Turning Back the Carbon Clock: Restoring Soil Organic Matter for a Sustainable Future

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Abstract

Soil organic matter (SOM), the organic component incorporated into the soil matrix, is fundamental to sustaining soil quality. Heterotrophic microorganisms play a central role in breaking down organic materials through various enzymes, using carbon and energy from the substrates for their growth. SOM greatly influences long-term food production by enhancing nutrient and water use efficiency, improving soil structure, and stimulating biological activity. Several factors such as temperature, oxygen availability, rainfall, parent material, soil fertility, microbial activity, organic substrate characteristics, and land use regulate SOM decomposition and consequently soil organic carbon (SOC) levels. Decline in SOC and associated nutrient supply is a major cause of yield stagnation in intensively cultivated systemsworldwide.Agricultural intensification has accelerated carbon loss to the atmosphere, contributing to greenhouse gas emissions. Maintaining SOM is therefore critical for restoring soil health, fertility, and crop productivity. This is achievable through practices such as carbon sequestration, balanced and integrated nutrient management (INM), improving farmyard manure (FYM) and compost quality, use of vermicompost and green manure, mulching, recycling crop residues, promoting bio-inoculants, increasing forest cover, and adopting suitable cropping systems.

Keywords: Soil matrix, Carbon sequestration, Integrated nutrient management, Farmyard manure, Cropping systems.

Introduction

Soil organic matter refers to the organic fraction of soil, including decomposing plant and animal residues, microbial cells and tissues, and compounds synthesized by soil organisms. Organic matter is essential for transforming soil into a dynamic, living system capable of supporting life. Its presence enhances soil fertility and productivity in multiple ways. Adding organic matter raises soil carbon levels, which in turn boosts soil fauna, microbial activity, and biodiversity. It improves soil aggregation and macro porosity, thus promoting water infiltration, reducing erosion and land degradation, and increasing water-holding capacity. SOM also enhances soil cation-exchange capacity (CEC), increases the availability of nutrient cations such as Ca, K, and Mg, and improves soil buffering capacity [1]. During microbial decomposition, various organic acids are released. Together with CO_2, these acids dissolve soil minerals, making nutrients like Ca and K available. They also form chelates with micronutrients (Fe, Zn, Cu, Mn), preventing precipitation and enhancing their availability. In acidic soils, organic-matter-derived chelates reduce Fe and Al toxicity and minimize phosphate fixation. Additionally,

DOI: https://doi.org/10.5281/zenodo.17830600

microbial decomposition produces plant-growth-promoting compounds, such as vitamins, auxins, and gibberellins that stimulate plant development. SOM levels are controlled by climate (especially temperature and rainfall), oxygen supply, parent material, soil fertility, biological activity, vegetation type, and land use. Indian soils generally have low SOC (0.1–1%) due to high temperatures prevailing year-round [2]. Globally, soils store about 1500 Pg of carbon [3]. Conversion of natural ecosystems to agriculture typically depletes SOC. Because SOM is a key indicator of soil fertility, productivity, and sustainability [4], its decline particularly in intensive cropping systems—contributes significantly to yield stagnation [5]. Therefore, effective agroecosystem management is essential for building SOC and improving SOM content.

Organic Matter in Soil

Soil organic matter consists of fresh plant residues and soil organisms, decomposing organic materials, and stable humus. Organic constituents occur in the following forms:

Litter: large undecomposed residues on the soil surface (e.g., crop residues, fallen leaves)

Light fraction: partially decomposed plant residues within the soil

Microbial biomass: living cells of bacteria, actinobacteria, fungi, algae, and cyanobacteria

Faunal biomass: living and dead tissues of soil animals, mainly invertebrates

Belowground inputs: roots and their exudates

Water-soluble organic compounds: dissolved organic substances

Stable humus: long-lasting, highly decomposed organic material.

Most SOC originates from plant materials. Forest ecosystems, particularly those in hilly regions, accumulate large quantities of organic carbon. Natural forests can accumulate leaf litter equal to about 2% of their belowground biomass [6]. Temperate forests often produce several tons of leaf litter annually per hectare. Tropical plantations may accumulate even more than natural forests. In contrast, tropical agricultural soils typically contain only one-fifth to one-sixth of the organic matter found in temperate agricultural soils. Animals also contribute organic matter through their waste and carcasses. Soil fauna such as earthworms, termites, ants, and dung beetles are particularly important for incorporating and transforming organic residues. India generates substantial organic waste from crops, agro-industries, and natural biomass about 350 million tonnes annually. Organic matter reaches the soil either through cover crops, pastures, and crop residues, or through externally added inputs such as manures, composts, biosolids, and organic fertilizers [7].

Crop Residues and Soil Organic Matter Dynamics

Terrestrial plants and aquatic algae collectively fix about 120 Pg of carbon annually from atmospheric CO_2 through photosynthesis, transforming it into a wide array of organic compounds. A portion of this assimilated carbon initially retained within plant tissues and microbial biomass—is eventually returned to the soil following their decomposition. In agricultural ecosystems, crop residues constitute the primary source of soil organic inputs. The overall soil organic matter (SOM) pool comprises multiple fractions, generally categorized as active, slow, and passive pools, each with distinct turnover rates and vulnerability to microbial decomposition. Microbial processes continually mediate the movement of organic carbon among these pools, and during these transformations, a portion of carbon is released back into the atmosphere as CO_2 [8].

Fractions of Soil Organic Matter

The active pool of soil organic matter (SOM) consists of living microbial biomass, small fragments of decomposing residues (particulate organic matter), most polysaccharides, and a wide range of non-humic substances such as low-molecular-weight organic acids, proteins, and easily decomposable fulvic acids. This fraction generally has a C:N ratio between 15 and 30

DOI: https://doi.org/10.5281/zenodo.17830600

and typically persists in soil from several months to a few years**.** The active pool is the primary source of readily mineralizable nitrogen, and its contribution to soil aggregation enhances water infiltration, erosion resistance, and tilth. Incorporation of crop residues rapidly increases this fraction; however, it is also highly susceptible to depletion under intensive tillage. In most soils, the active pool constitutes approximately 10–20% of total SOM [9].

The passive pool comprises highly stable organic materials that may remain in soils for hundreds to thousands of years, undergoing extremely slow turnover. This fraction includes humus strongly protected within clay humus complexes, most of the humin fraction, and a large proportion of humic acids. Passive SOM typically accounts for 60–90% of total organic matter in many soils. This pool is intimately linked with the colloidal properties of soil humus and contributes substantially to cation exchange capacity (CEC) and soil water-holding capacity, making it a critical component of long-term soil fertility [10].

The slow pool of SOM represents an intermediate category between the active and passive fractions. It is composed of finely decomposed plant residues rich in lignin and other chemically stable compounds that degrade at a moderate pace. The estimated half-life of these materials may extend over several decades. This fraction serves as an important reservoir of mineralizable nitrogen and other nutrients, providing a sustained supply of substrates for autochthonous soil microorganisms, thereby supporting long-term microbial activity [11].

Soil Organic Carbon Stocks

Global assessments indicate that soils contain approximately 1500 Pg of organic carbon within the top 1m of the soil profile. By comparison, geological carbon reserves comprise about 4000 Pg in coal**,** 500 Pg in natural gas**,** and 500 Pg in petroleum. In the context of India, the total soil organic carbon (SOC) pool is estimated at 21 Pg to 30 cm depth and 63 Pg to 150 cm depth. Additionally, soils in India store roughly 196 Pg of inorganic carbon within the upper 1m of the profile [3].

Soil Organic Matter as a Source of Plant Nutrients

Soil organic matter (SOM) serves as an important reservoir of essential plant nutrients. On average, the dry matter of plants, soil microflora, and fauna contains roughly 25% solid constituents, of which carbon, oxygen, and hydrogen account for 90–95% by weight. The remaining 5–10% consists of mineral nutrients including N, P, K, S, Ca, Mg, Fe, Zn, Mn, and other essential elements [12]. A substantial proportion of these nutrients occurs in organic forms approximately 95–99% of total N**,** 33–67% of total P, and 75% of total S necessitating microbial mineralization to release them into plant-available forms. Although the rate of mineralization is often slow and may not fully satisfy the nutrient demands of high-yielding crop varieties, SOM still functions as a long-term nutrient reservoir [13]. Crop residues are the dominant source of SOM inputs. During their decomposition, 55–70% of carbon is lost as CO_2, 5–15% is converted into microbial biomass, and 15–40% becomes stabilized as humus. India produces an estimated 686 million tonnes of crop residues annually [14]. The nutrient (NPK) contribution from organic resources was about 14.85 Mt in 2000, with projections suggesting an increase to 32.41 Mt by 2025. Rice and wheat residues contribute the largest share due to their high biomass and nutrient concentrations [15].

Nitrogen Dynamics from Crop Residues

Nitrogen availability from residues depends on residue quality, decomposition rate, and environmental conditions. Leguminous residues can contribute approximately 60–70 kg N ha^{-1} to cropping systems through biological fixation and subsequent mineralization. However, the proportion of legume-derived N recovered by following crops typically ranges from 10–35%. Their decomposition follows a two-phase pattern: a

DOI: https://doi.org/10.5281/zenodo.17830600

rapid mineralization phase, during which easily decomposable, N-rich components meet microbial N demands; and a slower phase, dominated by lignin-bound or lignin-protected N with lower mineralization rates. Legume and non-legume residues differ markedly in chemical composition. Non-leguminous residues, which characteristically have wide C:N ratios (low N content) such as those from maize, sorghum, rice, and wheat—tend to promote microbial N immobilization during early decomposition. Net mineralization from such residues generally begins only after 50–60% of the material has decomposed or when the C:N ratio narrows to below 30 [16].

Carbon Assimilation by Key Soil Microbial Groups

Soil microorganisms perform several indispensable functions that directly influence soil health and plant productivity. These include decomposition of organic matter**,** formation of humic substances**,** biological nitrogen fixation**,** nutrient transformations, and nutrient recycling. Microbial cells contain roughly 50% carbon, obtained either from organic substrates in heterotrophs or from CO_2 in autotrophs. The conversion of substrate carbon into cellular biomass is termed carbon assimilation. Heterotrophic microbes acquire both carbon and energy from organic materials; therefore, carbon assimilation is tightly coupled with organic matter decomposition, which generally involves three steps: breakdown of plant and animal residues by enzymes such as cellulase and ligninase, microbial biomass growth through the uptake of carbon and other nutrients, and formation or release of end products, including CO_2, CH_4, organic acids, alcohols, and humus. The first step corresponds to mineralization, where organic nutrients are converted to inorganic forms. The second step, microbial uptake and biomass formation, is the reverse process and is known as immobilization. The third step reflects overall microbial activity and contributes to humus formation [17]. On average, microorganisms assimilate 30–35% of substrate carbon, while the remaining two-thirds is released as CO_2 or accumulates as metabolic by-products. Carbon assimilation efficiencies vary among microbial groups: bacteria assimilate 5–10%**,** actinobacteria 15–30%, and fungi 30–40% of the carbon they consume. Fungi release comparatively less CO_2 per unit of carbon assimilated, making them metabolically more efficient. Aerobic bacteria are the least efficient, whereas anaerobic bacteria often leave behind large amounts of carbon-rich residues due to poor carbon utilization [18].

Microbial Ecology of Residue Decomposition

Decomposition of plant residues proceeds through a dynamic succession of microbial groups, each responding to the chemical nature of the substrate. Microbial populations fluctuate based on the availability of easily decomposable compounds. Some groups dominate only briefly, whereas others maintain high populations over extended periods. Each microorganism possesses a unique array of enzymes that enable it to oxidize specific substrates. When an appropriate substrate becomes available, organisms capable of using it proliferate provided they can compete successfully with other microbes that have similar enzymatic capabilities. The first decomposers to colonize fresh organic residues form the primary flora, mainly heterotrophic bacteria, which rapidly utilize soluble compounds such as sugars, proteins, and simple polysaccharides. Slow-growing, indigenous (autochthonous) microbes are quickly outcompeted by fast-growing zymogenous organisms that respond to the sudden availability of carbon-rich substrates[19]. (Pal, 2016). These zymogenous groups constitute the secondary flora, growing on intermediate products formed by the primary decomposers or on the remains of the initial microbial community. As decomposition proceeds and the C:N ratio gradually narrows, additional microbial groups with different biochemical capacities become dominant. Fresh, succulent residues encourage rapid microbial proliferation. In

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contrast, mature residues rich in lignin and cellulose support communities better adapted to degrade resistant carbon fractions primarily fungi, with contributions from bacteria and actinobacteria [9].

Microbial Uptake of Nutrients with Significance

During carbon assimilation, microorganisms simultaneously take up essential elements such as N, P, K, S, and micronutrients from both soil and plant residues. Because plant materials typically contain these nutrients in very limited quantities, soil inorganic pools play a critical role in sustaining microbial growth during the early stages of decomposition. Thus, soil nutrient availability strongly influences microbial immobilization, which, in turn, governs the rate of organic matter decomposition. The extent of immobilization depends on microbial biomass and the C:N, C:P, and C:S ratios required for synthesizing new microbial cells [20]. Although these ratios vary among soils and climatic conditions, globally averaged proportions in soil humus approximate C:N:P:S =140:10:1.3:1.3 [21].

C:N

Ratio and Soil Organic Matter Decomposition

The C:N ratio of microbial cells is approximately 5:1 in bacteria, 5:1 in actinobacteria, and 10:1 in fungi. To decompose 100 units of carbon, bacteria require 1–2 units of N, actinobacteria need 3–6 units, and fungi require 3–4 units of nitrogen (Alexander, 1977). Based on the relative proportions of microbial groups in soil, the weighted average C:N ratio of soil microbial biomass is around 8:1. The C:N ratio of organic residues plays a crucial role in determining the rate of decomposition and nitrogen mineralization. Residues with wide C:N ratios or low N content such as corn stalks (1.2% N), wheat straw (0.5% N), sorghum stalks (0.87% N), sugarcane trash (0.88% N), and rice straw (0.7% N) decompose slowly. When such residues are added to soil, intense competition arises among microorganisms for available N, leading to initial nitrogen immobilization. Plant dry matter generally contains 42% carbon, whereas nitrogen content varies widely typically from <1% to >6%. Overall, plant materials exhibit C:N ratios ranging from 10:1 in legumes to 600:1 in sawdust. As plants mature, their protein content decreases while lignin and cellulose content increases, causing the C:N ratio to widen. Although C:N ratio is a good predictor of decomposition rate, it is not the sole determinant. Younger, succulent tissues decompose rapidly not just because of low C:N ratio, but due to lower lignin content, while woody tissues with high lignin content decompose much more slowly [22]. In cultivated surface soils, the carbon-to-nitrogen (C:N) ratio generally falls between 8:1 and 15:1, with an approximate mean of 12:1. In contrast, forest soils typically possess much wider C:N ratios often 30:1 to 40:1 due to slower organic matter turnover. When forest land is converted to agriculture, accelerated decomposition gradually reduces the C:N ratio to around 12:1 [23].

Most soil microorganisms utilize organic substrates as sources of energy, carbon, and nutrients. Along with metabolizing carbon-rich materials, microbes require sufficient nitrogen for synthesizing essential nitrogenous biomolecules such as amino acids, enzymes, and nucleic acids. Active organic matter degradation stimulates microbial growth, which increases their nitrogen demand. Microbial biomass generally has a C:N ratio of 8:1, and because roughly one-third of the carbon consumed is lost as CO_2 during respiration, microbes effectively require 1g of N for every 24g of carbon in the substrate. When organic materials added to soil have C:N ratios greater than 25:1, microbes withdraw nitrogen from the soil to meet their demand. This leads to nitrogen immobilization and temporary N deficiency for crops. Decomposition also slows if neither the residue nor the soil contains enough readily available nitrogen. For residues with 40% C and 0.5% N, the nitrogen required for

DOI: https://doi.org/10.5281/zenodo.17830600

microbial activity varies among microbial groups approximately 0.4–0.8 units for bacteria, 1.2–2.4 for actinobacteria, and 1.2–1.6 for fungi per 100 units of residue. Nitrogen deficits (0.1–0.3, 0.7–1.9, and 0.7–1.1 units, respectively) are compensated by microbes extracting N from the soil environment, resulting in immobilization [24].

The nitrogen requirement during decomposition of high C:N residues is expressed as the N-factor, defined as the amount of inorganic nitrogen immobilized per 100 units of decomposing organic material, or operationally, the quantity of nitrogen that must be added to prevent net immobilization. Organic materials with wide C:N ratios promote immobilization, whereas narrow C:N ratios enhance mineralization. Therefore, fresh high-C residues should not be incorporated into soil during the growing season. An optimal C:N ratio of 20–25 (1.4–1.7% N) allows balanced mineralization and immobilization. When the ratio falls below this range, mineralization dominates, causing excess nitrate accumulation, which can lead to nitrate toxicity or leaching losses. During decomposition, both carbon and nitrogen undergo mineralization and immobilization. Over time, their rates converge, and the residue's C:N ratio stabilizes around 10–12:1, characteristic of stable soil humus. In humid temperate forest soils, where carbon mineralization proceeds slowly, C:N ratios remain relatively high [18].

Environmental and biological controls on Decomposition

Decomposition is governed by numerous factors, including residue chemistry, microbial community structure, and soil environmental conditions. Among these, oxygen availability is the most critical determinant of decomposition rate and pathway. Temperature also plays a major role, with optimum decomposition occurring at 30–40°C, and moisture near 60–80% of water-holding capacity. Neutral soils generally favor faster breakdown compared to acidic or alkaline soils [25].

Aerobic decomposition

In oxygen-rich soils, where most decomposers are aerobic microbes, decomposition proceeds rapidly. Oxygen acts as the terminal electron acceptor during oxidation of organic compounds. Incorporation of plant residues initially causes a rapid decline in O_2 concentration and a rise in CO_2, shifting the redox potential toward more reduced conditions. Easily degradable compounds such as sugars and proteins are metabolized first, while structural components like cellulose, hemicellulose, and lignin persist longer. Cellulose degradation is mediated by a suite of enzymes, cellulases, endo-glucanases, exo-glucanases, cellobiohydrolases, and β-glucosidases which collectively release glucose units. Hemicellulases depolymerize hemicellulose into hexoses, pentoses, and uronic acids. Pectic substances are degraded by protopectinases, pectin methyl esterases, and polygalacturonases. Chitin is decomposed by chitinase and chitobiase.

Because plant residues are rich in carbohydrates, aerobic decomposition can be summarizedby:

Carbohydrate + $2O_2 \rightarrow CO_2 + H_2O$ + energy (478 kJ mol^{-1} C)

Lignin, being highly resistant, increases proportionally in the remaining material. Ligninases break lignin into aromatic compounds such as vanillin, syringic acid, and ferulic acid. Phenolic compounds and tannins can inhibit decomposition. As decomposition progresses, mineralization of nitrogen (ammonification, nitrification, denitrification) and other nutrients also occurs. The proportion of phenolic OH groups decreases, whereas COOH groups and cation exchange capacity (CEC) increase. Organic residue addition stimulates humus turnover, as microbial proliferation accelerates both humus formation and degradation [26].

Anaerobic decomposition

Under oxygen-deficient conditions, organic carbon is only partially metabolized, leading

DOI: https://doi.org/10.5281/zenodo.17830600

to accumulation of intermediate compounds. Anaerobic decomposition is characterized by production of CH_4, organic acids, and small amounts of H_2. Mesophilic and thermophilic bacteria particularly Clostridium species dominate cellulose breakdown. Complex carbohydrates and proteins are initially converted to organic acids and alcohols. Secondary fermentation generates lactic, acetic, and butyric acids, which act as substrates for methanogenic bacteria such as Methanobacterium,Methanobacillus, Methanosarcina,andMethanococcus,producing methane.Anaerobicconditionsyield considerably less energy for microbes. Decomposition products often include foul-smelling substances, phytotoxic phenolics, H_2S, and volatile sulfur compounds (mercaptans, dimethyl disulfide, etc.). Under strict anaerobiosis (Eh < –200 mV), about 90% of carbon is released as CH_4 and CO_2, while only 10% is assimilated. Under mildly reducing conditions, alcohols, organic acids, and hydrogen accumulate [27].

Management of Soil Organic Matter and Soil Fertility

Soil organic matter plays a central role in sustaining agricultural productivity. Adequate SOM enhances nutrient- and water-use efficiency, improves soil physical structure, stimulates biological activity, and enhances crop quality (Figure 1). Maintaining soil organic carbon is equally critical for mitigating greenhouse gas emissions. Restoration of soil health in India depends heavily on maintaining SOC through appropriate organic inputs and judicious SOM-management practices [28].

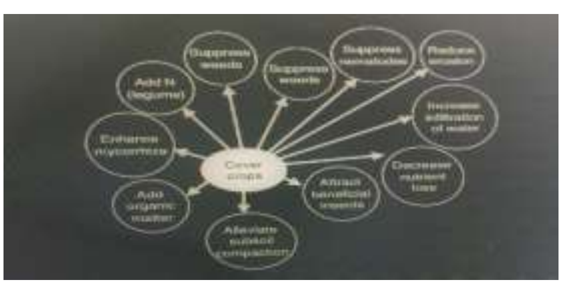

Figure 1. Cover crops as a management practice

Addition of Organic Materials

Maintaining the active fraction of soil organic matter (SOM) is essential for soil fertility and productivity. This is primarily achieved by regularly adding organic materials to the soil and by adopting management practices that minimize SOM losses. Major sources of organic inputs include crop residues, compost, farmyard manure (FYM), green manures, and other biodegradable wastes. Improved plant growth increases the return of organic materials to the soil through root biomass, even when aboveground residues are removed during harvest. Coarse organic matter helps loosen soil, enhances macropore development and channel formation, and increases water infiltration. This reduces surface runoff and water pollution. Better aeration from increased gas exchange allows more oxygen to reach plant roots, ultimately improving water-use efficiency and boosting crop yields. Green manuring crops can supply about 3–4 tons of dry matter per hectare, contributing both carbon and significant nitrogen to the soil. Organic materials such as enriched compost, vermicompost, FYM, and municipal compost support recycling of animal waste, household biodegradable waste, and crop residues, helping restore the carbon removed from soils during crop harvest [29].

Management Practices
Soil Carbon Sequestration

Soil carbon sequestration involves capturing atmospheric CO_2 through plant photosynthesis and storing it in the soil as SOM. Practices that reduce carbon loss or enhance soil carbon buildup include:

- Integrated nutrient management (INM)
- Use of quality FYM, compost, vermicompost, and green manures
- Mulching and crop residue incorporation
- Controlled grazing
- Afforestation and agroforestry
- Efficient water management
- Soil and moisture conservation

DOI: https://doi.org/10.5281/zenodo.17830600

- Land reclamation
- Selecting suitable cropping systems

These practices help maintain soil fertility while mitigating atmospheric CO_2 [30].

Integrated Nutrient Management for Soil Organic Carbon

INM aims to maintain soil fertility and ensure balanced nutrient supply by combining organic, inorganic, and biological nutrient sources (Chandrasekhar Rao 2012). FYM is a widely used organic manure containing approximately 0.5% N, 0.2% P, and 0.5% K along with micronutrients. It enhances soil moisture retention and overall soil health. Efficient management of crop residues is crucial for restoring soil fertility. These residues can be converted into nutrient-rich materials like phosphocompost and vermicompost (Basak et al. 2012). Biofertilizers (e.g., Rhizobium, Azotobacter, Azospirillum, PSB, VAM) also play an important role in nutrient supply, especially in low-input dryland areas. Long-term studies in India show that balanced fertilization can increase SOC in the upper 42 cm of soil by 8 t ha^{-1} over several years, at a rate of 0.25 t ha^{-1} yr^{-1} [2].

Cropping Systems for Improving SOC

Crop species and cropping systems influence SOC levels because residue amount, residue composition, and decomposition rate vary across crops. In sandy loam soils of Anantapur, sunhemp–rice–rice and greengram–rice–rice systems showed significant SOC improvement (7.0 and 6.7 g kg^{-1}, respectively) after two years [31].

Land Use Systems for Improving SOC

Agroforestry is an effective system for increasing soil carbon stocks, as trees contribute large amounts of biomass both above and below ground. India's average agroforestry carbon sequestration potential is 25 t C ha^{-1} across 96 million hectares, though this varies regionally. In horticultural systems, SOC loss can be minimized through:

- Reduced tillage
- Enhanced water-use efficiency
- Surface mulching
- Inclusion of legumes for increased belowground biomass
- Conversion of vegetable residues into biochar for long-term carbon stabilization [32].

On-Farm Strategies for Improving SOC

On-farm soil management can reduce carbon loss and enhance sequestration. Key practices include:

- Site-specific nutrient management based on crops and soil test results
- Minimizing tillage to reduce SOM oxidation
- Conservation tillage to slow residue decomposition and reduce erosion
- Crop re
- sidue retention
- Soil moisture conservation measures [33].

Opportunities and Challenges

Excessive exploitation of natural resources including soil, water, and biodiversity has resulted in severe degradation. Loss of SOM, intensive cultivation, overgrazing, and groundwater depletion reduce fertilizer use efficiency and increase greenhouse gas emissions. Modern agricultural chemicals can contaminate food and harm the environment. Nanotechnology offers a promising future tool for precise nutrient detection and delivery, improving productivity while reducing environmental risks.

Priority Needs for Future Soil Management to Turn Back the Carbon Clock

To sustain and improve soil health, the following challenges must be addressed:

1. Enhancing sustainable productivity and soil quality through effective SOM management
2. Increasing soil carbon sequestration through improved land use and cropping systems
3. Adopting site-specific and integrated nutrient management practices
4. Promoting value-added composts, vermicompost, biochar, and similar soil amendments

DOI: https://doi.org/10.5281/zenodo.17830600

5.Expanding conservation agriculture practices**,** such as
- minimum soil disturbance,
- diverse crop rotations,
- cover cropping,
- continuous residue cover,
- integrating crops with livestock.

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DOI: https://doi.org/10.5281/zenodo.17830600