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Soil Organic Matter Dynamics and Soil Health: A Critical Synthesis of Formation, Persistence, Function and Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Soil organic matter (SOM) is central to soil functioning, yet its significance cannot be inferred reliably from bulk carbon concentration alone. The processes that generate, transform, redistribute and protect organic compounds operate across interacting biological, mineralogical, hydrological and management gradients. This critical narrative review evaluates how contemporary understanding of particulate organic matter, mineral-associated organic matter and microbial transformation changes interpretations of soil health and agricultural carbon management. Peer-reviewed experimental studies, long-term field investigations, meta-analyses and conceptual papers were selected through topic-specific scholarly searching and citation tracing, with particular attention to contrasting results and measurement limitations. Evidence supports substantial roles for organic matter in aggregation, nutrient cycling, biological habitat and, in particular settings, hydrological regulation. The magnitude and direction of these functions nevertheless depend on soil texture, mineralogy, climate, depth and the composition and spatial distribution of carbon pools. Microbial-derived material contributes importantly to mineral-associated organic matter, but mineral association is neither a guarantee of permanence nor a direct measure of biological usefulness. Meta-analyses indicate that cover crops and organic amendments can increase soil carbon, while benefits differ among fractions, soil layers and management histories. The assumption that no-tillage necessarily sequesters carbon is weakened when whole-profile stocks and equivalent soil mass are considered. Likewise, observed carbon–yield and carbon–water relationships should not be interpreted as invariant causal responses. The review argues for a function-oriented framework that assesses organic carbon stocks alongside accessibility, turnover, aggregation, nutrient supply and context-specific biological indicators. Its priorities include long-term depth-resolved experiments, transparent fractionation, source tracing, whole-system greenhouse-gas accounting and locally calibrated soil-health benchmarks. SOM management is most defensible when it seeks multiple measurable soil functions rather than treating a single carbon indicator as a universal proxy for resilience or climate benefit.

Keywords: *Particulate organic matter; mineral-associated organic carbon; microbial necromass; soil aggregation; carbon sequestration; rhizosphere processes; soil quality assessment; sustainable land management.*

1. Introduction

Soil organic matter (SOM) is simultaneously a reservoir of carbon and nutrients, a substrate for soil biota, and a structural component of the terrestrial environment. It emerges from the continuous exchange of plant, animal and microbial materials with minerals, water and the atmosphere. Its centrality to soil health is therefore both obvious and surprisingly difficult to quantify. A management practice may increase measured surface soil carbon without increasing whole-profile stocks, improve aggregation without producing a comparable change in available water, or accumulate carbon in protected forms while leaving short-term nutrient release relatively unchanged. These are not minor qualifications to a general beneficial effect. They expose the inadequacy of a single numerical interpretation of SOM as a universal measure of soil functioning (Bünemann *et al.*, 2018; Lehmann *et al.*, 2020; Minasny & McBratney, 2018). A recent agricultural field study reported associations between particulate and mineral-associated organic carbon and soil-health scores, although these observational relationships do not establish causation (Lane *et al.*, 2026).

The historical conception of humified organic matter as a collection of chemically recalcitrant substances has given way to a more dynamic description of organic compounds whose persistence depends heavily on their environment. Physical separation, mineral interactions, accessibility to decomposers, microbial growth and turnover, and soil structural organisation may be at least as important as intrinsic molecular composition. Schmidt *et al.* (2011) made the influential argument that persistence is an ecosystem property, challenging explanations that privilege molecular resistance alone. The subsequent particulate–mineral-associated framework has improved comparative analysis because the two broad fractions often have different origins, average turnover, management responsiveness and functional roles. Even that distinction is operational rather than absolute and should not be mistaken for two homogeneous pools (Lavallee *et al.*, 2020; Witzgall *et al.*, 2021). Experimental evidence also indicates that litter quality interacts with microbial communities and mineralogy, complicating simple predictions of mineral-associated carbon formation (Elias *et al.*, 2024).

These conceptual revisions matter for practical decisions. Soil-health assessment commonly seeks indicators that can be measured cheaply and translated into management advice, whereas climate accounting requires stocks, baselines, time horizons and credible additionality. The same carbon increment may have different significance for soil fertility, erosion resistance, microbial energy supply and atmospheric mitigation. Soil carbon is also distributed vertically and laterally, and mineral soil inventories can conceal losses from particular layers or transfers between fractions. Disagreement about the benefits of reduced tillage illustrates how different sampling depths and reference masses can reverse the apparent direction of an effect (Baker *et al.*, 2007; Don *et al.*, 2024; Wendt & Hauser, 2013). Global estimates of particulate and mineral-associated carbon turnover further illustrate why fraction identity and soil depth matter when interpreting soil carbon dynamics (Zhou *et al.*, 2024).

Interest in SOM has intensified because agricultural landscapes face erosion, nutrient depletion, climatic extremes and pressures to lower greenhouse-gas emissions. Long-term cultivation and land conversion have redistributed substantial amounts of soil carbon, although reconstructed global losses are model dependent rather than direct inventories of a uniform historical process (Guo & Gifford, 2002; Sanderman *et al.*, 2017). Restoration strategies therefore frequently aim to increase organic inputs, keep living roots in the soil, reduce disruptive operations or apply organic amendments. Meta-analyses generally find positive average carbon responses to cover cropping and amendments, yet effect estimates vary with duration, depth, texture, climate and comparison treatment (Jian *et al.*, 2020; Kelly *et al.*, 2026; Poeplau & Don, 2015). Experimental work in agricultural soils additionally suggests that both existing mineral-associated carbon and the estimated saturation deficit can influence the formation of new mineral-associated carbon (King & Sokol, 2025).

The ecological interpretation is equally nuanced. Stable aggregates may protect organic substrates, while their formation can itself depend on roots, fungal networks and organic binding agents. Soil fauna and microorganisms both derive resources from organic inputs and transform them into new residues that become part of the SOM continuum. Soil fertility can consequently depend on decomposition as well as persistence: maximising a stable carbon pool may not maximise nutrient availability or biologically mediated suppression of stress. The diversity–multifunctionality relationship found in experimental research indicates why soil health cannot be reduced to carbon storage, even when carbon availability supports biological activity (Bender *et al.*, 2016; Tisdall & Oades, 1982; Wagg *et al.*, 2014).

Several influential reviews have addressed soil health concepts, SOM persistence, fraction-based interpretation or particular management practices. Their contributions are substantial but occupy different explanatory scales: some advance carbon-cycle mechanisms, some evaluate single functions, and others aggregate management outcomes. Recent evidence complicates the conventional association of mineral-bound carbon with uniformly slow turnover, while new meta-analyses resolve distinct particulate and mineral-associated responses to amendments and management (Jilling *et al.*, 2025; Kelly *et al.*, 2026; Zhou *et al.*, 2026). Integrating these lines of evidence requires attention not merely to whether soil carbon changes, but to which fraction changes, where it occurs, which functions are affected and what claims the measurements can sustain.

1.1 Scope, Research Gap and Objectives

This review examines mineral agricultural soils and relevant ecological studies needed to explain SOM dynamics, with attention to arable and managed grassland systems and transferable evidence from natural soils. It covers biological input and decomposition pathways, physicochemical persistence, vertical and spatial distribution, soil-health functions, management effects and the reliability of indicators used for monitoring. Organic soils and peatland drainage are not treated as a separate management literature because their dominant carbon and hydrological processes require different analytical boundaries. The review also distinguishes improvement in soil function from net atmospheric carbon removal, which demands additional counterfactual and whole-system evidence.

The unresolved gap is the weak integration between fraction-resolved carbon science, soil-health outcomes and the practical inference of management benefit. The objectives are to distinguish competing mechanisms of SOM formation and persistence; evaluate evidence linking SOM to physical, chemical and biological functioning; explain why management studies yield divergent results; identify measurement and causal-inference weaknesses; and propose a defensible route from mechanistic understanding to context-specific assessment. The intended contribution is a critical, function-oriented synthesis rather than a catalogue of practices or a universal prescription for maximising soil carbon.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative design was adopted because the central questions span mechanisms, field management, soil physics, soil biology and measurement theory. Their study designs and outcome definitions differ too widely to support one meaningful pooled effect estimate. The purpose was therefore to interrogate explanatory coherence, apparent contradictions and the conditions under which findings can be transferred across soil types. Transparent citation selection and evidence appraisal were used without describing the exercise as a systematic review. The SANRA framework informed attention to the importance of the review question, the suitability of literature coverage, scientific reasoning and the distinction between evidence and interpretation; it was not used to create unsupported numerical quality scores (Baethge *et al.*, 2019).

2.2 Information Sources

Searches consulted accessible records in PubMed, AGRIS, DOAJ and OpenAIRE, together with scholarly article records retrieved through Google Scholar and Semantic Scholar discovery, DOI-indexed bibliographic records and backward citation tracing from seminal reviews and recent meta-analyses. Journal full texts or abstracts and DOI landing pages were examined where accessible to check bibliographic identity and the relevance of findings. Source selection privileged peer-reviewed primary research and transparent meta-analyses while retaining influential conceptual publications necessary to explain changes in interpretation. Journal and publisher pages served to verify individual articles, rather than being represented as separate literature databases.

2.3 Search Strategy and Search Period

The principal search period was 1 January 2000 to 2 September 2026. Earlier foundational studies were eligible when they introduced mechanisms or stock-comparison methods still relevant to current evidence. Representative combinations included ('soil organic matter' OR 'soil organic carbon') AND ('soil health' OR 'soil quality' OR fertility OR aggregation OR 'water retention'); ('particulate organic matter' OR 'mineral-associated organic matter' OR 'microbial necromass') AND (formation OR persistence OR turnover); and ('cover crop' OR no-till OR manure OR biochar OR 'organic amendment') AND ('carbon stock' OR sequestration OR soil function). Additional concept searches addressed temperature sensitivity, priming, soil depth, equivalent soil mass, mineral sorption, carbon saturation, microbial carbon use efficiency and greenhouse-gas trade-offs. Search language and combinations were adapted to source indexing rather than presumed to behave identically across discovery interfaces.

2.4 Eligibility Criteria

Eligible material comprised peer-reviewed experimental, observational, long-term field, isotope-tracing and modelling studies, well-documented meta-analyses and major theoretical syntheses with a direct bearing on the stated questions. Preference was given to evidence that identified soils, management comparisons, analytical fractions, sampling layers or measurement conditions. Papers concerning soil health without an interpretable SOM mechanism, purely promotional claims, insufficiently identified records and unreviewed preprints were not treated as evidential anchors. The synthesis was limited to English-language scholarly material accessible for credible appraisal, but geographical setting was not an exclusion criterion. Historical foundational studies were included selectively even when published before 2000.

2.5 Screening, Duplicate Handling and Study Selection

Records were considered first for topical relevance and then for the contribution of their methods and results to a defined review question. When the same article appeared through more than one scholarly source, title, author, year and DOI were used to recognise the duplicate citation. Abstracts and available full texts were checked for the direction and limits of the reported evidence, particularly where summaries made broad claims from surface samples or context-specific trials. Bibliographic records with unresolved authorship, mismatched DOI identities or inadequate information for interpreting a claimed result were not used. Because no exhaustive, documented screening census was undertaken, no search-yield, exclusion or inclusion counts are asserted.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was compared by experimental control, replication, timescale, sampling depth, stock calculation, fractionation procedure, treatment contrast, environmental heterogeneity and potential confounding. Longitudinal experiments and replicated manipulations were considered more informative for causal interpretation than unadjusted cross-site correlations, but observational gradients retained value for revealing broad geographical constraints. Meta-analyses were assessed in relation to their inclusion rules, heterogeneity and outcome definitions rather than regarded as automatically conclusive. Contradictions were organised around scale, carbon pool, soil environment and counterfactual comparison; confidence statements represent a qualitative interpretation, not an invented quantitative risk-of-bias rating.

3. Defining the Organic-Matter Continuum and Its Functional Pools

3.1 From Bulk Organic Carbon to Operational Fractions

SOM refers to a complex and continuously changing assemblage of organic substances in soil, including plant residues, microbial cells and products, faunal materials and compounds associated with minerals. Soil organic carbon (SOC) is its carbon component; the two terms are not interchangeable in quantitative reporting because conversion between them assumes a carbon fraction that varies among materials and settings. Bulk SOC is valuable for stock accounting and long-term monitoring, but it does not disclose the accessibility, chemistry, origin or likely residence time of the material measured. A single stock can therefore coexist with very different biological activity, aggregate architecture and nutrient dynamics (Bünemann *et al.*, 2018; Lavallee *et al.*, 2020).

Much contemporary interpretation separates particulate organic matter (POM) from mineral-associated organic matter (MAOM). The former typically includes relatively coarse or low-density fragments of plant and microbial origin; the latter comprises organic compounds co-isolated with fine mineral material by operational fractionation. Exact size and density cut-offs depend on laboratory protocols, which means apparent differences among studies may partly reflect analytical definitions. The fractions should be understood as broad continua rather than discrete chemical species. This improves conceptual clarity without claiming that every particle can be placed unambiguously into a fixed functional category (Lavallee *et al.*, 2020; Sokol *et al.*, 2019).

POM is often sensitive to recent plant inputs and disturbances, making it useful for interpreting management-responsive carbon cycling. Its coarse material can supply microbial energy, influence physical architecture and be occluded within aggregates. It is not necessarily short-lived: mineral surroundings, aggregate location, oxygen supply and the spatial segregation of decomposers can permit persistence that challenges simplistic labels of 'labile' POM. Direct investigation of particulate carbon has highlighted contributions to persistent SOC that cannot be inferred from a two-pool model equating coarse material with rapid loss (Six *et al.*, 2002; Witzgall *et al.*, 2021).

MAOM is frequently enriched in microbial transformation products and compounds interacting with mineral surfaces. Its average turnover can be slower than that of freely exposed plant fragments, but such averages conceal mixtures with different exchange rates and binding mechanisms. Recently described fast-cycling mineral-associated components are particularly relevant to soil-health assessment: molecules can be associated with fine mineral material yet remain available for exchange and microbial processing. Consequently, a greater MAOM proportion is not, by itself, proof of permanent sequestration or a direct measure of improved function (Jilling *et al.*, 2025; Schmidt *et al.*, 2011).

Dissolved organic matter, microbial biomass and organic matter within aggregates represent additional components of the continuum. Dissolved compounds can move through pores and contribute to sorption or leaching; microbial biomass is a small, rapidly responsive pool that regulates transformations disproportionately to its mass; and occlusion creates a spatial rather than purely chemical form of protection. These components connect plant production and microbial metabolism to mineral pools, while also complicating attempts to isolate 'active' and 'stable' carbon through one measurement. Thus, measurable pools overlap

conceptually and differ in analytical recovery, residence time and relevance to a given soil function (Cotrufo *et al.*, 2013; Kallenbach *et al.*, 2016; Kuzyakov, 2010).

3.2 Pool Definitions and Their Interpretive Limits

The distinction between quantity and function is essential. A fraction with a large stock may change slowly in response to management but still participate in nutrient buffering, whereas a smaller input-responsive fraction can disproportionately support microbial growth and aggregate turnover. The same chemical compounds may pass repeatedly between dissolved, microbial, particulate and mineral-associated forms. Their fate depends on where and when transformations occur and whether the products encounter reactive mineral surfaces. Conceptually, SOM is better regarded as a connected network of transformations than as a ladder terminating in inert humus (Cotrufo *et al.*, 2013; Liang *et al.*, 2017; Schmidt *et al.*, 2011).

Operational classifications are useful when matched to an explicit question. Physical fractionation can test whether an amendment mainly stimulates recently derived particles or finer associated material; oxidation-based assays can evaluate sensitivity to disturbance; and whole-soil combustion can quantify total carbon under a consistent analytical definition. None provides an independently complete account of age, ecosystem service or vulnerability. Evidence remains strongest when multiple indicators are combined and when their analytical meaning is reported rather than presumed to be universal (Culman *et al.*, 2012; Lavallee *et al.*, 2020; Witzgall *et al.*, 2021).

Table 1 summarises these distinctions and the interpretation errors that arise when operational pools are treated as fixed ecological states. The critical implication is that an indicator should be chosen in relation to the function or mechanism under investigation, rather than promoted as a universal substitute for total soil health.

Table 1. Operational soil organic matter pools: meaning, use and limitations

Pool or indicator	Operational interpretation	Most useful inference	Principal interpretive limitation	Supporting references
Total SOM/SOC	SOM includes organic constituents; SOC denotes their carbon, measured by a defined analytical method.	Bulk stock inventory; monitoring across consistent soil masses.	Stock does not identify carbon age, nutrient supply or function; SOM-to-SOC factors vary.	Bünemann *et al.* (2018); Lavallee *et al.* (2020)
Particulate organic matter (POM)	Relatively coarse or low-density material after specified size/density separation.	Input responsiveness, aggregate-associated substrates and potential energy supply.	Some POM persists; fraction depends on separation protocol.	Six *et al.* (2002); Witzgall *et al.* (2021)
Mineral-associated organic matter (MAOM)	Organic material co-isolated with fine or dense mineral fractions.	Mineral interaction and longer average persistence in many contexts.	Includes rapidly cycling components; mineral association is not permanence.	Jilling *et al.* (2025); Lavallee *et al.* (2020)
Microbial biomass and necromass	Living microbial carbon versus residues from microbial growth and turnover.	Biological transformation and microbial contributions to SOM formation.	Markers are indirect; production cannot be equated to long-term retention.	Kallenbach *et al.* (2016); Liang *et al.* (2019)
Permanganate-oxidisable carbon	Carbon oxidised in a standardised chemical assay.	Relatively responsive management indicator.	Not a direct residence-time or mineralisation measurement.	Culman *et al.* (2012)
Dissolved and aggregate-occluded material	Mobile solutes and spatially protected material, respectively.	Transport, sorption, accessibility and physical protection.	Dynamic pools overlap with POM and MAOM; extraction can alter associations.	Cotrufo *et al.* (2013); Kuzyakov (2010)

Note. SOM = soil organic matter; SOC = soil organic carbon; POM = particulate organic matter; MAOM = mineral-associated organic matter. Fractions are operational rather than universal chemical classes

4. How Soil Organic Matter Forms, Turns Over and Persists

4.1 Carbon Inputs and the Microbial Transformation Pathway

Organic matter formation begins with above- and below-ground carbon inputs, but the fate of new material depends as much on its point of entry as on its initial composition. Surface litter is subject to the microclimate, fauna and decomposer assemblages near the soil boundary. Root exudates, sloughed cells and dead fine roots enter within an active rhizosphere, often close to aggregation processes and reactive mineral surfaces. The relative importance of these channels differs across vegetation, depth and soil structure. Source-tracing work suggests that plant carbon entering through roots can have distinct opportunities to form mineral-associated organic matter, making input location a mechanistic variable rather than a minor agronomic detail (Sokol *et al.*, 2019).

The microbial efficiency–matrix stabilisation framework redirected attention from selectively preserving chemically resistant plant compounds to the transformation of substrates by microorganisms. Under this interpretation, microbial products can be stabilised through proximity to mineral surfaces, while plant-derived material may also persist by other mechanisms. The central insight is not

that microbial origins guarantee permanence, but that microbial processing and physicochemical context jointly govern the pathways linking inputs to stored carbon (Cotrufo *et al.*, 2013). Laboratory work demonstrating the production of microbial-derived organic matter under controlled ecological conditions supports this pathway more directly than simple chemical fingerprints, although laboratory incubations do not fully reproduce field-scale movement and disturbance (Kallenbach *et al.*, 2016).

Microbial carbon use efficiency influences how assimilated carbon is allocated between growth and respiration. Greater growth allocation can generate more microbial residues, but it does not necessarily maximise lasting carbon storage because subsequent residue decomposition and mineral association remain decisive. Arguments that a favourable efficiency ratio automatically generates additional MAOM therefore overstate a conditional mechanism. Microbial community composition, nutrient stoichiometry, substrate availability and moisture may all change the balance between new residue formation and loss. Recent work on anabolic controls and necromass has strengthened the plausibility of microbial contributions while maintaining uncertainty about their long-term persistence across heterogeneous soils (Liang *et al.*, 2017, 2019).

4.2 Mineral Interactions, Aggregation and Saturation

Mineral association is shaped by surface area, charge, iron and aluminium phases, calcium-mediated bridging and the arrangement of minerals within pore networks. Fine fractions can protect organic molecules by limiting enzymatic access or by changing the energy needed for desorption. Yet texture is at best an incomplete proxy for these processes; two soils with comparable clay content may have very different mineralogy and environmental histories. Evidence for soil-dependent preservation capacity emerged from studies of carbon and nitrogen associations with clay and silt and later developed into saturation concepts that connect finite reactive surfaces with changing response to additional carbon inputs (Hassink, 1997; Six *et al.*, 2002).

Carbon saturation should not be interpreted as a universal fixed ceiling. Estimated deficits relative to empirical mineral-associated capacities can help identify potentially responsive soils, but estimates depend on the minerals, sampling domain, observed reference range and definition of the associated fraction. Global mapping of mineral-associated carbon capacity highlights broad geographical constraints and potential, not guaranteed field-scale additions from a prescribed practice. It would be particularly misleading to turn a mapped 'capacity gap' into a forecast without accounting for roots, microbial processing, nutrient limitation, moisture and the timescale of management change (Georgiou *et al.*, 2022).

Physical protection overlaps with chemical and mineral mechanisms. Roots and microbial products can help bind smaller particles into aggregates, whose internal spaces may restrict decomposer access. Disruption by tillage or wetting–drying can change this access, but an aggregate does not create permanent isolation: cracks, pores and faunal activity continue to connect substrates to organisms. Aggregate turnover can simultaneously protect some residues and expose others. Foundational aggregate-based explanations remain important precisely because they place organic matter within a changing physical architecture rather than within an isolated chemical category (Six *et al.*, 2002; Tisdall & Oades, 1982).

4.3 Decomposition, Priming and Time Dependence

A carbon input can stimulate microbial decomposition of existing SOM, a phenomenon described as priming. The direction and magnitude of priming depend on nutrient supply, microbial demand, substrate composition and environmental conditions. Positive priming may partially offset new carbon additions; negative priming may occur where new substrates reduce decomposition of existing material or change resource allocation. Short incubations can demonstrate a mechanism but not establish the net field-scale stock outcome. Treating all fresh inputs as cumulative carbon gains ignores the possibility that new carbon and older carbon follow different, simultaneous trajectories (Kuzyakov, 2010).

Temperature and moisture regulate decomposition through microbial physiology, substrate movement and physical accessibility. Warming can increase decomposition where temperature is limiting but can interact with drying, nutrient constraints and vegetation changes. The long-term warming experiment reported by Melillo *et al.* (2017) documented a dynamic temporal pattern in soil carbon responses that is not captured by constant-rate assumptions. Theoretical and empirical work on temperature sensitivity likewise warns against treating a single incubation-derived response as a fixed feedback under future climates. Management-induced additions must be evaluated against the environmental conditions that determine their persistence (Davidson & Janssens, 2006; Melillo *et al.*, 2017).

Emerging studies further challenge a division in which POM is necessarily ephemeral and MAOM effectively inert. A decade-long grassland experiment tracing labelled litter and pyrogenic inputs found distinct persistence trajectories that depended on source and pool (Leuthold *et al.*, 2025). Meanwhile, synthesis of rapidly cycling mineral-associated material demonstrates that physical association can coexist with biologically meaningful turnover (Jilling *et al.*, 2025). These findings are not inconsistent with mineral protection as an average tendency. They show instead that particle class, residence time and ecological function answer different questions and cannot be collapsed into a single stability ranking.

4.4 An Integrated Interpretation of Persistence

A credible explanation of persistence must accommodate chemical accessibility, microbial demand, pore connectivity, mineral reactivity and environmental disturbance. It must also specify the duration over which a claim is made. Material remaining after an incubation is not necessarily stable over decades; material detected within a fine fraction is not necessarily isolated from living processes; and a stable bulk stock can conceal rapid replacement of its constituent molecules. Such distinctions reconcile much of

the apparent conflict between traditional decomposition frameworks and contemporary molecular or isotope evidence (Haddix *et al.*, 2020; Jilling *et al.*, 2025; Schmidt *et al.*, 2011).

The practical consequence is that carbon accumulation is a balance of inputs and multiple losses, not an intrinsic property of an amendment. The evidence in Table 2 connects formation and loss mechanisms with their observable signatures and principal uncertainties. No single pathway is sufficient across the mineralogical, biological and climatic range covered by the literature.

Table 2. Mechanisms governing the formation and persistence of soil organic matter

Mechanism	Supported process	Key condition or contradiction	Supporting references
Root and litter input pathways	Point of carbon entry affects substrate–microbe–mineral contact.	Input placement, rooting depth and plant production constrain outcomes.	Balesdent *et al.* (2018); Sokol *et al.* (2019)
Microbial transformation	Growth and turnover produce residues that may enter associated pools.	Microbial production does not guarantee persistence of the residues.	Cotrufo *et al.* (2013); Kallenbach *et al.* (2016); Liang *et al.* (2019)
Mineral association	Sorption and co-association reduce accessibility in many contexts.	Reactive mineralogy matters; associated material can also cycle quickly.	Georgiou *et al.* (2022); Hassink (1997); Jilling *et al.* (2025)
Aggregation and occlusion	Aggregate architecture alters contact between substrates and decomposers.	Protection varies with wetting, disturbance and aggregate renewal.	Six *et al.* (2002); Tisdall & Oades (1982)
Carbon saturation	Existing mineral-associated stocks can constrain additional retention.	Capacity is context-dependent, not a universal attainable ceiling.	Georgiou *et al.* (2022); Six *et al.* (2002)
Priming and decomposition	New carbon can accelerate or suppress decomposition of older material.	Incubation results may not equal net long-term field stock changes.	Kuzyakov (2010)
Environmental change	Temperature and moisture affect input, access and decomposition processes.	Long-term responses can vary temporally; no fixed universal feedback.	Davidson & Janssens (2006); Melillo *et al.* (2017)

Note. Mechanisms interact; a treatment may activate several processes simultaneously

5. Contributions to Soil Health: Functions, Dependencies and Trade-offs

5.1 Soil Structure, Infiltration and Erosion Resistance

SOM is closely connected with soil aggregation, but the mechanism is more intricate than a simple 'organic glue' model. Roots exert mechanical effects, fungal hyphae traverse particle boundaries, microbial exudates contribute binding substances, and partially decomposed residues provide nuclei for aggregate development. Depending on texture and mineralogy, these interactions can affect aggregate stability, pore continuity, surface sealing and erosion resistance. Classical work described the association between organic matter and water-stable aggregates, and later mechanistic analyses emphasised multiple scales of protection and disruption (Six *et al.*, 2002; Tisdall & Oades, 1982). The agronomic implication is that a carbon input may alter structural properties before a large change becomes detectable in whole-soil SOC.

Observed associations nevertheless cannot be assumed to indicate that carbon concentration alone caused better structure. Well-managed soils may have more roots, less compaction, higher biological activity and improved pore networks simultaneously. Each of these conditions can contribute to aggregation and water movement. Conversely, a carbon-rich surface layer can coexist with a compacted subsoil, erosion-prone landscape position or poorly drained horizon. Trials that report only aggregate stability at one depth cannot establish the performance of the full rooting zone, particularly where tillage has redistributed carbon or where machinery traffic creates mechanical constraints. The strongest inference comes from factorial comparisons that measure physical outcomes alongside carbon fractions and root activity over time.

There is also a functional tension between carbon persistence and nutrient release. Physical occlusion can protect organic substrates from microbial access, potentially retaining carbon while slowing turnover. Greater aggregate stability is not equivalent to a larger permanent stock, because binding agents may be renewed continuously and aggregate breakdown is part of normal soil dynamics. Soil health requires functioning pores and biotic exchange rather than complete protection from decomposition. Consequently, recommendations framed as 'maximum stabilisation' may conflict with those intended to maintain nutrient cycling and productive microbial processes (Lehmann *et al.*, 2020; Witzgall *et al.*, 2021).

5.2 Soil Water Relations and the Problem of Universal Claims

Organic matter may influence water retention through its own sorption properties and through indirect changes in porosity, bulk density and aggregation. Its contribution is often considered especially relevant in sandy or structurally degraded soils, yet both its direction and magnitude vary with texture and the moisture range being evaluated. Rawls *et al.* (2003) found that SOC–retention relationships depended jointly on soil properties rather than supporting a texture-independent rule. Equally important, water retained at a given matric potential does not necessarily represent additional plant-available water if retention at wilting conditions also increases. Plant access further depends on root growth, soil depth, hydraulic conductivity and atmospheric demand.

A broader synthesis by Minasny and McBratney (2018) concluded that the average effect of increasing organic carbon on available water capacity is limited. This does not mean organic matter is irrelevant to drought resilience. Management can improve infiltration, reduce crusting and support roots without generating a proportionate increase in the difference between field capacity and wilting point. The disagreement between broad claims of dramatic water storage gains and modest meta-analytical effects reflects different hydrological outcomes, units and soils being compared. It is more defensible to specify whether the outcome is infiltration rate, water retention, extractable water, rooting depth or crop water stress than to describe them all as 'water-holding capacity'.

Management experiments often combine residue retention, cover crops or manure with changes in soil surface protection and biological structure. These treatments influence evaporation and runoff as well as water retention. A mulched soil may conserve water by reducing evaporation even where laboratory water-release curves have changed little. Similarly, increased surface infiltration might not yield higher plant-available water if restrictive layers or poor drainage dominate the profile. Measurements taken immediately after amendment addition can misrepresent long-term behaviour because decomposition changes material volume and pore organisation. Thus the hydrological contribution of SOM is conditional, functional and best evaluated with field water balance rather than carbon concentration alone (Bünemann *et al.*, 2018; Minasny & McBratney, 2018; Rawls *et al.*, 2003).

5.3 Nutrient Cycling, Chemical Buffering and Fertility

Organic matter stores nitrogen, phosphorus, sulphur and other nutrients in forms that become available through mineralisation or microbial turnover. It also contributes to cation exchange and chemical buffering in many soils. These properties matter for long-term fertility, but the nutrients in an increased carbon stock are not necessarily accessible at the rate crops need them. High-carbon residues can cause short-term nitrogen immobilisation, whereas nutrient-rich amendments can release nitrogen rapidly and introduce risks of loss. Soil health therefore depends on the timing and synchrony of mineralisation with plant demand as much as on the amount of organic material present (Cotrufo *et al.*, 2013; Lehmann *et al.*, 2020).

Microbial processing links these opposing effects. An amendment can stimulate growth and temporarily immobilise mineral nutrients while generating microbial residues that later contribute to associated carbon. The same transformation may improve long-term nutrient retention but depress short-term availability if the nutrient balance is unfavourable. Interpretation should therefore incorporate the carbon-to-nutrient composition of inputs, existing nutrient constraints and the management of mineral fertiliser. A comparison against an unfertilised control can produce a large yield or carbon response that does not isolate the unique benefits of organic matter, whereas a nutrient-balanced comparison asks whether the physical and biological properties of the carbon input confer additional value (Kelly *et al.*, 2026; Zhou *et al.*, 2026).

Organic compounds may also complex metals or influence contaminant mobility. This is sometimes presented as an unqualified remediation service, yet the direction of effect depends on compound properties, soil pH, redox conditions and the contaminant involved. Complexation can reduce bioavailability by sorption, but mobile dissolved organic compounds can facilitate transport under some circumstances. It is therefore unsafe to equate greater SOM with universally lower contaminant exposure. Metal bioavailability is operationally defined and influenced by multiple soil properties, making site-specific chemical assessment indispensable (Kim *et al.*, 2015). Carbon management cannot substitute for a contaminant-risk evaluation where legacy pollution is present.

5.4 Biological Activity, Diversity and Multifunctionality

SOM supplies energy and habitat for organisms that decompose residues, transform nutrients and interact with plants. Its composition and spatial arrangement influence the microbial and faunal communities that use it. Soil biodiversity, however, is not governed by carbon supply alone. pH, water availability, cultivation intensity, pesticide exposure, crop diversity and habitat continuity all affect community composition. Experimental research indicates that soil-community diversity and composition can influence multiple ecosystem functions, but not every community change is causally attributable to SOC concentration (Wagg *et al.*, 2014). Biological indicators should be interpreted as functional measurements, not automatically as proxies for carbon accumulation.

Microbial necromass is particularly revealing because living communities generate organic residues that can accumulate in soil. Estimates of substantial microbial contributions to SOM emphasise this transformation pathway, but the magnitude depends on the measurement method, assumed conversion factors and soil environment. Residue markers provide useful process information yet do not by themselves identify residence time or the contribution to crop productivity. The relative importance of microbial turnover and plant-derived fragments also changes with depth and the presence of mineral surfaces. A high microbial-residue signature is consequently evidence of a pathway, not a universal ranking of soil health (Kallenbach *et al.*, 2016; Liang *et al.*, 2019).

The idea of soil multifunctionality helps integrate these relationships but introduces another measurement challenge: functions can respond in different directions. A soil may show improved water infiltration but unchanged biological diversity, or higher nutrient mineralisation alongside faster carbon loss. Averaging such variables into a composite index can hide trade-offs and create arbitrary dependence on indicator selection and weighting. Practical soil-health assessments should retain separate physical, chemical and biological domains and ask whether thresholds are appropriate for the local soil and land use. The conceptual breadth of soil health is valuable only if it is not converted into an unjustified single number (Bender *et al.*, 2016; Bünemann *et al.*, 2018; Lehmann *et al.*, 2020).

5.5 Productivity Associations and Causal Interpretation

Carbon-rich soils often sustain higher yields, but this observation may reflect favourable climate, soil formation, access to nutrients, rooting volume, management and historical investment. A global meta-analysis found a positive relationship between SOM and crop yield with diminishing marginal associations at higher levels, yet this cannot be treated as evidence for a universal biological threshold or a guaranteed yield response to raising SOC (Oldfield *et al.*, 2019). Especially across continents, heterogeneity in crops, baseline fertility and environmental limitations makes causal attribution difficult. A site-specific management experiment that changes carbon inputs without controlling nitrogen, water and other agronomic variables faces the same problem at smaller scale.

The distinction is consequential for policy. Soil-carbon targets can be practical indicators of rebuilding depleted systems, but a crop response requires that carbon-linked functions alleviate an actual limitation. Where nutrient imbalance, waterlogging, salinity or severe compaction dominates, adding organic matter alone may not remove the constraint. Conversely, organic inputs may maintain production through nutrient delivery or surface protection before enough carbon accumulates to register as a large stock gain. Soil-health outcomes thus need to be evaluated directly, and carbon should be treated as one explanatory component of a wider causal system rather than a sufficient endpoint.

Table 3 compares the strength and boundaries of the evidence connecting SOM with selected soil-health functions. It shows why mechanisms established in controlled settings cannot automatically be translated into a uniform effect size at the field or regional scale.

Table 3. Soil-health functions linked to organic matter and their evidential limits

Soil-health domain	What the evidence supports	Limit on interpretation	Supporting references
Aggregation and erosion resistance	Roots, organisms and organic agents contribute to aggregate formation and renewal.	Bulk SOC cannot isolate compaction, texture or disturbance effects.	Six *et al.* (2002); Tisdall & Oades (1982)
Water storage and infiltration	Organic inputs may change porosity, retention and runoff pathways.	Average gains in plant-available water can be modest and soil-specific.	Minasny & McBratney (2018); Rawls *et al.* (2003)
Nutrient turnover and buffering	Organic substrates and microbial residues contribute to nutrient cycling.	Immobilisation, mineralisation and fertiliser contrasts alter short-term effects.	Cotrufo *et al.* (2013); Kelly *et al.* (2026)
Biodiversity and soil processes	Biological community composition can influence several ecosystem functions.	Carbon, habitat and management effects are not interchangeable.	Bender *et al.* (2016); Wagg *et al.* (2014)
Productivity	Across environments, SOM and crop yields can be positively associated.	The association is not a universal SOC threshold or proof of causation.	Bünemann *et al.* (2018); Oldfield *et al.* (2019)
Contaminant interactions	Organic compounds modify metal complexation and mobility.	Greater SOM does not invariably reduce exposure or leaching.	Kim *et al.* (2015)

Note. SOC = soil organic carbon; SOM = soil organic matter. The table describes conditional functional links, not universal effect sizes

6. Environmental and Landscape Controls on Soil Carbon Dynamics

6.1 Climate, Water Regimes and Soil Temperature

Temperature and moisture affect both carbon inputs and decomposition, creating feedbacks that resist a simple warm-versus-cold classification. Higher temperature can accelerate microbial metabolism and biochemical reactions when moisture and substrates are available, yet warm sites may also sustain vigorous plant production. Water limitation may restrict decomposition while simultaneously limiting root inputs, whereas prolonged saturation can suppress aerobic mineralisation and alter redox pathways. The resulting SOC balance depends on how these controls combine through seasons and years. Reviews of temperature sensitivity show that different organic substrates and physical environments can express different responses, undermining the idea of one transferable decomposition coefficient (Davidson & Janssens, 2006).

Experimental warming provides stronger causal evidence about one driver than comparisons among climatic zones, but even long-term warming treatments allow vegetation, nutrient availability and microbial communities to adjust. Carbon losses may consequently change over time rather than proceed at a stable annual rate. The multi-decade soil-warming evidence described by Melillo *et al.* (2017) is valuable because it challenges extrapolation from brief incubations, not because its exact trajectory applies everywhere. Forecasting SOM under climate change requires recognising simultaneous changes in plant productivity, heat extremes, seasonal moisture and the likelihood of disturbance.

6.2 Mineralogy, Texture and Geochemical Context

Soil mineralogical composition determines where organic compounds can be retained and how readily they exchange with the soil solution. Fine particle content is a useful starting variable but masks differences between clay minerals and reactive oxides, including variation in surface chemistry. A soil with low existing SOC relative to its mineral-associated capacity may have scope for additional association, whereas a soil with abundant carbon and limited reactive surfaces may respond primarily through particulate

pools. Global estimates of mineral-associated capacity make this heterogeneity visible at broad scales, but uncertainty remains when map units are translated to individual fields (Georgiou *et al.*, 2022; Hassink, 1997).

Mineral association is also constrained by delivery. Reactive surfaces contribute little to carbon storage if plant inputs are insufficient, microbes have limited access to substrates, or pores do not connect carbon sources to mineral particles. Conversely, strong biomass production does not assure mineral association when available sites are already occupied or transport is restricted. This helps explain why models using texture alone can overpredict a management response. Fraction-based work indicates independent controls on the formation and persistence of particulate and mineral-associated matter, including climate, carbon content and texture, which cannot be resolved through total SOC correlations alone (Haddix *et al.*, 2020).

6.3 Depth, Rhizosphere Access and Subsoil Carbon

Vertical distribution is a defining feature of soil carbon dynamics. Plant roots, texture, moisture, microbial activity and management disturbance change with depth; the concentration of carbon at the surface is therefore not representative of the whole profile. Global analyses established that vegetation type and climate influence the vertical distribution of SOC, while later research examined how atmospheric carbon reaches and persists at different depths (Balesdent *et al.*, 2018; Jobbágy & Jackson, 2000). Subsoil carbon may turn over slowly on average, but slow turnover can arise from sparse fresh inputs, physical inaccessibility or mineral interactions rather than a universal chemical resistance.

Root-derived carbon can enter subsoils more directly than above-ground residues, suggesting a potential management opportunity in rooting depth, crop rotation and perennial vegetation. Its realisation depends on the capacity of deep roots to grow through mechanical and chemical constraints and on whether newly delivered carbon persists. Root distribution also changes the supply of fresh substrates to decomposers, potentially stimulating priming of existing carbon. The net result cannot be inferred from root biomass alone. Source-tracing and depth-resolved measurement are needed to determine whether management adds new subsoil carbon or simply changes vertical patterns of inputs and loss (Balesdent *et al.*, 2018; Kuzyakov, 2010; Sokol *et al.*, 2019).

6.4 Land Use, Legacy Effects and Spatial Heterogeneity

Land-use history is an important confounder in carbon management research. Conversion from grassland or forest to cropland often reduces SOC, while the effect of a later practice depends on the depleted state, previous amendments, tillage intensity and soil depth. A meta-analysis of land-use conversion identified large variation across transitions, showing that mean changes cannot be assigned indiscriminately to every field (Guo & Gifford, 2002). Global reconstruction of historical carbon debt illustrates the magnitude of accumulated human influence but depends on spatial models, reference conditions and assumptions about land use over long periods (Sanderman *et al.*, 2017).

Landscape position further affects erosion, deposition, soil wetness and the movement of carbon-rich particles. Increasing carbon in a depositional location need not mean that atmospheric carbon has been removed; it may reflect material transported from elsewhere in the catchment. Likewise, differences between adjacent management systems may pre-date the compared treatments. Baseline measurements, replicated topographic positions and explicit treatment histories are needed to prevent pre-existing spatial heterogeneity from being interpreted as a management effect. For climate mitigation, the fate of displaced carbon matters in addition to its position within the measured field (Don *et al.*, 2024).

The interaction of climate, mineralogy, depth and landscape history argues against transferring carbon-response coefficients between regions without calibration. A practice that increases surface POM in a cool, fine-textured soil may have a different balance of gains and losses in a hot, coarse-textured or water-limited system. Similarly, slow apparent change can result from long turnover times rather than ineffectiveness, while rapid gains can represent a transient buildup of particulate residues. Soil health remains a context-defined performance question rather than the attainment of a single SOC target (Chenu *et al.*, 2019; Lehmann *et al.*, 2020).

7. Management Interventions: What Increases Carbon, and What Improves Health?

7.1 Cover Crops, Living Roots and Rotational Diversity

Cover crops provide organic inputs outside the main crop growing period, often through both shoots and roots. They may also reduce bare-soil exposure, compete with weeds and change nutrient capture. Meta-analyses indicate that cultivation of cover crops can increase agricultural SOC on average, supporting their role as a viable carbon-management practice rather than a universally effective one (Jian *et al.*, 2020; Poeplau & Don, 2015). Effect estimates nevertheless combine sites with different climates, durations, baselines, cover-crop biomasses and sampling depths. Broad adoption forecasts should not treat an average trial response as a perpetual rate of carbon gain.

Fraction-resolved evidence improves this interpretation. A meta-analysis found positive average cover-crop effects in particulate and mineral-associated carbon fractions, with proportionally greater changes in particulate material in the studies included (Fohrafellner *et al.*, 2024). This matters because rapid POM accumulation may signify increased energy supply and improved surface condition without demonstrating equivalent long-term stable-carbon formation. Mineral-associated responses can be smaller, slower or constrained by soil properties, while some experimental designs have insufficient duration to resolve them. The mechanistic question is not whether cover crops 'work' in the abstract but how they alter carbon inputs, transformation and losses under an identifiable baseline.

Cover cropping also has opportunity costs and conditional environmental effects. In water-limited systems, a cover crop may use moisture needed by the subsequent crop unless timing and termination are appropriate. Leguminous species can alter nitrogen inputs, while non-legumes often affect nutrient scavenging and residue stoichiometry differently. Yield and greenhouse-gas outcomes should therefore be reported alongside carbon stocks rather than assumed to follow the same direction. Trials evaluating multifunctionality are especially informative when they distinguish direct root-carbon effects from the indirect influences of fertiliser, residue retention and soil cover (Bender *et al.*, 2016; Chenu *et al.*, 2019).

7.2 Manure, Compost and Crop-Residue Return

Returning organic materials can increase the quantity and diversity of carbon entering soil while replenishing nutrients. Recent global synthesis indicates that manure and crop-residue amendments raise total SOC and, on average, both particulate and mineral-associated fractions compared with the relevant controls. The largest proportional response often appears in POM, while the magnitude of the observed treatment contrast depends heavily on whether controls also receive mineral fertiliser (Kelly *et al.*, 2026). These findings strengthen confidence that added carbon inputs can change SOM, but they do not show that every observed gain represents newly removed atmospheric carbon or an identical soil-health benefit.

Amendment composition and quality are crucial. Fresh residues, mature compost and animal manure vary in decomposability, nutrient ratios, salts and contaminants, and they may alter microbial allocation and priming. Their effects depend on application rate, crop nutrient demand, existing SOC and mineral sorption capacity. Input-driven SOC gains may partly represent transfers from another production system. Where manure is moved between farms, the receiving soil gains carbon, but whole-system climate accounting must also consider the source of the manure, alternative management and emissions during handling. The distinction between a local stock change and net sequestration is therefore conceptual, not merely administrative (Don *et al.*, 2024).

Synthesis focused on the division between POM and MAOM finds that combinations of organic material and nitrogen can increase both pools in particular contexts but are more frequently additive than synergistic at the scale of pooled evidence (Zhou *et al.*, 2026). This challenges claims that applying multiple inputs must produce disproportionate persistence gains. It also highlights the importance of what the control receives. A large contrast between manure and no inputs may include improved nutrient supply, crop growth and subsequent root inputs, not just stabilisation of the added manure carbon. Mechanistic explanation requires measurements of both direct amendment carbon and secondary plant-derived inputs.

7.3 Reduced Tillage and Residue Management

Conservation tillage is often associated with greater SOC near the surface because residues accumulate and soil disruption is reduced. Yet soil carbon concentrations are strongly stratified by tillage, and near-surface sampling can exaggerate the contrast in whole-profile stocks. Baker *et al.* (2007) argued that methodological weaknesses in early comparisons limited conclusions about total sequestration, a concern later reinforced in assessments of no-tillage mitigation potential (Powlson *et al.*, 2014). The issue is not that no-tillage has no environmental value, but that its benefits for erosion, energy use and soil structure should not be presented as automatic proof of net carbon removal.

Carbon redistribution is only one source of ambiguity. Changes in bulk density affect the mass of soil represented by a fixed sampling depth, while altered residue placement influences which layers accumulate carbon. A no-till treatment may contain more carbon in the top few centimetres but show little difference across the rooting zone, or a treatment may improve aggregate stability despite uncertain changes in stock. Whole-profile equivalent-soil-mass comparisons and an appropriate pre-treatment baseline are particularly important for separating real stock changes from sampling artefacts (Ellert & Bettany, 1995; Wendt & Hauser, 2013).

The functional case for reduced disturbance consequently needs a wider outcome set. Surface cover can suppress erosion and evaporation, preserve biopores and create habitat for organisms, while continuous no-tillage in some environments may intensify surface nutrient stratification or compaction concerns. The net response depends on crop sequence, residue management, traffic, local soils and climatic conditions. Management recommendations become more defensible when they specify the targeted soil constraint and report both beneficial and adverse outcomes rather than relying on a general carbon-sequestration label (Bünemann *et al.*, 2018; Powlson *et al.*, 2014).

7.4 Perennial Systems, Grasslands and Land-Use Change

Perennial vegetation and grasslands can supply carbon through extensive root systems and long periods of biological cover, but the effectiveness of conversion or restoration varies with prior land use and ecological context. Changes in land management modify both below-ground inputs and decomposition conditions. Converting degraded cropland to perennial cover may increase SOC over time, whereas disturbance of existing carbon-rich grasslands may generate large losses that are difficult to reverse quickly. Because the baseline stock and potential losses are asymmetric, policies that maintain vulnerable existing stocks may provide more reliable climate protection than those promising rapid accumulation after degradation (Guo & Gifford, 2002; Sanderman *et al.*, 2017).

Long-term source-tracing in grassland soil demonstrates why comparisons based only on total stock cannot establish the fate of newly added material. Litter-derived and pyrogenic carbon may persist differently over a decade, and distinct soil fractions exhibit different residence behaviour (Leuthold *et al.*, 2025). These results are not a universal endorsement of one input source. They illustrate the value of experiments that distinguish new carbon from inherited stocks and quantify the exchange between free and mineral-associated pools. Such designs should be extended to cropping systems with variable root depth and disturbance regimes.

7.5 Biochar and Other Altered Carbon Inputs

Biochar introduces a form of pyrogenic organic material whose thermal history and chemical structure differ from many fresh plant residues. Its effects depend on feedstock, production conditions, soil chemistry and the use of co-amendments. A field study following the distribution of carbon between particulate and mineral-associated fractions found management-dependent responses to biochar and combined amendments, providing a more discriminating picture than a bulk-carbon measurement alone (Giannetta *et al.*, 2024). Yet a detectable increase in carbon after applying carbon-rich material does not establish that native SOC has increased or that the same benefit occurs under other soils and application rates.

There are additional accounting and functional questions. If the carbon originated from biomass that would otherwise have been used elsewhere, the climate effect depends on the counterfactual fate of that biomass and production emissions. Some biochars can change pH, pore structure or nutrient availability, but responses differ according to their properties and the receiving soil. A single demonstration of enhanced carbon retention should therefore be kept separate from claims about yield, water security or net greenhouse-gas mitigation. Long-term experiments with source separation, health indicators and lifecycle boundaries are more useful than short trials measuring total SOC alone (Don *et al.*, 2024; Giannetta *et al.*, 2024).

7.6 Regional Transferability and Indian Agroecosystems

Global meta-analyses are useful for locating consistent tendencies but can underrepresent tropical and subtropical soils, smallholder systems and short rotations exposed to intense rainfall or seasonal moisture deficits. Evidence specific to India and the Indian subcontinent indicates positive average SOC responses to selected conservation and regenerative practices, alongside substantial heterogeneity in management combinations, farming systems and study conditions (Padbhushan *et al.*, 2024; Patil *et al.*, 2025). These syntheses should inform regional hypotheses, not substitute for trials matched to crop rotations, soil types and residue constraints.

In many intensively cropped systems, crop residues have competing uses and access to organic amendments is uneven. Livestock integration, residue removal for fuel or fodder, irrigation, small field size and nutrient management can influence the feasibility of increasing organic inputs. A practice measured as technically effective in an experiment may be less durable where it requires repeated biomass additions that farmers cannot source without transferring carbon from neighbouring land. Regional evaluations should measure net biomass production, realistic management costs, soil layers and competing resource demands rather than extrapolating average response rates uncritically (Chenu *et al.*, 2019; Padbhushan *et al.*, 2024).

7.7 Distinguishing Soil Improvement from Climate Mitigation

The strongest management finding is that many practices can improve selected soil properties or raise local carbon stocks; the weakest generalisation is that these changes always constitute net, durable climate mitigation. Additional sequestration requires an appropriate counterfactual, evidence that gains persist and consideration of displaced carbon and greenhouse-gas emissions. Carbon inputs may carry upstream emissions, and organic amendments may affect nitrous oxide or methane fluxes under particular nitrogen and moisture regimes. Don *et al.* (2024) demonstrate why definitions and system boundaries are essential before a measured gain is converted into a mitigation claim.

Table 4. Management interventions: expected soil carbon response, co-benefits and unresolved trade-offs

Intervention	Often-observed carbon response	Potential soil-health benefit	Critical qualification	Supporting references
Cover crops	Average SOC and fraction-specific increases in meta-analyses.	Root inputs, surface protection and nutrient capture.	Response varies by site, time and soil depth; water competition may matter.	Fohrafellner *et al.* (2024); Jian *et al.* (2020)
Manure or residue return	Increased POM and MAOM in many annual cropland contrasts.	Nutrient renewal, aggregation and microbial resources.	Amendment origin, fertiliser control and upstream emissions matter.	Kelly *et al.* (2026); Zhou *et al.* (2026)
No-tillage	Common surface enrichment; whole-profile net gains are less certain.	Reduced disturbance, cover retention and erosion control.	Depth stratification and unequal soil mass can mislead.	Baker *et al.* (2007); Powlson *et al.* (2014)
Perennial cover	Potentially larger below-ground inputs and maintenance of existing stocks.	Continuous rooting and reduced bare-soil periods.	Depends on previous land use and conversion-related losses.	Guo & Gifford (2002); Leuthold *et al.* (2025)
Biochar	Added pyrogenic carbon changes measured stocks and fraction distributions.	Possible changes in chemistry or structure.	Input provenance, production conditions and soil context govern net benefit.	Don *et al.* (2024); Giannetta *et al.* (2024)
Regional regenerative packages	Positive average SOC responses but variable crop outcomes.	Multiple potential functions.	Local crop, water and input constraints prevent simple transfer.	Padbhushan *et al.* (2024); Patil *et al.* (2025)

Note. SOC = soil organic carbon; POM = particulate organic matter; MAOM = mineral-associated organic matter. A field-level gain is not, without additional evidence, net atmospheric carbon sequestration

Time horizons also matter. Rapid increases in the first years after practice adoption cannot necessarily continue once carbon inputs and losses approach a new balance. Conversely, slow changes may be real but difficult to detect against spatial variability. Whole-system assessments should report both stock trajectories and soil-health functions, including constraints that matter to growers. Maintaining an existing carbon-rich soil, preventing erosion and improving productive resilience may be compelling objectives even when net additional sequestration is small or uncertain.

Table 4 brings the management literature together by separating typical carbon responses, co-benefits and reasons that the results cannot be transferred without qualification. It emphasises that each intervention is a combination of carbon inputs, biophysical context and measurement choices rather than a universally positive treatment.

8. Measuring Organic Matter and Testing Its Relationship to Soil Health

8.1 Concentration Is Not a Carbon Stock

SOC concentration is generally expressed as carbon per unit of soil mass, whereas a stock expresses carbon mass over a specified land area and depth. Confusing these quantities is among the most consequential problems in management interpretation. A change in concentration can reflect altered bulk density or the proportion of stones as well as a change in stored carbon. Conventional fixed-depth calculations use measured bulk density and coarse fragment correction, but comparisons between treatments with different soil mass at the same depth may remain biased. Equivalent-soil-mass approaches were developed to compare comparable quantities of mineral soil and to reduce this distortion (Ellert & Bettany, 1995; Wendt & Hauser, 2013).

Appropriate depth is part of the estimand, not merely a sampling convention. Studies restricted to the uppermost soil layer may capture a valid management benefit but cannot support a claim about whole-profile sequestration. Tillage comparisons particularly require attention to redistribution, while deep-rooted vegetation can shift carbon inputs below conventional sampling limits. Repeated monitoring should define its target depth, reference soil mass, handling of stones and uncertainty from sampling. Changes in sampling protocol during a long-term programme can produce an apparent trend even when underlying stocks are stable, so field metadata and repeatable procedures are as important as laboratory analytical precision (Baker *et al.*, 2007; Jobbágy & Jackson, 2000; Wendt & Hauser, 2013).

8.2 Fractionation, Indicators and the Illusion of Direct Mechanistic Measurement

Physical fractionation offers a practical link between carbon stocks and process hypotheses but is sensitive to dispersion energy, size thresholds, density media and aggregate disruption. A study reporting 'mineral-associated carbon' may not recover a fraction directly comparable to another study using a different protocol. Operational measurements also risk conflating the location of compounds at extraction with their prior origin or future stability. Standardised and fully described fractionation improves comparability, but mechanistic interpretation still benefits from isotopic source tracing, microbial residue measurements and environmental characterisation (Haddix *et al.*, 2020; Lavallee *et al.*, 2020).

Permanganate-oxidisable carbon is used as a responsive indicator of processed carbon. It can detect management-associated changes, but the term 'active carbon' may invite a stronger interpretation than the assay permits. The measured quantity depends on chemical susceptibility under an operational oxidation method and need not correspond precisely to microbial accessibility, turnover time or a single ecological mechanism. Research comparing this indicator across management contexts confirms its practical sensitivity without establishing it as a direct measurement of future mineralisation or an integrated soil-health outcome (Culman *et al.*, 2012). Combining it with total SOC, POM/MAOM and functional outcomes provides a better basis for inference.

Microbial biomass, extracellular enzyme activity, respiration and molecular markers also require careful interpretation. High respiration may signal vigorous nutrient cycling or rapid loss of stored carbon; low respiration may indicate substrate limitation or suppressed biological functioning. A rise in microbial necromass may reflect greater production, slower breakdown or both. Even a fraction described as mineral-bound may contain fast-cycling components. A multi-indicator approach should therefore avoid classifying every increase as beneficial and should state the directional hypothesis for each indicator before analysing treatment effects (Jilling *et al.*, 2025; Liang *et al.*, 2019; Wagg *et al.*, 2014).

8.3 Experimental Design, Attribution and External Validity

The most informative experiments begin with a clear baseline and an intervention contrast that isolates the mechanism of interest. A trial comparing manure with an unfertilised control does not isolate carbon-specific benefits from added nutrients. Similarly, a comparison of cover cropping with bare fallow changes crop cover, root activity and nutrient use at once. These treatments are realistic management packages, but the causal interpretation should match the package tested. Factorial designs separating carbon input, nitrogen supply and disturbance are especially valuable where claims concern stabilisation rather than the broader agronomic effect of a practice (Kelly *et al.*, 2026; Zhou *et al.*, 2026).

Duration and statistical power are difficult to standardise. SOC stocks change slowly relative to the spatial variance often observed in field sampling. Short experiments can reveal rapid shifts in POM, microbial activity or aggregates but may be poorly suited to detecting changes in deep carbon. Long-term experiments offer stronger evidence of sustained trends but can have fewer sites and imperfect control of historical management. Meta-analyses enlarge the evidence base while inheriting inconsistencies in depth, baseline treatment and analytical fractions. Their average effects should be interpreted alongside heterogeneity and site-level response distributions rather than treated as universal predictions (Fohrafellner *et al.*, 2024; Jian *et al.*, 2020; Poeplau & Don, 2015).

Observational evidence can illuminate climatic and pedological limits that single-site experiments cannot reproduce. Yet its correlations between SOC, crop yield and soil water are especially vulnerable to shared environmental drivers. Spatial adjustment may reduce confounding but does not make a cross-sectional regression a management experiment. Field studies should report the complete set of measurements relevant to the proposed causal chain, including input biomass, nutrient balance, carbon pools, structural properties and crop outcomes. This makes it possible to distinguish improvements mediated by SOM from benefits arising independently through residue cover, fertilisation or altered crop sequence (Minasny & McBratney, 2018; Oldfield *et al.*, 2019).

8.4 Scaling, Reference Conditions and Monitoring Claims

Regional soil-health monitoring and carbon programmes must trade analytical detail against cost and sampling coverage. Bulk SOC can support broad inventories, while fractionated analysis and isotope tracing are suited to subsets chosen to test mechanisms. This nested design is preferable to requiring expensive measurements everywhere or assuming that a simple proxy explains all functions. Monitoring should account for baseline soil type, land use, climate and previous management, and distinguish indicators that can change within a season from stocks that require longer observation. Soil-health benchmarks are most credible when they compare like soils under comparable uses and describe uncertainty (Bünemann *et al.*, 2018; Lehmann *et al.*, 2020).

Attribution becomes more difficult when carbon-rich materials cross boundaries. A farm may import manure or biochar and show a local gain even though the carbon was transferred from elsewhere. A landscape may redistribute eroded organic particles without removing additional carbon from the atmosphere. A management package may improve SOC while increasing other greenhouse-gas emissions. These problems cannot be solved by precise SOC analysis alone because they concern the definition of the system and its counterfactual. A defensible climate account requires explicit spatial boundaries, additionality assumptions, leakage consideration, time horizon and appropriate greenhouse-gas accounting (Don *et al.*, 2024).

Evidence quality is also affected by reporting conventions. Papers sometimes give significant differences in SOC concentration but omit bulk density, replicate numbers, baseline values or depth-resolved stocks. Others generalise from one fraction to the whole soil or use 'stability' without defining an operational timescale. Such omissions limit synthesis even where field experiments are technically sound. A more consistent minimum reporting set would identify soil classification, texture and relevant mineralogy, sampling depth, equivalent mass method, management history, fractionation procedure, uncertainty and the soil-health outcomes being claimed. These are requirements for interpretable comparison rather than a demand for identical designs in all locations.

Table 5 connects recurrent measurement choices to the claims they can legitimately support. Its central message is that analytical precision does not rescue an ill-defined comparison: the measured quantity, reference condition and intended soil function must align.

Table 5. Measurement choices and the claims they can support

Measurement/design	Legitimate inference	Common source of bias or overclaim	Supporting references
Bulk SOC concentration	Carbon per unit soil mass at a specified depth.	Concentration change presented as change in area-based stock.	Ellert & Bettany (1995); Wendt & Hauser (2013)
Equivalent-soil-mass stock	More comparable stock differences under changed bulk density.	Inadequate depth, coarse fragment correction or baseline.	Ellert & Bettany (1995); Wendt & Hauser (2013)
Physical fractionation	Allocation among protocol-defined particulate and mineral-associated pools.	Cut-off differences; treating MAOM as uniformly permanent.	Jilling *et al.* (2025); Lavallee *et al.* (2020)
Chemical oxidisability assay	Sensitivity of an operational carbon component to management.	Equating measured oxidation with turnover rate or biological function.	Culman *et al.* (2012)
Field soil-health functions	Structure, water, nutrient and biotic outcome under tested conditions.	Single proxy extrapolated to whole-soil health or crop causality.	Bünemann *et al.* (2018); Oldfield *et al.* (2019)
Whole-system greenhouse-gas balance	Net mitigation within defined baseline, boundaries and time horizon.	Leakage, imported carbon, N_2O and counterfactuals omitted.	Don *et al.* (2024); Powlson *et al.* (2014)

Note. SOC = soil organic carbon; MAOM = mineral-associated organic matter; N_2O = nitrous oxide. Each measure addresses a different estimand

9. Towards an Integrated Interpretation of Carbon and Soil Function

A coherent interpretation of SOM dynamics begins by separating three propositions. First, soil carbon enters, moves among and exits interrelated organic pools through microbial and physicochemical processes. Second, those pools support different soil functions in ways moderated by mineralogy, rooting, water regime and disturbance. Third, increasing the measured amount of carbon does not automatically establish that a given function improved or that atmospheric carbon declined. Each proposition can be tested at a different scale, and the strongest conclusions arise when evidence connects the scales rather than assuming the connection. This perspective reconciles the conceptual shift towards ecosystem-dependent persistence with the practical demand for measurable soil-health outcomes (Lehmann *et al.*, 2020; Schmidt *et al.*, 2011).

The particulate–mineral-associated distinction is particularly useful as an organising framework, provided it is not turned into a hierarchy of good and bad carbon. POM often registers recent inputs and may contribute to structure and microbial substrate supply; MAOM can contribute to long-term stocks and nutrient-related surface interactions. Both are heterogeneous, dynamically renewed and subject to environmental constraints. Evidence of persistent POM and fast-cycling MAOM demonstrates that their functional implications cannot be read from particle class alone. This calls for a shift from asking whether carbon is 'stable' to asking which carbon is retained, through which process, for how long and with what effect on soil functioning (Jilling *et al.*, 2025; Lavallee *et al.*, 2020; Witzgall *et al.*, 2021).

An integrated assessment should therefore use linked but distinguishable outcomes. Stock accounting addresses the quantity of carbon within a defined soil mass and profile. Fractionation helps identify the pathways through which management changes carbon allocation. Structural and hydrological tests reveal physical functions that may respond before or independently of stock growth. Biological and chemical indicators show nutrient transformation, habitat quality and possible trade-offs. Crop or vegetation performance tests whether such changes relieve productive constraints. Each level can be informative on its own, but none should be promoted as proof of the others (Bünemann *et al.*, 2018; Culman *et al.*, 2012; Oldfield *et al.*, 2019).

This framework helps explain apparently conflicting literature without removing all disagreement. Positive cover-crop meta-analyses and limited average effects of SOM on available water are not incompatible: cover crops influence carbon supply and numerous soil processes, while the hydrological outcome of interest may be only weakly responsive to carbon concentration. Likewise, increases in surface carbon under no-tillage and uncertainty about whole-profile sequestration can both be correct. Fraction, depth, comparison treatment and function specify the domain of each claim. Divergent studies should first be examined for differences in these domains before their results are labelled contradictory (Fohrafellner *et al.*, 2024; Minasny & McBratney, 2018; Powlson *et al.*, 2014).

The distinction between soil-health improvement and mitigation is a final test of conceptual clarity. A practice may reduce erosion, improve rooting conditions or enhance nutrient retention while producing an uncertain net climate benefit. Conversely, a practice that stores relatively persistent carbon may not improve an already well-functioning soil to the same extent as an intervention that targets compaction or nutrient imbalance. These outcomes should be evaluated honestly rather than forced into a single sustainability score. Maintaining existing carbon stocks, repairing impaired functions and increasing additional storage are complementary aims, but they require different baselines, indicators and policy incentives (Chenu *et al.*, 2019; Don *et al.*, 2024).

10. Future Directions

The highest immediate priority is a network of long-term, replicated field studies that compare depth-resolved carbon stocks and a common core of soil functions across contrasting textures, mineralogies and climates. Existing studies often measure only surface concentration or a small set of indicators, limiting causal inference about soil-health mechanisms. Randomised management treatments with documented baselines, equivalent-soil-mass calculations and repeated measurements over sufficient periods would allow more credible estimates of persistent change. These trials should report treatment components separately, including cover-crop biomass, nutrient additions, residue removal and irrigation, rather than attributing all observed changes to a broad management label (Ellert & Bettany, 1995; Wendt & Hauser, 2013).

A parallel priority is to connect SOM fraction measurements with source tracing and measurable functions. POM and MAOM should be measured using transparent, interoperable fractionation protocols; selected isotope and microbial-residue analyses could then establish the routes by which roots, litter and amendment carbon enter and leave those fractions. Repeated physical tests, nutrient budgets and biological measurements would help establish whether a stock increase has functional significance. This would directly test the assumption that increases in mineral-associated carbon represent permanently protected material and clarify when particulate additions support lasting soil structure. Emerging evidence of fast-cycling MAOM and persistent POM makes this a substantive question rather than a merely technical refinement (Jilling *et al.*, 2025; Leuthold *et al.*, 2025; Witzgall *et al.*, 2021).

Third, experiments should separate carbon and nutrient effects in realistic management comparisons. Factorial treatments that vary organic inputs, mineral nitrogen, residue placement and tillage would establish whether gains reflect altered microbial efficiency, greater primary production or simple transfer of imported carbon. Measurements of nitrous oxide and other greenhouse gases are needed where carbon is presented as a climate intervention, while whole-system boundaries should include production and movement of amendments. This design would improve estimates of additional climate benefit without diminishing the importance of legitimate non-climate soil improvements (Don *et al.*, 2024; Kelly *et al.*, 2026; Zhou *et al.*, 2026).

A fourth priority is greater geographical representation, particularly in smallholder, tropical, subtropical and water-limited agroecosystems where residue competition, seasonal water constraints and diverse soils may change management effects. Regional research should test practices within feasible farm resource budgets rather than applying a globally averaged carbon response. Indian and wider South Asian evidence provides a starting point, but comparative networks with transparent soil classification, depth and management history would better resolve transferability. Such studies should assess functional outcomes that matter locally, including erosion resistance, nutrient efficiency, root access and yield stability, alongside carbon storage (Padbhushan *et al.*, 2024; Patil *et al.*, 2025).

The longer-term research challenge is to model carbon dynamics and soil health as an interconnected but non-equivalent set of processes. Models should represent input pathways, microbial transformation, mineral capacity, structural accessibility and depth, while being evaluated against independent long-term observations. Remote or proximal sensing may support stratification and monitoring, but any prediction must be calibrated to reference soil masses and verified functional measurements. A useful decision framework would distinguish confidence in a stock change, confidence in a soil-health improvement and confidence in net

mitigation. Keeping these judgements separate could make both agronomic advice and public carbon programmes more scientifically accountable (Georgiou *et al.*, 2022; Lehmann *et al.*, 2020).

11. Conclusions

Soil organic matter is best understood as a dynamic continuum maintained by carbon inputs, biological transformation, mineral interactions, aggregation and environmental constraints. Its persistence is not governed by molecular composition alone, and operational carbon fractions do not correspond to fixed categories of active or permanently stable material. Particulate and mineral-associated organic matter provide a valuable organising framework, but each contains materials with different turnover and functional roles.

The strongest evidence links SOM to the functioning of soil structure, nutrient cycling and biological processes, while the magnitude of particular hydrological and productivity benefits depends on the soil and the limitation being addressed. Cover crops and organic amendments can increase carbon under many conditions, but their effects differ across fractions, depths, management histories and timescales. Greater carbon concentration in a surface layer is not sufficient evidence of increased whole-profile stocks, and a field-level stock gain is not necessarily equivalent to net atmospheric mitigation.

A defensible soil-health assessment must therefore combine measured carbon stocks with indicators of soil processes and outcomes, using comparable soil masses and explicitly defined environmental and management contexts. Sustained benefits are more credible when interventions are designed to repair locally important functional constraints, protect existing carbon and monitor trade-offs rather than pursue a universal carbon threshold. The practical value of SOM lies in the functions its dynamics help sustain, not solely in the quantity that can be measured at one time.

12. Limitations

This critical narrative review is inherently vulnerable to literature-selection and interpretive bias despite transparent search concepts, citation tracing and explicit attention to conflicting evidence. It was not an exhaustive systematic review, and no quantitative pooled effects or formal risk-of-bias scores were produced. Access to some full texts and subscription-only records was incomplete, and restriction to assessable English-language scholarship may have underrepresented locally published or non-English evidence. The selected studies also differ markedly in soil type, experimental duration, treatment definition, baseline condition, fractionation method, sampling depth and reported functions, making direct comparison difficult.

Many propositions about management and soil health rely partly on observational associations, controlled incubations or experiments that monitor only surface layers, and their conclusions may not transfer to longer time horizons or different environments. Research from particular agricultural regions is better represented than studies from some resource-constrained systems. This synthesis does not provide an independent global carbon budget, a quantitative estimate of climate mitigation or a universal minimum SOC threshold. Its conclusions are consequently strongest for identifying mechanisms, conditional patterns and necessary measurement safeguards, while quantitative local decisions require site-specific evidence.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. ChatGPT, Claude and Perplexity were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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