrification, nitrite oxidation, and denitrification processes (43). Organic fertilizers boost the enzymatic activities of microorganisms engaged in the mineralization processes of C, N, and P (44). Organic agriculture promotes soil sustainability by enhancing soil biophysical and biochemical activities. However, due to variations in on-farm management efficiency, careful attention is necessary regarding soil health issues in organic farming. Nevertheless, when implemented according to standard practices, organic agriculture represents a potent and eco-friendly system for agricultural production (45) (Fig. 3).

Utilizing organic soil amendments has been linked to favorable soil characteristics, such as increased plant-available water retention, CEC and reduced bulk density. Moreover, it can promote the proliferation of beneficial microorganisms (46). Various organic fertilizers significantly impact soil health, exerting indirect effects, such as alterations in physicochemical properties and immediate impacts on soil microbial communities (47). Organic matter is crucial in sustaining well-balanced soil biological communities, primarily responsible for preserving soil structure, enhancing water infiltration, and developing the soil's capacity to store and release water and nutrients essential for crop growth. Different organic amendments can affect soil's physical, chemical, and biological properties. Therefore, decisions should be made based on identified limitations and goals for managing soil health. Soil comprises its physical components and the dynamic interactions among its diverse physical, biological, and chemical elements (47).

The health of the soil is enhanced by organic agricultural methods, which additionally lead to increased soil fertility and quality. According to research, organic farming improves soil structure, porosity, and moisture retention and increases soil microbial variety and SOC concentration. Higher amounts of SOC, N, P, and K demonstrate how much organic farming promotes soil fertility. Additionally, by eliminating poisonous compounds and hazardous residues, organic farming practices support the soil-plant system's natural equilibrium and generate nutritious food. Additionally, by generating humus-rich topsoil, reviving above- and below-ground diversity, holding onto water, and aiding in the formation of solutions for water pollution, organic farming helps counteract the detrimental effects of industrial agriculture, such as desertification, erosion of soil, decline in biodiversity, and water pollution. Organic agricultural methods are essential for improving soil health, encouraging sustainable agriculture, and lessening conventional farming systems' damaging effects on the ecosystem and public health (48).

Soil physical health

Optimal soil physical health is critical for sustainable agricultural production and effective natural resource management (49). Understanding soil physical processes and their interactions with roots can lead to innovative methods that enhance crop access to water and nutrients. Meanwhile, empirical data indicates that bulk density declines as organic matter content increases (50).

Organic matter is essential in enhancing soil physical health by affecting various soil properties, though the mechanisms are intricate. It helps form soil aggregates,

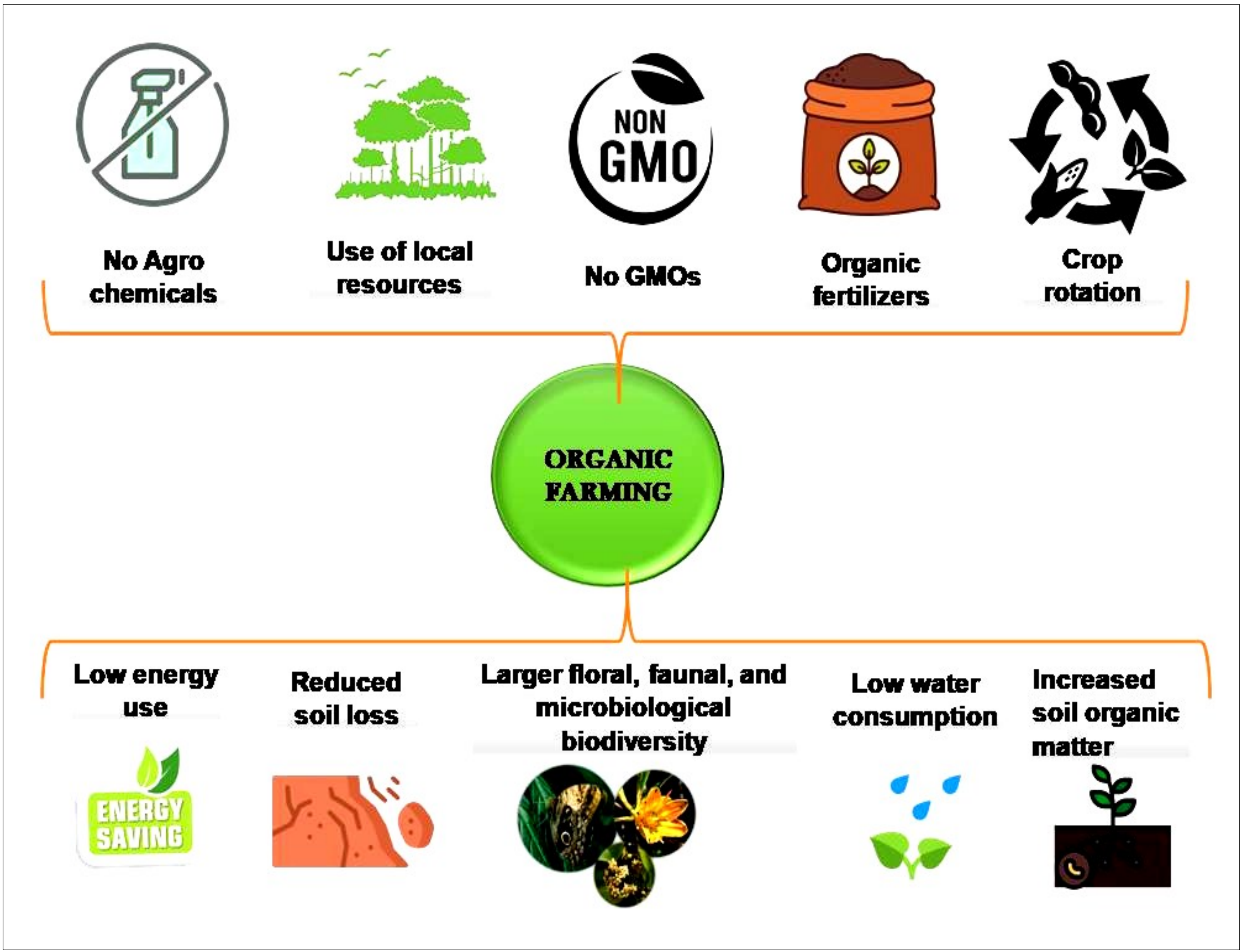

Fig. 3. Components and impact of organic farming.

improving soil structure, porosity, and water infiltration. By acting as a binder, organic matter facilitates the formation of stable aggregates, which reduces bulk density and increases pore spaces. This allows for better root growth aeration and enhances water retention and drainage.

Moreover, organic matter contributes to the soil's ability to hold water and manage moisture distribution. As organic materials decompose, they release humic substances that interact with soil particles, boosting moisture retention while maintaining proper aeration. However, these processes are dynamic and vary based on factors like soil type, climate, and organic matter quality. While the benefits of organic matter are well-documented, a deeper understanding of how different types of organic C interact with soil particles at the molecular level and how they contribute to long-term soil structure stability is still evolving. This complexity creates gaps in fully grasping the detailed biochemical and physical interactions involved (51).

The soil's physical condition, encompassing factors like compaction, water storage capacity, and drainage efficiency, significantly influences soil and plant well-being. Optimal soil structure facilitates rainfall infiltration, minimizing runoff and enabling moisture retention for future plant utilization. Additionally, it supports healthy root growth. Soils possessing favorable physical structure maintain adequate aeration even in wet periods, and unlike compacted soils, they exhibit reduced prone to forming obstacles to root growth during dry conditions. Aeration in soil is enhanced by organic matter, which facilitates the bonding of soil particles.

Additionally, the presence of mycorrhizal fungi, thriving in organic matter, contributes to improving a soil's physical properties. Organic matter and biological characteristics influence soil's physical structure, which in turn affects hydrological phenomena such as erosion, drainage, runoff, and infiltration rates (47). Implement measures to improve soil physical properties and foster healthier soil conditions shown in Table 4.

Soil chemical health

Soil health assessment, particularly for supporting high-yield crops, often relies on key chemical attributes such as soil pH, CEC, organic matter content, and nutrient levels (35). The primary chemical parameters for assessment included soil pH, available P, K, copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn). Soil pH is particularly significant as it directly influences nutrient availability, solubility, and microbial activity (52). Soil organic carbon (SOC) is crucial in evaluating soil health, typically showing a direct relationship with crop yield (37). Implement strategies to optimize soil chemical characteristics for improved soil health, as demonstrated in (47) (Table 5).

Table 4. Soil physical properties and foster healthier soil conditions

Parameters	Short term management	Long term management
Available water capacity	Incorporation of enduring organic substances; Incorporation of biochar or compost amendments.	Minimize soil disturbance; Alternating with perennial cover crops; Integrate dense biomass cover crops.
Surface hardness	Utilize mechanical soil aerators (such as strip-till implements, broad forks, spaders); Cultivate shallow-rooted cover crops; Implement living mulch or interplant cover crop strategies.	Surface-rooted cover/rotation crops; Refrain from traversing on saturated soils; Minimize excessive load-bearing tillage; Employ controlled traffic flow arrangements.
Sub-surface hardness	Implement focused deep tillage techniques (such as subsoil chisel plough and spader); Cultivate deep-rooted cover crops.	Refrain from using disc plows that create compacted layers; Minimize heavy loads; Decrease traffic on wet soil surfaces.
Soil structure cohesion	Integrate newly sourced organic materials; Cultivate surface-rooted cover crops; Apply green fertilizers and organic wastes.	Minimize soil disturbance; Employ surface mulching techniques; Rotate with perennial grass crops.
Organic material	Incorporation of long-lasting organic substances; Incorporation of biochar or compost supplements.	Minimize soil disturbance; Rotate with perennial grass crops; Integrate cover crops with abundant biomass.

Table 5. Soil chemical characteristics for improved soil health

Parameter	Short term management	Long term management
Low soil pH	Apply lime according to soil analysis results; Introduce gypsum alongside lime for elevated aluminium levels; Reduce the application of ammonium or urea fertilizers.	Conduct annual soil testing and apply maintenance lime according to soil test recommendations to maintain optimal pH levels; Enhance organic matter content to enhance buffering capacity.
High soil pH	Incorporate elemental S or gypsum based on the findings of the soil test analysis.	Conduct soil testing on an annual basis; Use larger percentage of ammonium or urea fertilizers.
Limited available P	Apply P supplements according to the soil test guidelines; Cultivate cover crops to facilitate the recycling of bound P; Adjust pH levels to 6.2-6.5 to release bound P.	Encourage mycorrhizal colonization; Maintain pH levels between 6.2 and 6.5; Cultivate cover crops to recycle bound P.
Elevated soluble P	Discontinue the application of manure and compost; Opt for low or zero-P fertilizer blends; Apply only 20 pounds per acre of P starter if needed; Apply P at or below the rate of crop removal.	Utilize cover crops that tend to gather P and transport it to fields with low P levels.
Reduced available K	Incorporate wood ash, fertilizer, manure, or compost according to soil testing recommendations; Employ cover crops to recycle bound K; Select fertilizers with a high K content.	Conduct annual soil testing and apply maintenance K as per the soil test recommendations to ensure a continuous supply of K.
Scant trace elements	Incorporate chelated micronutrients according to soil testing recommendations; Maintain pH levels below 6.3 for most crops.	Enhance mycorrhizal colonization; Enhance organic material content; Reduce soil P levels.
Elevated trace elements	Adjust soil pH to 6.5-6.7; Avoid fertilizers containing micronutrients.	Sustain pH within the range of 5.5 to 2.6; Monitor irrigation practices or enhance soil drainage; Enhance calcium levels in the soil.

Soil biological health

Soil microorganisms play a crucial role in converting C, N, P, sulfur (S), and iron (Fe). Biological properties of soil, such as microbial biomass carbon (MBC), microbial biomass N (MBN), microbial biomass phosphorus (MBP), and the activity of soil enzymes including amylase (AMY), dehydrogenase (DHA), cellulase (CA), pectinase (PA), phenoloxidase (POA), urease (UA), and phosphatase (PHA), respond rapidly to changes in soil quality and are considered superior indicators compared to soil physical and chemical properties. Soil enzymes play a significant role in energy transfer through the decomposition of SOM and nutrient cycling, thus playing a critical role in maintaining soil health. Enzymes serve as essential catalysts in the activities of soil microorganisms, and their by-products contribute to stabilizing soil structure (52).

The soil organisms present in soil are divided into two main categories: (i) soil flora, belonging to the plant kingdom, and (ii) soil fauna, representing animal forms (53). These categories are further classified into macro- and microorganisms based on their size. While macroorganisms are fewer in number compared to microorganisms, they play crucial roles in soil functions. Soil microflora, which consists of heterotrophic and autotrophic bacteria, fungi, actinomycetes, algae, and associations like mycorrhizae, is essential for nutrient cycling and soil health. These microbes facilitate the breakdown of organic matter, releasing vital nutrients for plants, thus supporting plant growth and productivity.

Additionally, soil microfauna, comprising protozoa and nematodes, can reduce or increase microbial populations, thereby accelerating microbial biomass turnover. This turnover enhances nutrient availability and promotes soil structure, facilitating better aeration and drainage. Moreover, these organisms promote better soil aeration, drainage, and mixing of substantial amounts of surface soil. Soil enzyme activities are valuable indicators of biological soil quality due to their operational practicality, high sensitivity, integrative nature, ease of measurement, and greater responsiveness to soil tillage and structure than other soil variables (54).

Decomposition rates are associated with enzymes that directly target the primary structural components of plant material, providing valuable insights into specific aspects of microbial community dynamics and succession(55). Many studies have shown that soil phosphatase activity increases with the application of organic materials and the presence of mycorrhizal species (56). Additionally, the increase in urease activity resulting from organic fertilization highlights the close relationship between this enzyme and SOM and N circulation (54). Overall, organically managed soils maintain greater biodiversity and exhibit lower occurrences of soil-borne diseases than conventional farming practices. The prevalence of mycorrhizal fungi is also consistently higher in organically managed soils, a phenomenon noted for some time.

Challenges and limitations of organic agriculture on soil health

Despite the numerous advantages of organic agriculture for soil health, there are several challenges and limitations associated with its practices. Organic farming often requires more land to produce equivalent crop yields compared to conventional methods due to initially lower outputs (57). This land necessity stems from the absence of synthetic fertilizers and pesticides, which leads to reduced yields early on, though yields generally improve as soil health improves over time. Organic farming is also heavily dependent on weather patterns, making it difficult to predict annual harvests and leading to variable income streams for farmers. Additionally, organic methods are labor-intensive, relying on manual weeding, crop rotations, and natural pest management, which can increase production costs. Prohibiting chemical pesticides makes crops more susceptible to pests and diseases, posing the risk of crop failures and financial setbacks. Furthermore, organic products are often priced higher, limiting consumer access and reducing demand, especially during economic instability. These factors present significant hurdles that organic farmers must navigate while managing soil health and sustainability (58).

Successful organic cropping systems prioritizing soil health

Recent meta-analyses covering a global scope indicate that organic crop yields typically range from 66% to 95% (59), with an average of 80% (60) or 81% (61). Based on research, encompassing 34 studies from Sweden, Finland, and Norway, organic yields in this geographical region were determined to be approximately 70% of conventional yields (60). Organic farmers employ diverse crop rotation and integrate livestock to maximize nutrient use and optimize inter-species spacing. Soil organic matter management is a cornerstone of soil fertility enhancement in organic systems, focusing on using biologically derived nutrients (BDN) rather than readily soluble forms. Nutrients from bulky organic materials, which are less readily available, are used, requiring the release of nutrients to plants through soil microbes and animals' actions. Enhanced soil biological activity also plays a significant role in weed, pest, and disease suppression (62).

A key feature of successful organic systems is managing soil organic matter using BDN rather than readily soluble chemical fertilizers. Organic materials, such as compost and green manures, are applied to fields to provide slow-release nutrients. These bulky organic inputs depend on soil microbes and organisms like earthworms to break them down, gradually releasing nutrients. This process enhances soil fertility and increases soil biological activity, crucial in naturally suppressing weeds, pests, and diseases. For example, covering crops like vetch or rye helps suppress weeds while adding organic matter to the soil, leading to a healthier and more productive farming system. Although these methods make organic farming systems both sustainable and productive, they often require more labor and careful planning to achieve yields comparable to conventional systems (59, 61).

Call to action

We must advocate for innovative solutions and policies that promote sustainable organic farming practices, ensuring that they are supported by research and practical implementation. Stakeholders, including farmers, researchers, policymakers, and consumers, should collaborate to develop and share best practices that address the specific challenges faced by organic agriculture. Additionally, educating consumers about the benefits of organic farming can increase market demand for organic products, creating a more sustainable food system. By fostering a greater understanding of the importance of organic practices for soil health, we can encourage more individuals to choose organic options, ultimately driving agricultural sustainability and protecting our environment for future generations.

Conclusion and Future Perspective

Organic farming principles, rooted in ecological balance and resource conservation, present promising pathways to improve soil health and fertility. By employing holistic approaches such as soil conservation and biodiversity enhancement, organic farmers prioritize sustainable methods that significantly enhance soil health. The interconnection between organic agriculture and soil health is essential for promoting sustainable farming practices. While nutrient management and pest control challenges persist, successful organic farming systems prioritize soil health through crop rotation and cover cropping. Recognizing the synergies between organic farming and soil health objectives, collaborative efforts among stakeholders are crucial to fostering resilient agricultural systems and achieving global food security goals.

In conclusion, the nexus between organic agriculture and soil health presents a critical area for inquiry and action in sustainable agriculture, offering opportunities to mitigate environmental impacts and promote long-term agricultural sustainability. Continued research is essential to deepen our understanding of these relationships, develop innovative solutions to nutrient management and pest control challenges, and implement supportive laws and strategies for sustainable organic agricultural systems. Furthermore, promoting stakeholder engagement can maximize the synergies between organic agriculture and soil health. Educating consumers and increasing market demand for organic products is key to driving agricultural sustainability.

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Authors' contributions

CL framed the research idea and wrote the manuscript. Conceptualization, editing, and manuscript revision were done by SS. KGS, RA, PP, PS[1], JP and PS[2] reviewed and helped in editing the article. All authors read and approved the final manuscript. (PS[1] stands for P Sujatha and PS[2] stands for P Saravanapandian)

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While preparing this work, the author used ChatGPT, QuillBot, and Perplexity AI to improve the manuscript's language, readability, and clarity. After utilizing these tools, the author thoroughly reviewed and edited the content as needed and took full responsibility for the final publication.

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