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SOIL ORGANIC MATTER CHEMISTRY AND ITS ROLE IN ENVIRONMENTAL RESILIENCE

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ABSTRACT

Soil organic matter (SOM) is a chemically diverse and biologically active component of terrestrial ecosystems. It regulates carbon and nutrient cycling, influences soil structure and water relations, supports below-ground biodiversity, and affects the fate of pollutants. These functions make SOM central to environmental resilience: the capacity of soils and associated ecosystems to absorb disturbance, maintain essential processes and recover after climatic or anthropogenic stress. This paper critically reviews SOM chemistry and examines how molecular composition and interactions with microorganisms, minerals and soil structure influence resilience. It moves beyond the assumption that persistence is determined primarily by the intrinsic recalcitrance of complex organic molecules. Contemporary research describes SOM as a continuum of plant- and microbe-derived compounds whose persistence emerges from environmental context, microbial transformation, mineral association and physical inaccessibility. The distinction between particulate organic matter (POM) and mineral-associated organic matter (MAOM) is used to explain differences in formation, turnover and management response. The paper evaluates SOM contributions to aggregation, infiltration, water retention, nutrient cycling, microbial habitat, contaminant interactions and climate regulation. Particular attention is given to semi-arid and sub-humid Indian environments, where high temperatures, variable rainfall, residue removal and land-use pressure can constrain SOM accumulation. A critical narrative review methodology is adopted; no primary field measurements or experimental results are claimed. The synthesis indicates that resilience depends not simply on increasing total soil organic carbon, but on understanding the quality, location, accessibility and turnover of different SOM fractions. Site-specific management, long-term monitoring and integrated chemical, physical and biological analysis are therefore essential for scientifically defensible soil restoration.

Keywords: Soil organic matter; soil organic carbon; mineral-associated organic matter; particulate organic matter; soil chemistry; microbial transformation; climate resilience; soil health; semi-arid soils

REVIEW APPROACH

This paper uses a critical narrative review approach. It synthesizes foundational and recent peer-reviewed research on SOM chemistry, microbial transformation, mineral association, soil structure, hydrological function, pollution interactions and climate-related soil resilience. Sources were selected through targeted searches of scholarly publisher platforms, bibliographic databases and institutional sources, with emphasis on influential conceptual reviews and literature relevant to Indian semi-arid and sub-humid soils. This is not a registered systematic review, meta-analysis or primary field experiment; no original measurements or statistical results are presented.

1. INTRODUCTION

Soil is a dynamic living system in which minerals, organic compounds, water, gases and organisms interact. Soil organic matter (SOM) is central to this system because it links biological production with mineral processes and the wider carbon and nutrient cycles. It includes fresh plant and animal residues, partially decomposed materials, microbial biomass and products of microbial activity, as well as organic compounds associated with minerals or protected within aggregates. Soil organic carbon (SOC) is the carbon component of SOM and is widely used as an indicator of soil condition, although it does not describe the complete chemical or functional character of organic matter (Vargas-Rojas et al., 2019).

SOM affects agricultural productivity, but its significance extends further. It influences water entry and storage, resistance to erosion, nutrient supply, microbial habitat and the exchange of carbon dioxide and other greenhouse gases with the atmosphere. These functions connect SOM with environmental resilience. In this paper, resilience means the capacity of soil and land-based ecosystems to withstand disturbances—such as drought, intense rainfall, heat, erosion, nutrient depletion, land-use change and contamination—while maintaining or recovering essential ecological functions. A soil may retain carbon yet lose infiltration capacity; therefore, resilience is multidimensional.

The chemistry of SOM is important because its constituents differ in solubility, functional groups, microbial accessibility and affinity for mineral surfaces. However, molecular complexity alone does not determine persistence. Current research emphasizes interactions among plant inputs, microbial transformation, minerals, physical protection and environmental conditions (Schmidt et al., 2011; Lehmann & Kleber, 2015). This paper reviews these relationships, examines their implications for environmental resilience, and identifies research priorities relevant to Indian conditions, particularly semi-arid and sub-humid soils. It is a literature-based review and does not claim new experimental results.

2. CONCEPTUALISING SOM AND ENVIRONMENTAL RESILIENCE

SOM is not a single substance but a continuum of organic compounds at different stages of transformation. Its composition varies with vegetation, climate, soil texture, mineralogy, topography, land use, depth and management. Consequently, two soils with similar SOC concentrations may differ in aggregate stability, nutrient supply, biological activity and susceptibility to disturbance. Bulk carbon measurement is valuable for establishing stocks, but it cannot independently explain how carbon is distributed or protected.

Resilience includes resistance during disturbance, recovery after disturbance and the ability to reorganize while maintaining essential functions. SOM may support resistance by strengthening aggregates and reducing erosion; it may support recovery by providing substrates for microbial processes and nutrients for plant regrowth. Its contribution depends on local conditions. The same amendment may decompose rapidly in a warm, moist soil but persist differently in a cooler or mineral-rich soil.

A functional understanding therefore distinguishes the amount of organic matter from its organization. Fresh particulate residues supply energy and contribute to aggregation; microbial products may become associated with clay and metal oxides; organic matter inside aggregates may be less accessible to enzymes; and dissolved organic matter can move through soil profiles. Recent conceptual frameworks treat plant, microbial, mineral and physical controls as interacting processes rather than fixed pools defined only by assumed stability (Rocci et al., 2024). For resilience assessment, stock measurements should be combined with fractionation, chemical characterization, biological indicators and measurements of soil physical function.

3. CHEMICAL COMPOSITION AND MOLECULAR CHARACTERISTICS OF SOM

The principal inputs to SOM are derived from plants, roots, animals and microorganisms. Plant residues contain cellulose and hemicellulose, lignin, proteins, lipids, waxes, soluble sugars, organic acids and phenolic compounds. Their relative abundance differs among species, tissues and growth stages. Root exudates supply soluble compounds that can be rapidly used by microorganisms, while leaves, stems and woody residues differ in structural composition. Kögel-Knabner (2002) highlighted the importance of understanding the macromolecular composition of plant and microbial residues entering soil.

Carbohydrates are important microbial energy sources and may be decomposed rapidly when moisture, temperature and aeration are favourable. Cellulose and hemicellulose are structural polysaccharides broken down by specialised enzymes. Lignin is an aromatic biopolymer that can influence decomposition and microbial transformations, but its presence does not guarantee

permanent preservation. Lipids and waxes may be hydrophobic and affect water interactions. Proteins and amino compounds contribute nitrogen, while phenolic and carboxylic compounds participate in sorption, complexation and redox reactions.

Microorganisms transform rather than merely consume plant material. Bacteria and fungi assimilate substrates, build biomass and release enzymes and metabolic products. After microbial death, cell residues—often described as microbial necromass—can contribute to SOM. Amino sugars and other biomarkers may help estimate microbial contributions. The microbial efficiency-matrix stabilization framework proposes that microbial processing can convert accessible plant inputs into microbial products that subsequently associate with the mineral matrix (Cotrufo et al., 2013). The outcome depends on microbial physiology, nutrient availability, mineral surfaces and environmental conditions.

SOM contains carboxyl, hydroxyl, phenolic, carbonyl, amide and aliphatic functional groups. These influence polarity, acidity, charge, hydrogen bonding, metal complexation and mineral interactions. Carboxyl and phenolic groups can contribute negative charge as pH increases, affecting cation exchange and metal binding. Older accounts often described humic and fulvic fractions as inherently persistent macromolecular substances. These remain operationally useful in some procedures, but they should not be treated as proof of a universal, permanently stable molecular class. Lehmann and Kleber (2015) describe SOM as a continuum of decomposing organic compounds, while Schmidt et al. (2011) identify persistence as an ecosystem property shaped by environmental and biological controls.

Composition also changes with depth. Surface soil receives substantial litter and root inputs, whereas subsoil receives root-derived material and dissolved compounds transported downwards. Mineral association, limited substrate availability and restricted microbial access may influence subsoil persistence. Deep carbon is not necessarily inert; some fractions remain responsive to warming, precipitation and land-use change (Sokol et al., 2022).

4. FORMATION, TRANSFORMATION AND STABILIZATION

SOM formation begins when litter, roots, exudates, animal residues and organic amendments enter soil. Soil fauna fragment residues, and microorganisms use soluble and particulate substrates. Enzymes break down complex compounds. Some carbon is released through respiration; some enters microbial biomass; and some is transformed into compounds that may remain in soil. Retention reflects the balance among inputs, decomposition, leaching, erosion and other losses.

A useful contemporary distinction is between particulate organic matter (POM) and mineral-associated organic matter (MAOM). POM generally consists of relatively recognisable plant- or faunal-derived fragments that are not tightly associated with mineral surfaces. It responds to fresh inputs and management and can be an important intermediate pool. MAOM consists of organic compounds associated with silt, clay and reactive mineral surfaces. It is often more processed and may have slower average turnover, although it is not immune to disturbance. The distinction is operational and depends on fractionation methods, but it helps explain differences in formation and management response (Lavallee et al., 2020).

Mineral association involves adsorption, ligand exchange, cation bridging, hydrogen bonding, electrostatic attraction and other interfacial processes. Iron and aluminium oxides, clay minerals and short-range-order minerals provide reactive surfaces. Association strength depends on mineral type, pH, ionic composition and molecular characteristics. The mineral-organic interface is dynamic: minerals can adsorb compounds, catalyse transformations or release organic matter as chemical conditions change (Kleber et al., 2021). Thus, association should not be equated with permanent immobilisation.

Physical protection occurs when organic matter is enclosed within aggregates or located in pores that restrict microbial and enzymatic access. Roots, fungal hyphae, microbial exudates and mineral particles contribute to aggregate formation. Tillage, erosion, compaction and

wetting-drying cycles can disrupt aggregates and expose protected material. Six et al. (2002) described microaggregation and associations with silt and clay as important stabilisation mechanisms and noted that soil properties constrain the capacity to protect additional carbon.

The integrated view is that persistence emerges from plant-input quality, microbial transformation, mineral protection, physical inaccessibility and environmental conditions. Recent synthesis identifies these as interacting controls rather than independent explanations (Rocci et al., 2024). This framework is valuable for evaluating resilience because it links carbon storage with the processes that determine whether soil functions are maintained under disturbance.

5. ANALYTICAL APPROACHES TO STUDY SOM CHEMISTRY

No single method can describe the complete composition, origin and function of SOM. Conventional measurements of organic carbon and total nitrogen provide essential baseline information, but molecular and fraction-based methods are needed when the research question concerns chemical composition and stabilisation. Carbon-to-nitrogen ratios can indicate substrate quality and nutrient status, although they vary across soil types, depths and fractions. Stable carbon isotopes may help distinguish sources or trace inputs from vegetation with contrasting photosynthetic pathways. Radiocarbon can inform estimates of carbon age and turnover, but age is not equivalent to chemical recalcitrance.

Solid-state carbon-13 nuclear magnetic resonance spectroscopy characterises broad carbon environments, including alkyl, O-alkyl, aromatic and carbonyl carbon. Fourier-transform infrared spectroscopy identifies functional-group patterns. Pyrolysis-gas chromatography-mass spectrometry analyses products generated when organic material is heated, providing molecular markers. Santoiemma (2018) reviews the use of elemental analysis coupled with isotope-ratio mass spectrometry, Py-GC-MS and NMR in SOM research. These techniques are complementary and require careful sample preparation and interpretation.

Physical and density fractionation can separate free particulate material, aggregate-occluded material and mineral-associated fractions. Particle-size fractionation distinguishes material associated with sand-sized particles from that associated with silt and clay. The resulting fractions are operationally defined, so methods and cut-offs must be reported. Lavallee et al. (2020) recommend POM and MAOM as a useful framework for comparison, provided that protocols are consistent.

A doctoral study can adopt a tiered approach. Baseline measurements should include texture, pH, electrical conductivity, bulk density, total organic carbon, total nitrogen and available nutrients. A second tier can include POM and MAOM, aggregate stability and water-retention characteristics. A third tier may use FTIR, solid-state 13C NMR, Py-GC-MS, isotope measurements or mineralogical analyses where facilities permit. Sampling should use replicated plots, consistent depth intervals and documented seasons. SOC stocks should be calculated using bulk density, depth and coarse-fragment correction rather than concentration alone. Combining chemical analysis with physical and biological indicators reduces the risk of drawing resilience conclusions from incomplete evidence.

6. SOM CHEMISTRY AND SOIL PHYSICAL RESILIENCE

Soil structure links SOM with environmental resilience. Aggregates create pores that regulate infiltration, drainage, aeration and root penetration. Organic binding agents from roots and microorganisms promote aggregation, while fungal hyphae can enmesh particles. Stable aggregates reduce the susceptibility of soil to surface sealing and erosion. Loss of organic matter, excessive disturbance and compaction may weaken structure and increase runoff (Six et al., 2002).

SOM affects soil water relations through its influence on porosity, surface chemistry and aggregation. Improved structure can support water entry and drainage, while organic matter can contribute to water retention. Better infiltration may reduce runoff during intense rainfall;

stored soil water may buffer plants during short dry periods. However, the magnitude of these effects depends on texture, mineralogy, bulk density, organic matter distribution and climate. Sandy, clayey and swelling soils do not respond identically. SOM is therefore one component of a larger hydraulic system rather than a substitute for pore structure and landscape water management.

Jha et al. (2023) connect soil structure, hydraulic properties and organic carbon dynamics, showing why hydrological and carbon processes should be considered together. Aggregate formation and breakdown alter pore-size distribution and the transport of water, oxygen and solutes. These changes also influence microbial activity and decomposition. Soil structure is both an outcome of SOM dynamics and a control over future SOM persistence.

SOM can support resistance to wind and water erosion by promoting aggregation and surface cover. Residue retention, cover crops, reduced disturbance and perennial vegetation protect the surface from raindrop impact and wind shear. A review of cover-crop studies found improvements in aggregate stability and infiltration in many studied systems, although effects differed across measures and locations (Blanco-Canqui & Ruis, 2020). Physical resilience should be evaluated through wet aggregate stability, infiltration, bulk density, penetration resistance, water-retention curves and erosion risk. A rise in SOC does not automatically prove that all these functions have improved.

7. NUTRIENT CYCLING AND SOIL BIOLOGICAL FUNCTION

SOM stores and regulates essential plant nutrients. Organic nitrogen, phosphorus and sulphur are released through microbial decomposition and mineralisation. Microorganisms also immobilise nutrients temporarily in biomass, limiting immediate losses and releasing nutrients later through turnover. Organic compounds can retain nutrients through adsorption and complexation, while functional groups contribute to cation-exchange behaviour in many soils. These processes influence nutrient supply and the timing of release relative to plant demand.

Organic-input quality affects decomposition and nutrient availability. Readily decomposable residues may stimulate microbial activity, while structurally complex residues may decompose more slowly. Carbon-rich materials can temporarily immobilise nitrogen when microbial demand exceeds available supply. Nitrogen-rich amendments may accelerate decomposition and alter carbon retention. Therefore, residue selection and amendment application should be integrated with soil testing and nutrient management rather than judged by carbon content alone.

Bacteria, fungi, archaea, protozoa, nematodes, earthworms and arthropods participate in decomposition, nutrient transformation, pore formation and food-web interactions. Diverse plant inputs can supply a wider range of litter and root exudates. Mycorrhizal fungi influence plant nutrient acquisition and below-ground carbon allocation. Microbial communities may promote SOM formation, accelerate decomposition, or perform both roles under different conditions.

Soil biological resilience can be assessed through microbial biomass carbon and nitrogen, basal respiration, potentially mineralisable nitrogen, enzyme activity and community composition. Each indicator has limitations: enzyme activity responds to moisture and temperature, while community composition does not always predict process rates. A combination of chemical, physical and biological measurements is therefore preferable. The FAO-linked synthesis by Vargas-Rojas et al. (2019) recognises SOC as important for nutrient cycling, soil structure, water regulation, pollutant retention and biodiversity.

8. POLLUTION CONTROL, CLIMATE AND LAND DEGRADATION

SOM influences the mobility and bioavailability of pollutants. Functional groups can bind metals through complexation, ion exchange and surface reactions. Mineral-organic associations create sorption sites and can alter the mobility of metal(loid)s. However, dissolved organic matter may either immobilise contaminants or transport them as soluble complexes,

depending on its composition, pH, redox conditions and contaminant form. More organic matter does not therefore always mean lower pollution risk. Qiao et al. (2024) discuss the importance of humic matter-mineral interactions for the remediation of heavy metals and organic pollutants, while emphasising the complexity of these processes.

Organic matter also interacts with pesticides, hydrocarbons and other organic pollutants through hydrophobic partitioning, adsorption and microbial degradation. Retention may reduce immediate bioavailability but can also prolong persistence. Dissolved organic carbon may increase transport through soil water. Risk assessment must consider both immobilisation and mobility and should be specific to the pollutant and soil environment.

For climate adaptation, SOM supports structure, infiltration, water retention, nutrient supply and biological activity. These functions can buffer ecosystems during drought or rainfall extremes. For mitigation, soil carbon storage can remove carbon dioxide from the atmosphere, but storage is vulnerable to decomposition, erosion, drainage, fire, land-use change and disturbance. Net climate benefit also depends on nitrous oxide and methane fluxes, not SOC alone.

The 4 per mille initiative proposed an aspiration to increase soil carbon stocks by 0.4 percent annually as a contribution to climate action and food security. Minasny et al. (2017) reviewed its potential and limitations across regions. This rate is not a universal outcome achievable by all soils: initial carbon, depth, climate, mineral capacity, management duration and monitoring affect results. Don et al. (2024) caution that sequestration claims require clear definitions, credible baselines, additionality, permanence and attention to trade-offs. Restoration should therefore aim to recover multiple soil functions rather than reduce success to carbon accounting.

9. RELEVANCE TO SEMI-ARID AND SUB-HUMID INDIA

SOM management is especially important in semi-arid and sub-humid India, where high seasonal temperatures, irregular rainfall, dry periods and competition for crop residues can limit organic-matter accumulation. Residues may be used as livestock feed or domestic fuel rather than returned to fields. Decomposition can be rapid when moisture becomes available, while biomass inputs may remain low during drought. Farmyard manure availability also differs with livestock ownership, collection and competing uses.

Swarup's review of Indian semi-arid and sub-humid soils identifies temperature, precipitation, soil type, tillage, fertiliser practices, residue quality and residue management as interacting controls on SOM. It notes that residue use as fodder and fuel can constrain soil return and discusses farmyard manure, legumes and alternative land-use systems such as agroforestry as management options (Swarup, 2008). These strategies require local evaluation against current cropping patterns, livestock use, water availability and economic conditions.

The Indian soil resource is highly diverse. Alluvial, black, red, lateritic, desert and hill soils differ in texture, mineralogy, salinity, drainage and carbon-stabilisation capacity. Identical amendments or tillage practices cannot be expected to produce identical outcomes. In arid and semi-arid Rajasthan, SOM may be particularly relevant in areas exposed to wind erosion, water scarcity, high evaporative demand and variable monsoon rainfall. This review does not report measurements from Rajasthan or any particular district; it identifies a research setting where site-specific work would be valuable.

A field study could compare cultivated fields, crop-livestock systems, agroforestry, grasslands and restored sites. Sampling should consider soil class, slope, irrigation history, residue management and depth. Along with total SOC, POM and MAOM fractions could show whether a system is increasing fresh particulate inputs, mineral-associated carbon or both. Infiltration, aggregate stability, plant-available water and surface crusting would link chemistry to function. Seasonal sampling could identify monsoon-related changes in dissolved carbon and microbial activity. Research should also assess the feasibility of residue retention, compost use and cover

cropping for farmers; practices that are not economically or socially workable are unlikely to provide durable resilience.

10. MANAGEMENT STRATEGIES FOR SOM-BASED RESILIENCE

SOM management should increase appropriate organic inputs, reduce avoidable losses and maintain conditions that support stabilisation. No single practice is universally optimal; effectiveness depends on climate, crop system, soil texture, mineralogy, water and local livelihoods.

Residue retention increases carbon inputs and protects the surface, but residues may be needed for fodder or fuel. Local options include partial retention, composting surplus biomass, incorporating selected residues, improving fodder systems or using cover crops where water permits. Burning should be avoided where feasible because it removes organic inputs and may damage soil organisms and surface properties. Recommendations should still account for pest management, sowing windows, labour and machinery.

Farmyard manure, compost and other organic amendments supply carbon and nutrients. Their maturity, salinity, nutrient content, heavy-metal contamination and pathogen risks should be checked. Immature or contaminated material can create environmental problems. Application should follow crop demand and soil tests, not a target of maximising carbon inputs. Integration with balanced mineral fertiliser can improve nutrient synchronisation and crop biomass production.

Crop rotation, legumes, intercropping and agroforestry diversify below-ground inputs. Legumes can contribute biologically fixed nitrogen, while deep-rooted perennials may deliver carbon to deeper layers and improve soil cover. Agroforestry can be useful in suitable drylands, but tree density and water competition require careful planning. Cover crops and green manures reduce bare-soil periods, but their water requirements must be matched to rainfall and irrigation availability.

Reduced or conservation tillage may protect aggregates, but it does not automatically increase whole-profile SOC and cannot compensate for low biomass inputs or erosion. Grazing management is important in rangelands: suitable stocking rates, deferred grazing where feasible and perennial vegetation cover can reduce soil exposure. Biochar may be useful in selected contexts, but its behaviour depends on feedstock, production conditions, pH and soil properties; it is not a substitute for living vegetation and balanced soil management.

An integrated strategy combines soil cover, suitable organic inputs, living roots, vegetation diversity, reduced destructive disturbance, balanced nutrients and erosion control. Monitoring should include carbon stocks and fractions, soil structure, hydrology and biological function. Carbon-credit projects should avoid overstating permanence or assuming that a short-term increase in surface carbon will continue indefinitely (Don et al., 2024).

11. RESEARCH GAPS AND PROPOSED DOCTORAL FRAMEWORK

Several gaps remain. Many studies report bulk SOC without resolving the chemistry and function of its fractions. The relative contributions of plant-derived compounds and microbial residues vary among ecosystems and remain an active research question. The mineral-organic interface is dynamic, and the response of MAOM to warming, moisture change, pH and land management is not fully predictable. Deep SOM is also underrepresented in many long-term experiments, despite its contribution to total soil carbon storage (Sokol et al., 2022; Rocci et al., 2024).

Another gap is the connection between SOM chemistry and measurable resilience outcomes. Some studies report carbon accumulation without measuring infiltration, plant-available water, aggregate stability, nutrient retention or biological recovery. Physical restoration may also occur before large changes in total SOC can be detected. Research should therefore integrate chemical indicators with hydrological, physical and biological measurements and assess both disturbance and recovery.

A doctoral framework aligned with the approved research theme can be organised around five components: (1) quantity and chemical quality of organic inputs; (2) microbial transformation and necromass formation; (3) mineral association and aggregate protection; (4) environmental controls, including temperature, moisture, pH, texture and mineralogy; and (5) resilience outcomes, including water regulation, structure, nutrient cycling, biological activity and carbon persistence. This model connects molecular processes with field-level environmental functions.

Possible research questions include: How do SOM fractions and functional-group characteristics differ among land uses? How do texture and mineralogy regulate MAOM formation? How responsive is POM to changes in residue management? Do SOC fractions explain aggregate stability and water retention beyond total SOC concentration? How do seasonal moisture changes affect microbial activity and dissolved organic carbon? Which combinations of residue management, organic amendments and vegetation diversification improve soil functions under local climatic conditions?

A defensible design would use replicated sites across relevant land-use types and soil classes, consistent depth intervals and seasonal observations. Core measurements could include organic carbon, total nitrogen, pH, electrical conductivity, texture, bulk density, POM, MAOM, aggregate stability and water-retention properties. FTIR or solid-state 13C NMR could be used on selected representative samples where facilities permit. Microbial biomass and enzyme activities would provide biological evidence. Statistical analysis should control for depth, texture, land use and climate, and should distinguish association from causation. Long-term monitoring or repeated measurements are preferable to inferring temporal change from a single spatial survey.

Quality assurance is essential: field duplicates, laboratory reference materials, calibration, documented storage and transparent reporting of detection limits should be used. Carbon stocks should be calculated with bulk density and, where relevant, equivalent soil mass. The study should report limitations and avoid claiming that a management practice caused a change unless the research design supports causal inference. This framework can explain not only whether SOM is higher under a land use, but also which mechanisms are associated with improved resilience.

12. DISCUSSION

The reviewed literature supports the proposition that SOM chemistry affects environmental resilience through interactions among organic molecules, microorganisms, minerals, water and soil structure. Organic-input quality determines available substrates; microbial activity transforms them; mineral surfaces and aggregates influence their accessibility and persistence; and environmental conditions regulate each stage. Soil carbon storage is therefore the outcome of interacting processes rather than one dominant chemical property.

This explains why management results differ. Organic amendments increase inputs, but persistent storage depends on decomposition and protection capacity. Reduced tillage may preserve aggregates, but cannot compensate for severe erosion or inadequate biomass. Mineral-rich soils may stabilise more organic matter than coarse soils under comparable conditions, but mineral capacity is finite and MAOM is not immune to global change. Total SOC can be an important indicator, but its distribution may be equally important for particular functions.

Resilience should not be evaluated through carbon sequestration alone. A restoration project should monitor carbon stocks and fractions, structure, infiltration, plant-available water, nutrient retention, microbial functioning, erosion and pollutant behaviour. Greenhouse-gas trade-offs should also be considered. The current evidence cautions against describing all persistent matter as chemically recalcitrant: molecular structure matters, but persistence often results from environmental protection and biological context (Schmidt et al., 2011; Lehmann

& Kleber, 2015). Management should therefore support continuous biological inputs and favourable soil conditions rather than simply add materials presumed to be permanent.

13. CONCLUSION

SOM is a chemically diverse and dynamic component of terrestrial environments. Its contribution to resilience arises from its capacity to connect biological production, mineral interactions and soil physical processes. Its constituents influence decomposition, nutrient transformations, sorption and mineral association, but persistence cannot be explained by molecular complexity alone. It emerges from microbial processing, mineral surfaces, physical inaccessibility, environmental conditions and the nature of organic inputs.

The POM-MAOM framework helps distinguish responsive particulate material from mineral-associated organic matter while recognising that both are diverse and dynamic. SOM supports aggregation, infiltration, water regulation, nutrient cycling, biodiversity and pollutant interactions. It can aid climate adaptation through improved soil functions and contribute to mitigation through carbon storage, provided permanence and greenhouse-gas trade-offs are assessed.

For semi-arid and sub-humid India, management must account for high temperatures, variable rainfall, residue competition, soil diversity and local livelihoods. A doctoral study should integrate chemical characterisation, fractionation, mineral and aggregate analysis, biological indicators and hydrological measurements across soils and land uses. Connecting SOM chemistry with measurable environmental outcomes can provide a stronger scientific basis for resilient soil management than carbon accumulation alone.

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