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SOIL ORGANIC MATTER AND NUTRIENT CYCLING IN AGRICULTURE: MECHANISMS AND MANAGEMENT

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Abstract
Soil organic matter (SOM) plays a vital role in maintaining soil fertility and supporting nutrient cycling essential for plant growth. Through processes like mineralization, immobilization, complexation, and sorption, SOM regulates the availability and retention of key nutrients such as nitrogen, phosphorus, sulfur, and potassium. It also enhances cation exchange capacity, buffers pH, and improves soil structure and moisture retention. This review explores the composition, classification, and nutrient interactions of SOM, along with the microbiological and physicochemical mechanisms driving SOM-mediated nutrient cycling. It also examines how agricultural practices—such as crop rotation, residue management, and organic amendments—affect SOM dynamics. While conventional practices can deplete SOM and disrupt nutrient cycles, conservation strategies like integrated nutrient management, biochar application, and precision farming can sustain SOM and improve nutrient-use efficiency. Overall, SOM-centered management is key to enhancing soil fertility, promoting agroecosystem resilience, and advancing sustainable agriculture.

INTRODUCTION

Soil health is fundamental to sustainable agriculture, and soil organic matter (SOM) forms the basis of its functionality. SOM is a complex mixture of partly decomposed plant and animal residues, microbial biomass, humified organic substances, and fine mineral matter that influences the chemical, biological, and physical properties of soil systems. Among these, one of the most important functions is the capacity to regulate nutrient cycling processes that govern soil fertility and crop productivity (Medina-Méndez et al., 2019). Cycling of nutrients, especially N, P, S, and K, is controlled not only by soil texture and pH, but also by the quantity, quality, and stability of organic matter (Hatfield et al., 2018). In agroecosystems with high nutrient requirements and dependencies on external inputs, the role of SOM as a buffer, mediator of change (in particular, organic matter), and storehouse for nutrients increases (Al-Wazzan & Muhammad, 2022).

The relationship between SOM and nutrient cycles is regulated through a complex chain of microbial/biochemical reactions such as mineralization, immobilization, and humification (Alekseev & Abakumov, 2020). These processes transform organic nutrients into inorganic forms that are accessible to plants and immobilize others within the soil structure (Luo et al., 2020). Rich SOM also increases soil cation exchange capacity (CEC), pH buffering, and water retention potential resulting in indirect influence on nutrient retention mitigating loss through leaching or via volatilization. Furthermore, SOM can also interact with clay particles and metal oxides to create organo-mineral complexes that help in the long-term storage of nutrients and in maintaining the soil structure. This complex system of processes emphasizes the multifunctional nature of SOM and its major role in keeping nutrient cycles dynamic under agricultural conditions (Maritasari et al., 2022).

However, modern intensive agricultural practices frequently result in the decline of SOM due to excessive tillage, monoculture cropping, and over-dependence on inorganic fertilizers (Nedewi, 2022). These management approaches result in a faster breakdown of organic matter, less fresh inputs that are high in organics, and thus reduce soil fertility while interrupting the natural recycling process (Bunkin et al., 2020). In contrast, conservation-based approaches, such as soil OM additions, cover cropping, and reduced tillage, can be used to rebuild SOM levels combined with more sustainable nutrient management practices. Proper cropping practices are important for both general productivity as well as for reducing greenhouse gas emissions, increasing carbon sequestration, and resilience to climate-induced stressors like droughts or erosion (Zhang et al., 2023).

Given that enhancing soil fertility and nutrient-use efficiency is increasingly important due to the increasing demand for food worldwide, as well as environmental problems associated with agriculture-related activities, a deeper comprehension of the role SOM plays in affecting nutrient cycling is essential (Billah & Ullah, 2008). This review synthesizes the available scientific information on the composition, dynamics, and functional importance of SOM for nutrient availability in agricultural systems. It considers how SOM interacts with important nutrients and the mediating mechanisms, as well as the factors that influence SOM stabilization and nutrient cycling efficiencies under different agricultural schedules (Akhtar et al., 2018). This review attempts to bridge recent research and developing management guidelines into a concept that encourages SOM optimized for sustainable agriculture in the long run (Salihu & Iyya, 2022).

1. Composition, Formation, and Classification of Soil Organic Matter (SOM)

Soil organic matter (SOM) is a key constituent of terrestrial ecosystems and provides soil health, fertility, and nutrient cycling as shown in Figure 1. It is a complex mixture of organic compounds in different stages of decomposition mainly derived from plant materials, root exudates, microbial mass, and fauna activity (Lu et al., 2023). SOM is generally divided into three fractions: (i) particulate organic matter (POM), which contains discernable plant and animal residues; (II) humic substances, consisting of fulvic acids, Fulvic Acids, and Humin that are products of advanced microbial and abiotic transformations; and (III) living biomass including bacteria and fungi protozoa fauna such as earthworms (Du et al., 2023). Chemically complex and highly resistant to decomposition, humic substances contribute significantly to long-term carbon retention and nutrient sequestration through their high cation exchange capacity or sorption (Ćirić et al., 2023). Factors such as climate (temperature, moisture), vegetation type, soil texture, land-use history, and agricultural management practices affect the amount and quality of SOM in any soil. Clayey soils, for instance, have higher SOM content because of stabilization of organic compounds by organo-mineral association and due to its physical protection into aggregates (Czyż & Dexter, 2016).

SOM is further divided based on its turnover rate into active (labile), slow, and passive(stable) pools, with each fraction varying in its biochemical nature and role in soil functioning (Han & Boyd, 2018). The labile fraction, containing simple carbohydrates, such as amino acids and microbial exudates, is quickly decomposed at the same time and is a key substrate for microorganism metabolism and nutrient mineralization. In contrast, the passive SOM pool is dominated by aromatic and condensed carbon structures that decompose on a timescale of centuries and primarily contribute to soil stability and long-term C sequestration rather than nutrient availability. Such a classification is essential for predicting the timeliness of nutrient availability in agro-ecosystems (Daniel et al., 2020). SOM is formed through additive and transformative processes, such as litter input or root turnover, microbial decay, synthesis of microbially derived compounds, and mineral-associated stabilization. Furthermore, SOM formation and stabilization are associated with soil aggregation which physically shields organic matter from enzymatic degradation (Medina-Méndez et al., 2019). Knowledge of the dynamics, composition, and classification of SOM is necessary to develop sustainable land-management systems that can optimize nutrient cycling processes as well as improve soil fertility and reduce GHG emissions. However, with ongoing agricultural intensification, particularly in tropical regions, it is becoming increasingly important to rely on targeted management of SOM, given its importance for overall soil productivity and environmental sustainability (Látal et al., 2017).

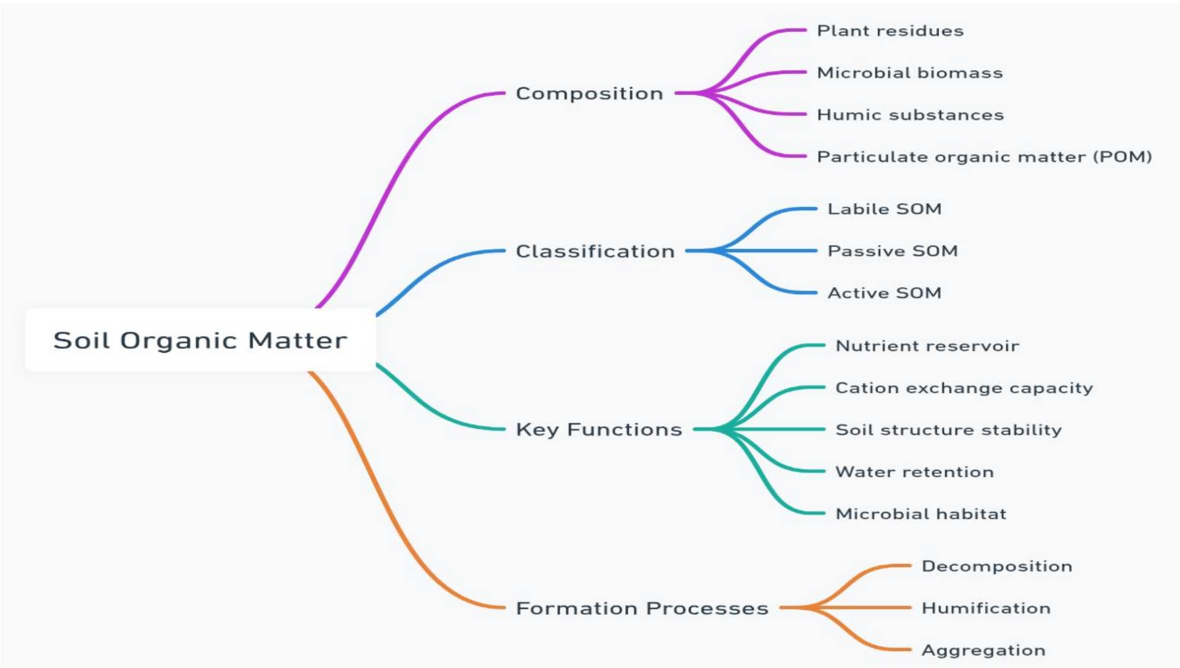

Figure 1: Mind map illustrates the composition, classification, key functions, and formation processes of soil organic matter (SOM) in agricultural systems.

2. SOM Dynamics and Interactions with Soil Nutrients

Soil organic matter (SOM) is an important determinant of nutrient dynamics, given its intricate physical and chemical bonds with key macronutrients as well as micronutrients. One of the most important contributions of SOM to soil fertility is its impact on cation exchange capacity (CEC), or the ability to adsorb and exchange positively charged nutrient ions, such as Ca^{2+} , Mg^{2+} K^{+}, and NH^{-}. The carboxyl and phenolic groups present in humic substances result in a high density of negative charges that increase the soil nutrient retention capacity, reducing leaching (of nutrients), especially in sandy or highly weathered soils (Lemtiri et al., 2016). Besides macronutrients, SOM also chelates essential micronutrients such as iron (Fe), zinc (Zn), copper (Cu), and manganese which are stable in nature and degrade organic compounds relatively slowly, increasing their solubility and bioavailability potential while simultaneously checking toxic accumulations (Narayan et al., 2023). SOM also acts as a buffer, providing protection against extreme pH fluctuations in the soil, which could adversely affect nutrient solubility and microbial activity (Khan et al., 2014). Such interactions not only maintain nutrients in forms available to plants but also lead to a stable and resilient soil ecosystem that can sustain long-term agricultural production (Fox et al., 2022).

Moreover, SOM affects the sorption–desorption processes and mobility of essential plant nutrients, primarily N, P, and S. The immobilization of these nutrients by microbial biomass and organo-mineral complexes owing to organic matter is then followed by their slow release as plant-available forms through mineralization from the process of degradation (van Hullebusch et al., 2019). In the nitrogen cycle, SOM is a source and sink in which organic N can be immobilized into stable forms or released as $NH4^+$ or NO3-during mineralization. In these soils, P is generally closely bound to Fe and Al oxides under acidic conditions so that SOM helps in the greater availability of this element because of chelation (conditional formation complexes or CFC), ligand-exchange, or competitive sorption interactions resulting in reduction fixation (Janke et al., 2024). Similarly, SOM also functions in sulfur cycling by storing organic forms of sulfur and converting them to sulfate. These processes are highly sensitive to organic matter quality and decomposition stage, soil moisture content, oxygenation state, and microbial community composition (de Moraes et al., 2019). The relationship between SOM and nutrients is therefore dynamic, context-specific, and core to nutrient cycling in agroecosystems. Efficient SOM management has the potential to increase nutrient use efficiency, decrease reliance on fertilization, and improve long-term soil fertility, with direct consequences for the sustainable functioning of agricultural landscapes (Salehin et al., 2020).

3. Mechanisms of SOM-Mediated Nutrient Cycling

Soil organic matter (SOM) is important for nutrient balance and acts as a pool or source of essential plant nutrients, especially nitrogen (N), phosphorus (P), and sulfur(S). The major associated features are mineralization, immobilization, and humification as shown in Figure 2. Mineralization is the process of microbial degradation of organic substrates, resulting in nutrients as ions (NH_4^+, NO_4^- PO_4^{3-}, and SO_4^{2-}) which are available to plants (Du et al., 2024). The decomposition of the substrate is governed by heterotrophic microorganisms and depends on temperature, moisture content, substitute quality (C:N ratio), and soil ph. Immobilization is a transient process in which these nutrients are temporarily retained in microbial biomass during decomposition and buffer nutrient release, thus reducing leaching loss (Zhu et al., 2022). Humification, the formation of stable humic substances by partially decomposed organic residues, has concomitant effects on the long-term sequestration and slow release of nutrients present in readily available form due to ongoing microbial or enzymatic activity (Köberl et al., 2022). These systems are interconnected by microbial activity, which serves as a biological motor for nutrient recycling in soil. Microbial enzymes such as urease, phosphatase, and sulfatase play a predominant role in N, P, and S transformation from organic to mineral forms (Ding & Yu, 2024).

Microbial composition and diversity Supplemental towards the above mentioned, soil microbes are as well important regulators of nutrient cycling SOM quality-Quantity regulated by SOM who have functionally varied microbial communities that motivated to help come for it is high-quality quantity signal. For instance, nitrogen-fixing bacteria (for example, Rhizobium and Azotobacter) or mycorrhizal fungi contribute to the availability of nutrients via symbiotic interactions; decomposing fungi and actinomycetes break down complex organic polymers, such as lignin and cellulose (Tobias-Hünefeldt et al., 2021). Through its interaction with soil aggregates, SOM is also involved in nutrient cycling, as it offers protected microhabitats for both the microbial population and enzymatic activity that are known to support consistent patterns of nutrient release (Burpee et al., 2016). In addition, redox-sensitive constituents such as iron and manganese are cycled by SOM via microbial reduction/oxidation reactions which affect nutrient solubility and mobility. These multifactorial procedures not only increase the availability of nutrients in relation to crop demand but also prevent loss due to leaching and gaseous emissions. Knowledge of these mechanisms is important for developing sustainable soil fertility management systems, especially in intensively cultivated agricultural lands where nutrient imbalances and losses are widespread (Fang et al., 2023). The management of organic matter input with quality to match microbial demands and enhance the formation of stable SOM is crucial for realizing its complete regulatory effect on nutrient cycles (Bastias et al., 2020).

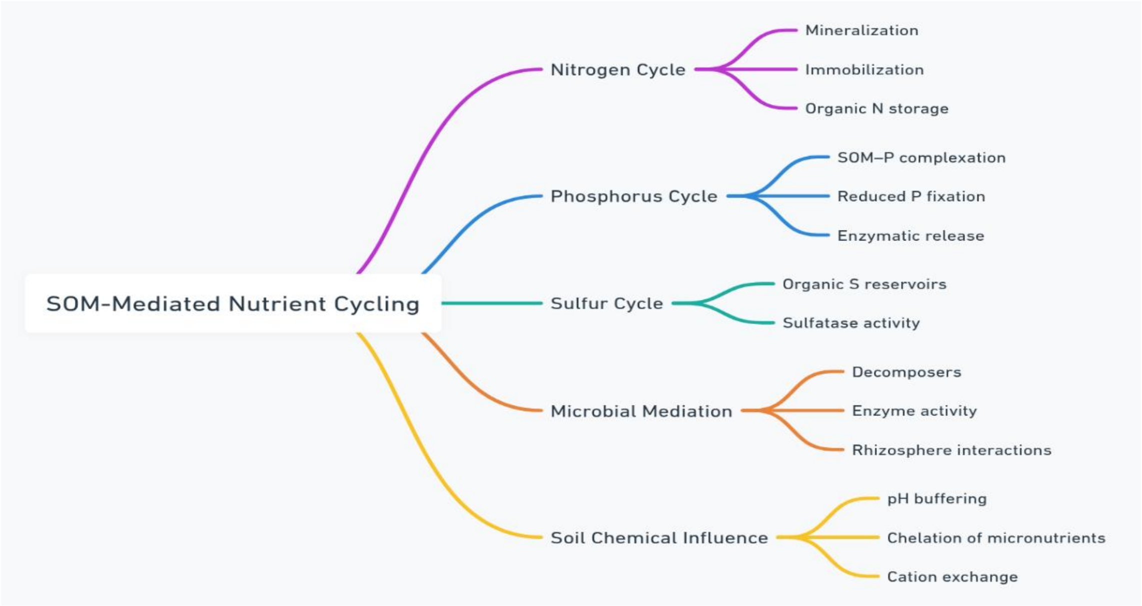

Figure 2: Mind map showing the key processes involved in SOM-mediated nutrient cycling, including its roles in nitrogen, phosphorus, and sulfur cycles, microbial mediation, and soil chemical interactions.

4. Impact of Agricultural Practices on SOM and Nutrient Availability

Agricultural land management significantly affects the amount and quality of soil organic matter (SOM), which modifies essential nutrient availability and cycling efficiency as shown in Figure 3. Intercropping system practices also include tillage intensity, which is crucial. Disturbance by ploughing of soil aggregates results in enhanced aeration and microbial oxidation of organic matter, favoring net SOM loss. These losses reduce the soil nutrient reserve, especially nitrogen (N) and phosphorus (P), diminish its capacity to supply nutrients, and increase erosion or leaching (Venkatesh et al., 2024). Meanwhile, conservation tillage and no-till systems protect SOM by reducing the physical disturbance of the soil and retaining organic residues on its surface (Selva Rani et al., 2024). Likewise, crop rotation and diversification increase SOM inputs through modification of root structures as well as residue quality, which supports a more diverse microbial community resulting in balanced nutrient cycling (Guo et al., 2019). Rotations based on legumes, for example, supply biologically fixed nitrogen, reduce applied synthetic fertilizer requirements, and increase microbial biomass carbon. The addition of cover crops also provides additional benefits to SOM accumulation and nutrient retention by shielding the soil surface, boosting input from biomass production, and scavenging residual nutrients in fallow situations (Hailu & Feyissa, 2023).

The type, time, and source of organic/inorganic inputs also play a great role in SOM dynamics as well as nutrient availability. The use of organic amendments, farmyard manure, green compost, and crop residues offers a direct supply of carbon and nutrients from the material for microbial assimilation promoted by humification. These additions increase microbial activity, enzymatic actions, and the binding of nutrients into organic-mineral complexes, thus decreasing nutrient loss by leaching or volatilization (Bashir et al., 2023). In contrast, the sole use of chemical fertilizers alone without being returned by organic matter can cause soil acidification and imbalance in the microbial community as well as reduction in SOM content with time. Long-term evaluations in various agroecosystems indicate that integrated nutrient management (INM), or the combination of organic and inorganic inputs, is more sustainable than individual inputs for increasing SOM content, enhancing nutrient use efficiency (NUE), and crop productivity (Roba, 2018). Biochar has recently been proposed as a carbon-rich, recalcitrant organic amendment able to increase the SOM pool and its ability to retain nutrients (sorption function) or support microbial habitats. Its effects are feedstock type, pyrolysis conditions, and soil specific. In general, the management of agricultural practices to preserve or increase SOM levels is key for sustainable nutrient retention and stability in soil structure under long-term environmental pressures due to climate change (Supriyo et al., 2021).

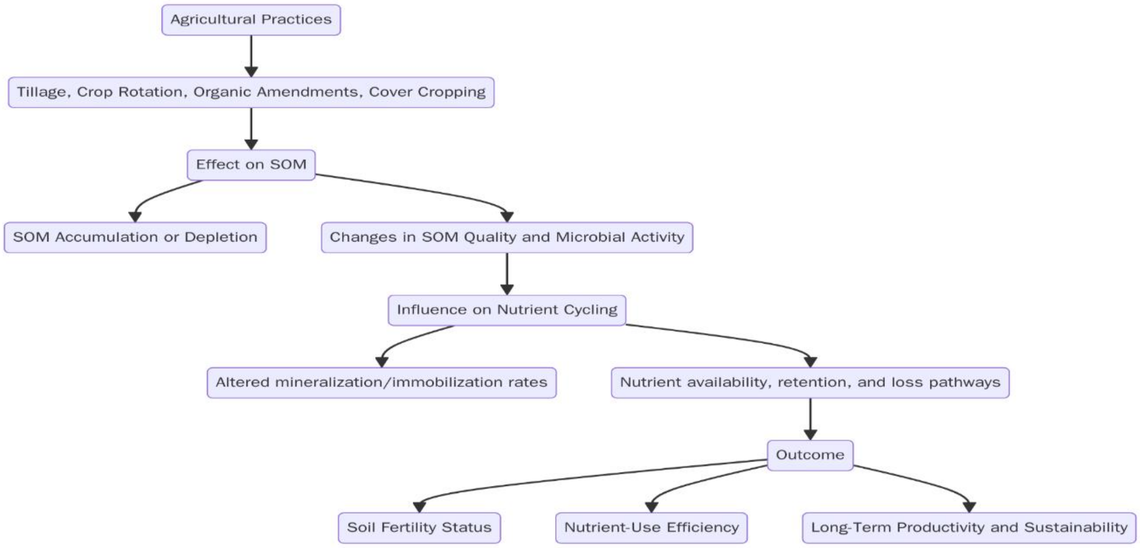

Figure 3: Flowchart illustrates how agricultural practices influence soil organic matter (SOM), nutrient cycling dynamics, and key outcomes such as soil fertility, nutrient-use efficiency, and long-term agricultural sustainability.

5. SOM Management Strategies for Enhancing Soil Fertility and Sustainability

Sustainable soil organic matter (SOM) management is essential for increasing soil fertility, nutrient-use efficiency, and long-term productivity in farming systems. Optimal SOM allelopathy is realized via practices that enhance the input of organic materials, reduce losses in OM and favor stable processes for accumulation within soil aggregates (Ayuke et al., 2019). Among the best management practices (BMPs) for SOM content enhancement, residue retention, reduced tillage, and diversified crop rotations or organic amendment applications are known for their capacity to improve SOM content and soil nutrient cycling/resilience (Novara et al., 2018). For example, using cover crops in rotations is a continuous source of organic input and can help control weeds, increase microbial biomass, scavenge N, and biologically fix it to improve its availability (Cucci et al., 2016). Additions of compost and well-decomposed manure add stabilized organic matter and provide a source for enhanced microbial activity to mineralize nutrients at sync with crop removal. Furthermore, conservation agriculture standards (inclusion of minimal soil disturbance, permanent soil cover, and crop diversity) improve aggregate protection and organic matter stabilization which is critical for maintaining SOM from decomposition (Altobelli et al., 2020).

For climate-smart agriculture and environmental sustainability, SOM management plays a role in wider ecosystem services (including carbon force storage efficiency), such as water holding capacity improvement, especially under fluctuating available water due to variable climatic conditions. Techniques such as biochar application, **integrated nutrient management** (INM), and precision fertilizer use are known to reduce nutrient losses but also enhance utilization of nutrients by the crop, ultimately leading to lower external synthetic input demand (Murindangabo et al., 2023). Agroforestry systems and perennial cropping also contribute to an increase in the SOM pool through deep rooting and continuous organic inputs. It is important to maintain the SOM input/output balance, that is, inputs should not exceed microbial processing capacity (so that immobilization may occur) nor be short stacking below consumption levels leading to nutrient depletion in soil solutions and losses (Carneiro et al., 2025). Policy and land-use planning are needed to encourage these practices with incentives, farmer training on best management, and research. Furthermore, site-based monitoring of SOM by means of indicators such as particulate organic carbon, microbial biomass carbon, and enzyme activity allows the individual adjustment of management options to local situations (Costa et al., 2021). Similarly, by combining SOM-based management with precision agriculture and ecology, nutrient cycling can be maximized, soil fertility can be improved, and more sustainable/robust agroecosystems can be developed (Kouakou et al., 2022).

6. Conclusion

SOM is a key element in the regulation of nutrient cycling and functional stability of agroecosystems. Its heterogeneous composition and polymorphic physiological properties allow organic matter to play the dual role of a bank as well as modulator of plant nutrients such as nitrogen, phosphorus, sulfur, and micronutrients. The interplay between SOM, soil microorganisms, and mineral particles controls processes such as mineralization, immobilization, and adsorption that determine the availability or stability of nutrients in the soil matrix. SOM is strongly influenced by agricultural practices, such as tillage and crop residue management, crop diversification, and the addition of organic amendments that have direct impacts on SOM dynamics and hence nutrient availability. Reduction in SOM through conventional agriculture jeopardizes soil fertility and the sustainability of agricultural production. As such, practitioners also need to focus on the integrated soil fertility management practices which ensue SOM conservation. Practices such as conservation tillage, compost addition, cover cropping, and application of biochar have proven promising to increase SOM content, along with enhancing nutrient use efficiency and microbial activity. This also contributes to climate change mitigation, with the sequestration of carbon and improved soil water-holding capacity. Given the mounting stress on global food supplies, SOM management is increasingly being recognized as a key leverage point for maintaining productivity while mitigating environmental impacts. The agriculture of the future will have to be built on principles centered around SOM and optimized not only for ecological sustainability but also for economic viability and climate resilience. Direct investments in research, farmer education, and policy frameworks that foster SOM-enhancing practices will be necessary to guarantee fertile, productive soils for the agriculture of future generations.

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