Review

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Responses and Feedbacks of Particulate Organic Matter to Straw Deep Incorporation in Northeast China

XU Wenhua[1,#], WU Junnan[1,#], TONG Yuxin[2], LI Binghao[1,3], LIU Hongxia[1], WANG Lichun[1,3], YANG Jinsheng[1,3]

(*[1]Jilin Academy of Agricultural Sciences (Northeast Agricultural Research Center of China), National Engineering Research Center of Major Food Crops, Changchun 130033, China; [2]Land and Water Resources Department, Food and Agriculture Organization of the United Nations, Rome 00153, Italy; [3]Agronomy College, Jilin Agricultural University, Changchun 130033, China; [#]These authors contributed equally to this work.*)

Abstract: Particulate organic matter (POM) represents the most active carbon (C) pool in agroecosystems. However, the contribution of POM to soil C sequestration under different straw return methods remains unclear, owing to its substantial interactions with soil physicochemical properties and microbial communities. This review gives a brief overview of the biochemical characteristics and analytical techniques of POM and then focuses on the actuation mechanisms regulating its spatiotemporal dynamics. It also discusses the application of POM management strategies, particularly through straw deep incorporation, to increase soil C stock and sequestration potential. In contrast to straw mulching and shallow incorporation, which concentrate C in the topsoil layer prone to C saturation, deep incorporation introduces fresh straw-derived C into the subsoil horizons. This process reshapes the pore networks by increasing the abundance of pores in the 30–90 μm range with high connectivity, and induces changes in soil aggregates, microbial communities, and enzyme activities. In the low-oxygen and thermally buffered environment of the subsoil, deep incorporation substantially increases POM-derived C and enhances C sequestration efficiency by 15%–30% compared with the traditional practices. Spatial optimization framework for agricultural POM management presented here provides a theoretical basis for enhancing C sequestration and improving ecosystem services in Mollisols of Northeast China.

Key words: agricultural management; carbon sequestration; deep tillage; particulate organic matter; straw return

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INTRODUCTION

Soil organic matter (SOM) is well recognized as a key indicator for evaluating ecosystem services in agricultural systems (Lal, 2004; Berhane et al., 2020). As a critical component of SOM, particulate organic matter (POM) plays a central role in carbon (C) dynamics by acting as a link between fresh residue inputs and the formation of mineral-associated organic matter (MAOM; Yu et al., 2025). In addition to its contribution to C cycling, POM also significantly influences soil structural properties, including the configuration of soil pore networks and the formation and stability of soil aggregates (Six et al., 2004; Kravchenko and Guber, 2017; Kravchenko et al., 2021; Ding et al., 2026). Given the interactive effects of POM with various soil physicochemical properties, the turnover of POM considerably affects soil C sequestration potential and nutrient supply capacity (Cambardella and Elliott, 1992; Haynes, 2005; Lehmann et al., 2015).

Straw return, which includes straw mulching, shallow incorporation, and deep incorporation, is a primary practice for enhancing soil C and POM pools in continuous maize cropping systems in Northeast China (Liu et al., 2014; Zhao et al., 2016; Berhane et al., 2020; Xin et al., 2024). Among the conventional straw return practices, straw mulching tends to induce C saturation in the topsoil, while frequent shallow incorporation often stimulates POM decomposition (Stewart et al., 2007; Zhao et al., 2016). In contrast,

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Corresponding authors: Lichun Wang (wlc1960@163.com); Jinsheng Yang (jsyang1@163.com)

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the incorporation of straw into the soil profile through deep tillage enables its mechanical redistribution. This process not only enhances the C sequestration potential of subsurface layers but also creates a relatively stable microenvironment in the plow subsoil, facilitating the physical protection of soil organic C (Zhao et al., 2018; Liang et al., 2021).

Numerous studies have investigated the physicochemical properties of POM and its impacts on soil structure and functions (Six et al., 2000; Kravchenko et al., 2019; Nunan et al., 2020). Nevertheless, a systematic understanding of how straw deep incorporation influences the synergistic changes in soil structure, microbial communities, and ecosystem functions through alterations in the spatial distribution of POM remains limited. This review synthesizes current knowledge regarding the composition, functional roles, and analytical techniques associated with POM, with a particular emphasis on the differential effects of various straw return practices on POM dynamics. By elucidating the regulation of POM on SOM mediated by spatial heterogeneity optimization, soil biopore formation, and microbial functional differentiation following deep incorporation, this synthesis aims to provide critical theoretical insights for quantifying soil C sequestration potential and developing sustainable management frameworks in Mollisol agroecosystems of Northeast China.

Composition, Functions, and Analytical Approaches

Composition and functional roles

The concept of POM was first introduced by Cambardella and Elliott (1992), who defined it as the light fraction of SOM with a particle size greater than 53 μm. The composition of POM typically includes decomposed plant residues, fungal hyphae, and other decomposition products (Gregorich et al., 2006; Von Lützow et al., 2007; Ding et al., 2026). Accordingly, POM is generally characterized by a relatively high C:N ratio (approximately 20–30), enrichment in structural compounds such as cellulose, hemicellulose, and lignin, along with labile components including soluble carbohydrates and proteins (Koorneef et al., 2023; Ding et al., 2026). For research purposes, POM is commonly fractionated based on particle size and density into free POM, occluded POM, and intra-microaggregate POM (Six et al., 2000).

The compositional attribute of POM underscores its role as a critical intermediary between fresh organic inputs and stabilized soil organic C pools. It serves as an essential substrate for microbial activity, an active hotspot for nutrient cycling, and a central agent in the formation and stabilization of soil aggregates. These properties confer on POM a substantial influence on SOM turnover, plant nutrient acquisition, and C sequestration potential in agricultural ecosystems (Six et al., 2004; Kravchenko et al., 2019).

Separation and analytical techniques

With advances in our understanding of POM, the methods used for its separation and analysis have undergone considerable development in recent years. The most widely used approaches for POM isolation are physical separation and density fractionation. Physical separation exploits the particle size difference between POM and MAOM by passing a soil suspension through a 53 μm sieve (Cambardella and Elliott, 1992). However, this approach has limitations in distinguishing between free POM and aggregate-protected POM (Poeplau et al., 2018). Density fractionation leverages the lower density of POM relative to MAOM and can effectively differentiate free POM, intra-aggregate POM, and intra-aggregate MAOM (Sohi et al., 2001; Sollins et al., 2006). However, this method is procedurally complex and raises environmental concerns associated with heavy liquid use. A combined fractionation approach, integrating both physical separation and density fractionation, has also been developed to enable better isolation and analysis of different POM fractions (Six et al., 2002).

To address the inherent limitations of physical and density fractionation, including time-intensive processing, limited methodological standardization, and the inability to preserve the spatial structure of POM, several more efficient isolation techniques have been developed (Poeplau et al., 2018). These include methods combining ultrasonic dispersion with microsphere grinding (Dorodnikov et al., 2009), rapid isolation based on microwave digestion (Kaiser and Berhe, 2014), and automated sieving and density fractionation systems (Paul et al., 2008). While these technological innovations enhance sample throughput, their contribution to improving methodological standardization and inter-study comparability remains limited. It has been suggested that the optimal method should be selected based on the required precision, sample size, equipment availability, and time cost, which provides a foundation for the comparison of results across different studies (Koorneef et al., 2023).

In-situ analysis and dynamic monitoring approaches

Traditional methods for studying POM are often constrained by the inherent limitations of destructive sampling and static analysis. Recent advances in *in-situ* analysis and dynamic monitoring methods offer new approaches for elucidating the real-time dynamics of POM in intact soil systems. X-ray computed tomography (X-ray CT) enables the non-destructive, *in-situ* visualization of POM spatial distribution and its relationship with soil pore networks (Kravchenko et al., 2021). Isotopic tracing techniques, utilizing either natural abundance approaches or enriched tracers, allow for the tracking of organic input transformation into POM and its subsequent turnover rates (Dungait et al., 2012). Molecular spectroscopic methods, such as Fourier-transform infrared spectroscopy (FTIR) and nuclear magnetic resonance (NMR) spectroscopy, can provide detailed resolution of POM chemical composition and structural attributes (Lehmann and Kleber, 2015). Integrated analytical approaches that combine X-ray CT, isotope tracing, and high-throughput sequencing further enable the simultaneous investigation of POM spatial distribution, C processes, and microbially mediated transformation, offering a critical tool for advancing the mechanistic understanding of POM functions (Nunan et al., 2020).

Dynamic monitoring of POM is essential for observing its decomposition, microbial colonization, and microenvironmental changes over time. This has been made possible by advanced microscale imaging techniques, including three-dimensional confocal laser scanning microscopy, micro-CT, and neutron radiography (Roose et al., 2016). The application of novel biosensors and molecular markers enables real-time *in-situ* monitoring of microbial activity associated with POM (Chen et al., 2019). Microelectrode arrays, fiber-optic chemical sensors, soil chips, and planar optode allow continuous, real-time measurement of key chemical parameters within the POM microenvironment, including pH, oxygen concentration, and redox potential (Blossfeld et al., 2011; Huang et al., 2017; Patko et al., 2024). At the field scale, buried soil respiration measurement devices, soil solution samplers, and automated gas sampling systems facilitate the continuous monitoring of C and nitrogen (N) fluxes associated with POM transformation, thereby providing crucial long-term datasets for understanding POM dynamics under field conditions (Wieder et al., 2013).

Functional Processes and Underlying Mechanisms

Soil pore structure

Soil pore structure exerts a substantial influence on POM stabilization and decomposition, while POM, in turn, actively shapes pore architecture through multiple feedback pathways (Kravchenko and Guber, 2017).

Soil pore structure affects POM dynamics through several mechanisms. First, the spatial relationship between pores and POM is critical. Advanced imaging techniques, such as X-ray CT, have demonstrated that elucidating the spatial relationship between soil pores and POM is essential for a mechanistic understanding of POM dynamics (Kravchenko et al., 2021). Second, it modulates micro-scale hydrological and oxygenation conditions. Soil pores of varying sizes and morphologies create distinct microenvironments with different water content and oxygen availability, thereby influencing the rates and pathways of POM decomposition (Keiluweit et al., 2017). Third, pore networks regulate microbial accessibility to POM substrates. The presence of well-connected pores of intermediate diameter (30–90 μm) is positively correlated with POM decomposition rates, whereas POM occluded within microaggregates and isolated from pore networks is subject to physical protection (Dungait et al., 2012; Kravchenko et al., 2019).

In contrast, POM directly contributes to the formation of soil biopores, as the decomposition of root residues within POM creates biological channels that facilitate water and oxygen transport (Kravchenko et al., 2019). POM also promotes the formation of inter-aggregate pores through its mediation of aggregate development, generating pore spaces that are critical for water infiltration and gas exchange (Horn and Smucker, 2005). Furthermore, X-ray CT investigations have revealed that the spatial distribution pattern of POM directly determines soil pore connectivity characteristics (Kravchenko et al., 2021).

Soil aggregate formation and stabilization

The formation and stabilization of soil aggregates are fundamental to soil structure and function, with POM playing a central role throughout aggregate development (Jastrow, 1996; Six et al., 2004). As a substrate for microbial activity, POM stimulates the secretion of extracellular polysaccharides and other binding agents that cement soil particles into microaggregates (53–250 μm; Tisdall and Oades, 1982). Kravchenko et al. (2019) have indicated that microbial activity in the vicinity of POM is 2–3 times higher than in the surrounding bulk soil, identifying these zones as hotspots for aggregate formation. In addition, POM at various stages of decomposition exhibits distinct binding capacities. Partially decomposed plant residues contain polysaccharides, proteins, and phenolic compounds that can directly participate in the cementation of soil particles (Martens, 2000). In addition, fungal hyphae networks within POM physically enmesh soil particles, promoting the formation and stabilization of macroaggregates (>250 μm; Miller and Jastrow, 2000).

The mechanisms through which POM contributes to aggregate stabilization operate across multiple pathways. First, POM acts as structural core within aggregates, providing a physical protection that supports aggregate architecture (Jastrow, 1996). A significant positive correlation has been observed between POM content and the stability of macroaggregates (>2 mm; Six et al., 2000). Second, microbial metabolites generated during POM decomposition, particularly extracellular polysaccharides and proteins, function as persistent organic binding agents that enhance aggregate stability (Tisdall and Oades, 1982). Third, reactive functional groups on POM surfaces (e.g., carboxyl, phenolic hydroxyl) can chemically bond with mineral particle surfaces, increasing aggregate stability through mineral-organic interactions (Kleber et al., 2007). Finally, certain POM constituents, such as lipids and waxes, have hydrophobic properties that reduce the rate of water infiltration into aggregates, thereby mitigating slaking and disruption upon rapid wetting (Piccolo and Mbagwu, 1999).

Nutrient cycling in agroecosystems

POM constitutes a primary reservoir and active turnover site for nutrients in agroecosystems. Relative to MAOM, POM is typically characterized by higher nutrient contents and more rapid turnover rates, functioning as an effective pathway in nutrient cycling (Cambardella and Elliott, 1992; Haynes, 2005).

POM contains a substantial quantity of organic N, with a higher C:N ratio (15–30:1) than that of MAOM (Gregorich et al., 2006). Mineralization of organic N within POM can release plant-available ammonium and nitrate. Studies have shown a positive correlation between N content within POM and annual N mineralization potential, rendering it a robust indicator of soil N supply capacity (Sequeira et al., 2011). Phosphorus (P) in POM exists in diverse organic forms, including phospholipids, nucleic acids, and inositol phosphates. Microbial decomposition of POM transforms these organic P compounds into soluble orthophosphate, making them accessible for crop uptake (Turner et al., 2005). In addition, POM contains an array of essential plant nutrients, including sulfur, potassium, calcium, and magnesium, whose release dynamics are closely coupled to C and N cycling processes (Kirkby et al., 2011). POM also plays an important role in enhancing the mobilization and bioavailability of micronutrients such as zinc and manganese (Dhaliwal et al., 2024).

Nutrient release from decomposing POM is governed by the interaction of element-specific properties, biotic factors, and abiotic conditions. Generally, ionic elements such as potassium are released most rapidly. Nutrients like N and P, which require enzymatic mineralization from organic compounds, are released more slowly. Elements that are structurally bound within structural constituents (e.g., lignin) exhibit the slowest release rates (Zhang et al., 2018). Environmental factors including soil temperature, moisture, pH, and oxygen availability (Conant et al., 2011), along with microbial community composition and metabolic activity (Cleveland and Liptzin, 2007) and their interactions with plant root exudates (Dijkstra et al., 2013), jointly regulate the rate and magnitude of nutrient release from POM.

Effective nutrient management in agroecosystems aims to synchronize nutrient release with crop demands on both temporal and spatial scales, while simultaneously minimizing losses and enhancing acquisition capacity. As an intermediate nutrient pool, POM releases nutrients at a rate between that of mineral fertilizers and stable organic matter, thereby buffering and improving the temporal dynamics of nutrient supply (Janssen, 1996). Appropriate distribution of POM across the soil profile can enhance nutrient acquisition by deep-rooting crops (Burger et al., 2023). During microbial processing, nutrients mineralized from POM can be temporarily immobilized in microbial biomass, reducing losses through leaching or volatilization (Schimel and Bennett, 2004). Furthermore, by influencing root morphology and mycorrhizal fungi development, POM can indirectly enhance the capacity for nutrient acquisition (Hodge et al., 2009).

Microbially mediated C processes

Owing to its distinct chemical composition and physical structure, POM functions as a critical hotspot for microbial activity in soil (Kuzyakov and Blagodatskaya, 2015). Microbial biomass and activity in the vicinity of POM are typically several-fold higher than in the surrounding bulk soil matrix (Kravchenko et al., 2019). This enrichment reflects the capacity of POM to provide microorganisms with abundant energy and nutrients (Cotrufo et al., 2013). Its porous architecture and surface properties offer an ideal habitat for microbial colonization, affording protection against predation and environmental fluctuations (Rillig et al., 2017). An X-ray CT investigation by Kravchenko et al. (2021) further demonstrated that the pore structures forming around POM create highly conducive conditions for microbial proliferation and activity. Additionally, the complex biochemical gradients generated by POM at different stages of decomposition sustain the coexistence of diverse microbial functional groups (Nunan et al., 2020).

Microbial community structure and function shift markedly across successive stages of POM decomposition. During the initial colonization phase, soluble components are rapidly assimilated following fresh crop residue inputs, with bacterial taxa, particularly from the phyla *Burkholderia* and *Proteobacteria*, becoming dominant (Bastian et al., 2009). As labile substrates are depleted, microorganisms equipped with enzymes to degrade cellulose and hemicellulose, such as fungi from the *Ascomycota* and *Basidiomycota* phyla, increase in relative abundance at the structural decomposition stage (de Boer et al., 2005). In the subsequent stabilization phase, the proportion of lignin-degrading bacteria and oligotrophic microorganisms (e.g., Actinobacteria) increases, while microbial necromass and metabolic byproducts progressively emerge as important organic matter sources (Cotrufo et al., 2013).

Soil microorganisms not only drive POM decomposition but also play a pivotal role in its transformation into stabilized organic C. The principal microbially mediated pathways of POM transformation include the following. First, microbial necromass constitutes a new source of organic matter following microbial assimilation of POM-derived substrates. Studies estimate that microbial necromass may contribute 30%–50% of stable SOC (Kallenbach et al., 2016). Second, enzymes and metabolic byproducts (e.g., organic acids, polysaccharides) secreted by microorganisms participate actively in POM transformation and stabilization (Kuzyakov, 2010). These metabolites can also bind to mineral particles, forming stable organo-mineral associations that enhance C persistence (Kleber et al., 2007). Third, microbial activity can improve soil microenvironment (e.g., pH, ionic concentrations) and promote the interaction of organic matter with mineral surfaces (Kleber et al., 2015). Finally, the input of fresh POM can stimulate or suppress the decomposition of native soil organic matter through its priming effect on microbial activity, thereby exerting an influence on soil C stabilization (Kuzyakov et al., 2000).

Soil quality

Due to its high sensitivity to environmental changes and management practices, POM is widely recognized as an effective indicator for assessing shifts in soil quality (Haynes, 2005). Compared to SOM, POM responds more rapidly to agricultural management practices such as tillage, crop rotation, and organic amendment application, thereby providing an earlier signal of emerging soil quality trajectories (Sequeira et al., 2011). Moreover, POM content is closely associated with key functional properties, including aggregate stability, cation exchange capacity, soil respiration, and enzymatic activity (Six et al., 2004). Consequently, monitoring POM dynamics enables timely evaluation of the impacts of agricultural management, offering a scientific basis for guiding sustainable soil management decisions.

Of particular significance is the capacity of POM to reflect not only quantitative changes in SOM, but also shifts in its quality and functional attributes. Parameters such as the C:N ratio of POM, its spectroscopic characteristics, and associated microbial community structure yield critical information regarding organic matter transformation and long-term stability (Cotrufo et al., 2019). This positions POM as a crucial bridge linking soil management practices to ecosystem services. In certain contexts, such as fine-textured soils with greater aggregate stability and physical protection capacity for POM, POM-based indicators may demonstrate heightened sensitivity compared to other physicochemical soil properties (Wang et al., 2023).

Effects of Maize Straw Return on POM

Impact of straw return on POM content and distribution

A substantial body of research demonstrates that different straw return methods exert markedly distinct effects on POM quantity and its spatial distribution. These effects are closely linked to the placement of straw within the soil profile, the degree of straw-soil contact, and the consequent differences in the decomposition environment (Table 1). Long-term straw mulching can increase POM-C content in the surface layer by 30%–50%, but its influence on soil layers below 10 cm is minimal (Blanco-Canqui and Lal, 2007). Shallow incorporation leads to POM accumulation primarily within the plough layer (0–15 cm), with a relatively uniform vertical distribution within this zone. Compared to straw mulching, shallow incorporation increases straw-soil contact area and accelerates microbial decomposition of straw residues (Luo et al., 2010). Zhao et al. (2016) reported that shallow incorporation increases POM-C content within the tillage layer by 20%−35%, though this effect diminishes rapidly with increasing depth. Deep incorporation is distinguished by a more homogeneous distribution of POM within the 30–40 cm soil layer. Liu et al. (2019) found that, compared to shallow incorporation, deep incorporation increased POM-C content in the 20–30 cm layer by 40%, with an even greater increment of 60% recorded in the 30–40 cm layer. This deep-layer enrichment offers new opportunities for increasing total soil C stocks (Angers and Eriksen-Hamel, 2008; Liang et al., 2021). Furthermore, the effects of different straw return methods on POM distribution are modulated by soil type and climatic conditions, through differences in hydrothermal regimes, mineral protection, and microbial decomposition. In fine-textured soils, deep incorporation is particularly beneficial for improving subsoil structure and promoting POM formation, whereas in dryland environments, surface mulching more effectively protects topsoil POM from erosion and oxidative loss (Wang et al., 2019; Sun et al., 2025).

Table 1. Responses of POM content, distribution, and physicochemical properties to different straw return methods.

Straw return methods	POM increment (%)	Soil layer (cm)	Soil properties	References
Straw mulching	30–50	0–5	Higher C:N ratio and lignin content	Blanco-Canqui and Lal, 2007; Abiven et al., 2009.
Shallow incorporation	20–35	0–15	Moderate C:N ratio and aromatic components	Luo et al., 2010; Zhao et al., 2016.
Deep incorporation	40–60	20–40	Lower C:N ratio with higher carboxyl content	Zhao et al., 2018; Liu et al., 2019; Zhang et al., 2021; Wang et al., 2023.

Impact of straw return on POM quality

Beyond influencing POM quantity and distribution, different straw return methods also affect its qualitative attributes, including chemical composition and turnover rate. POM derived from straw mulching typically has a higher C:N ratio and a greater proportion of lignin-derived components, accompanied by a slower decomposition rate (Abiven et al., 2009). In contrast, the C:N ratio of POM under shallow incorporation falls between those observed for straw mulching and deep incorporation (Zhao et al., 2016). Its POM fractions show a moderate proportion of aromatic components, along with increased contents of carboxyl and phenolic hydroxyl groups (Song et al., 2008). Under deep incorporation, POM demonstrates a lower C:N ratio, higher carboxyl group content, and a greater aliphatic-to-aromatic ratio (Fan and Wu, 2021).

Using isotope tracing techniques, Balesdent et al. (2000) have demonstrated that POM turnover rates differ significantly among straw return practices. Deep incorporation increases straw-soil contact, accelerating early-stage decomposition and yielding substantially higher POM turnover rates than surface mulching (Fontaine et al., 2007). However, factors such as limited oxygen diffusion in deeper soil layers can retard the decomposition of certain POM components, prolonging their residence time in the soil and giving rise to a protective mechanism for POM fractions within the subsoil layer (Fontaine et al., 2007).

Mechanisms of POM dynamics under deep incorporation

The process of deep incorporation, which redistributes POM into deeper soil horizons, triggers a co-variation of soil pores, aggregates, and microbial community through the reshaping of spatial heterogeneity (Fig. 1). The primary mechanisms through which deep incorporation influences POM dynamics are as follows.

First, deep incorporation creates a unique vertical gradient of POM within the soil profile compared to other straw management methods. This gradient represents a form of niche differentiation that can enhance microbial community diversity (Fontaine et al., 2007). The staggered decomposition of POM at different depths can lead to a more temporally balanced pattern of nutrient release, mitigating excessive nutrient accumulation at the surface and reducing seasonal fluctuations (Balesdent et al., 2000; Zhang et al., 2021). Surface soils in long-term cultivated fields often exhibit a C saturation limitation, in which its capacity to protect organic C reaches an upper threshold (Stewart et al., 2007). By directing POM into deeper soil layers where organic matter contents are inherently low, deep incorporation expands the spatial capacity for C sequestration (Lorenz and Lal, 2005). The POM-C increments in the 20–40 cm layer under deep incorporation substantially exceed that under shallow incorporation, indicating a considerable underutilized C sequestration potential in the subsoil (Zhao et al., 2018; Liu et al., 2019). The subsoil environment is further characterized by minimal temperature fluctuations, stable moisture conditions, and lower oxygen availability. These conditions may retard the decomposition of certain POM components and increase POM-C residence time (Mathieu et al., 2015). In addition, the resource-limited nature of the subsoil microbial community may lead to a preferential utilization of fresh, exogenous POM, potentially enhancing the efficiency of its transformation into more stable C forms (Fontaine et al., 2007).

Second, deep incorporation can optimize soil biopore structure, enhancing vertical connectivity and water regulation capacity. In contrast to conventional tillage, deep incorporation can induce vertically distributed POM and its associated decomposition channels to strengthen connectivity between topsoil and subsoil horizons (Ding et al., 2023). This facilitates a more uniform water distribution and enhances soil water holding capacity and subsoil water availability (Horn and Smucker, 2005; Rao et al., 2023). X-ray CT studies by Kravchenko et al. (2021) have revealed that deep incorporation fosters the development of POM-centered biopore systems in the subsoil. These pore networks have high

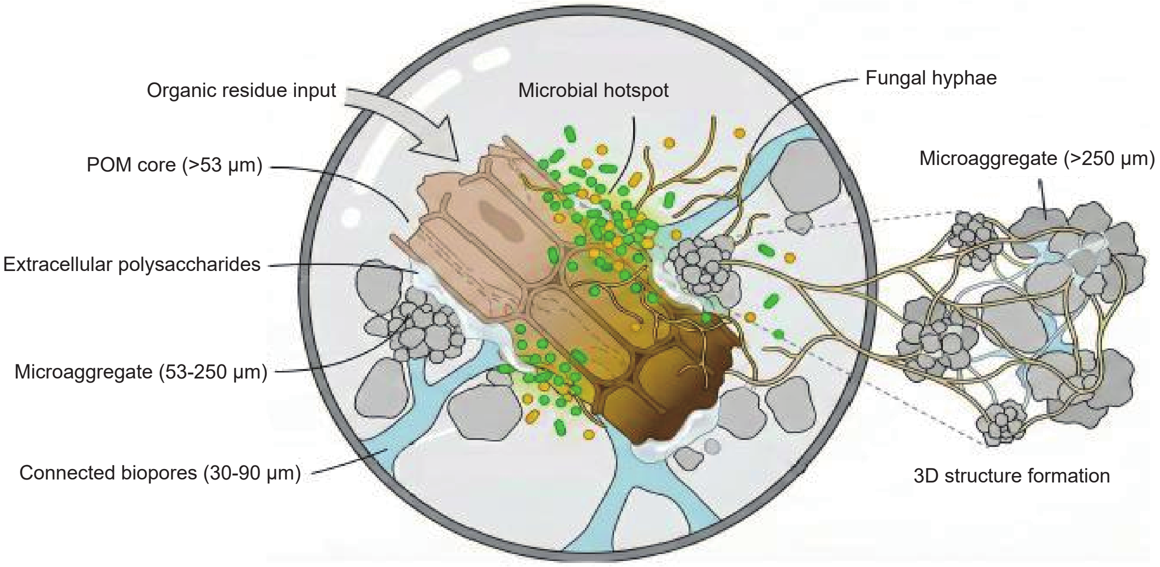

Fig. 1. Synergetic changes of soil pores, aggregates, and microbes driven by POM formation.

connectivity and pore sizes in the favorable range (30–90 μm) for microbial activity. Such structures improve water and air conditions in deeper layers, promoting not only crop root growth but also facilitating inter-horizon exchange of microbial communities and solutes (Nunan et al., 2020). Moreover, the pore system undergoes a successional process from initial biopore formation and microbial colonization through aggregate development to the establishment of a stable pore network under deep incorporation (Kravchenko and Guber, 2017). This is a trajectory fundamentally distinct from the pore evolution pathways observed under straw mulching and shallow incorporation (Ding et al., 2025).

Third, deep incorporation induces different microbial communities at various depths by altering the distribution of POM across the soil profile (Fan and Wu, 2021). The topsoil may be dominated by bacterial strategists. In intermediate layers, a balanced coexistence of fungi and bacteria is often observed. Deeper layers, in contrast, may be characterized by a predominance of fungi and Actinobacteria. These differences enhance microbial diversity and functional redundancy across the profile (Fontaine et al., 2007). It also leads to a corresponding variation in extracellular enzyme activities, as microorganisms at different depths produce distinct suites of enzymes with varying activities (Sinsabaugh et al., 2008). Cellulase activity predominates in the topsoil, β-glucosidase activity peaks at intermediate depths, and phenol oxidase activity increases in the subsoil. This enzymatic gradient results in depth-dependent differences in POM decomposition pathways and products, thereby diversifying the C cycling processes. The changes in microbial communities also exhibit functional complementarity in nutrient transformation (Van Der Heijden et al., 2008), which can enhance total nutrient use efficiency of the system (Fontaine et al., 2007). Through the variations of microbial communities, enzyme activities, and complementary nutrient transformations, deep incorporation optimizes the flow of C through different functional groups within the soil food web (Rousk and Frey, 2015). Isotopic tracing studies by Dignac et al. (2017) suggest that, due to the synergistic activity of distinct microbial communities across the soil profile, the efficiency of converting POM-C into microbial biomass and stable organic matter is higher under deep incorporation than under shallow incorporation.

Perspectives on POM Management in Sustainable Agriculture

POM and precision agriculture management

As mechanistic understanding of POM function continues to advance, several practical pathways have emerged for precision agricultural management strategies based on POM regulation. The first is incorporation regime optimization. Straw return method, depth, and frequency should be optimized based on specific soil and climatic conditions (Zhao et al., 2016). For instance, in long-term maize monoculture fields with surface soil C saturation, a rotation of deep incorporation and shallow tillage could be adopted to leverage the benefits of deep placement for vertical C distribution while minimizing the structural disturbance associated with frequent deep tillage. The second involves POM quality regulation. The quality and functional performance of POM can be influenced by adding specific materials (e.g., biochar, compost) or by adjusting straw pre-treatments (e.g., chopping intensity, fermentation; Lehmann et al., 2011). Dignac et al. (2017) indicate that co-incorporation of straw with biochar can significantly enhance POM stability and nutrient retention capacity, thereby increasing C sequestration. Third, microbial regulation technologies targeting POM transformation, such as functional microbial inoculants or enzyme promoters, could accelerate the conversion of POM to stable forms or optimize nutrient release patterns (Cotrufo et al., 2013). For deep incorporation systems, developing microbial formulations adapted to the subsoil environment could further promote C stabilization and nutrient cycling. Finally, POM monitoring-based precision management involves establishing dynamic POM monitoring networks to enable real-time assessment of soil quality trajectories and timely adjustment of management practices (Haynes, 2005).

POM and agricultural C sequestration potential

Given the importance of POM for agricultural C sequestration and the need for its accurate quantification, the primary concern is to develop a mechanistic understanding of POM transformation pathways under different management regimes (Lal, 2004). Liu et al. (2025) suggest that POM contributes most significantly to long-term SOC stabilization. By optimizing the distribution and protection of POM, deep incorporation can achieve 15%–30% higher C sequestration efficiency compared to conventional straw return methods, with the most pronounced increases observed in the 10–40 cm layer (Liu et al., 2019; Zhao et al., 2018; Wang et al., 2023). A comprehensive assessment of this potential is therefore crucial for informing regional and national C neutrality strategies. The second concerns the long-term stability of C sequestration. The efficiency and stability with which POM is converted to stable organic C are key indicators of the quality of agricultural C sinks (Lehmann et al., 2015). By altering POM protection mechanisms and microbial transformation pathways, deep incorporation may enhance the long-term persistence of sequestered C (Dignac et al., 2017). Furthermore, the relative stability of the subsoil environment provides additional protection for this C, mitigating its vulnerability to climate change (Balesdent et al., 2000). Third, the co-benefits of C sequestration and yield enhancement deserve particular attention. POM-mediated C fixation simultaneously improves soil structure, strengthens nutrient supply, and stimulates microbial activity, providing a theoretical basis for achieving synergistic gains in both C sequestration and crop productivity (Smith et al., 2020). By improving the root zone environment and subsoil nutrient availability, deep incorporation demonstrates more pronounced yield benefits under drought or nutrient-limited conditions, offering a pathway to achieve both ecological and economic gains (Wang et al., 2023).

POM and agroecosystem services

POM management not only governs C sequestration in agroecosystems but also influences a range of other ecosystem services. The effects of POM optimization techniques, including deep incorporation, on these services are as follows. First, POM-mediated improvements in soil structure directly enhance water regulation capacity (Six et al., 2004). By optimizing POM distribution and pore structure, deep incorporation can increase plant-available water capacity by 15%–25%, enhance infiltration rates by 30%–40%, and reduce runoff and soil erosion (Ding et al., 2025). This has positive implications for improving crop drought resilience and mitigating flood risks. The second concerns nutrient loss control under deep incorporation (Zhao et al., 2016). Deep POM hotspots can enhance the capacity to intercept and recycle soil nutrients leached from upper layers. Improved soil structure also reduces surface runoff and erosion, thereby decreasing the risk of particulate nutrient loss. Third, POM provides habitat and energy sources for soil organisms, making it a key determinant of soil biodiversity (Brussaard et al., 2007). The POM distribution created by deep incorporation expands the niche space for soil biota, potentially fostering a more diverse soil food web (Fontaine et al., 2007).

Future Research Directions and Perspectives

Key scientific questions

Despite considerable progress in POM research, several key scientific questions warrant further investigation. The first concerns the relationship between POM quality and ecological function. Establishing quantitative relationships between POM quality attributes (e.g., chemical composition, molecular structure, spatial distribution) and its ecological functions is crucial for predicting the environmental behavior of POM from different sources and for designing targeted POM management strategies (Cotrufo et al., 2019). The second question centers on the mechanisms determining microbial community-POM interactions. A deeper understanding is needed on the contributions of distinct microbial functional groups to POM transformation and the regulatory mechanisms involved (Liang et al., 2017). Third, the dynamics of POM under climate change require urgent attention. Predicting the impacts of climate change (e.g., warming, altered precipitation patterns, elevated atmospheric CO_2) on POM formation, transformation, and stabilization is essential. This includes assessing the adaptability and mitigation potential of different POM management strategies in a changing climate (Conant et al., 2011). Fourth, characterizing the long-term evolution of POM dynamics under sustained deep incorporation is necessary to identify potential critical thresholds or tipping points (Dignac et al., 2017). These include whether C saturation occurs in subsoils and whether long-term deep incorporation could lead to functional degradation of microbial communities. Fifth, exploring the synergies and trade-offs among the multiple functions of POM, such as C sequestration, nutrient cycling, and water regulation, is important (Smith et al., 2020). This knowledge would enable the optimization of POM characteristics to achieve multifunctionality under diverse environmental conditions and management goals.

Developing an integrated analytical framework

Given the inherent complexity of POM research, single indicators and methods are insufficient for capturing its full ecological functionality. The development of a comprehensive analytical framework is therefore essential. The first component is a multi-indicator integrated evaluation system. Integrating multiple POM attributes, including quantity, quality, distribution, and turnover characteristics, into a comprehensive evaluation system is needed (Haynes, 2005). For instance, combining POM-C content, C:N ratio, enzyme activities, turnover rate, and spatial distribution can provide a more holistic assessment of the impacts of different straw return methods on POM function. The second component is a multi-scale research framework. Establishing a coherent framework spanning from molecular to microaggregate to field scales would reveal POM behavior patterns across scales and the mechanisms of scale transfer (Lehmann and Kleber, 2015). Understanding the scaling from microscale mechanisms to macroscopic ecological effects is particularly important for optimizing practices like deep incorporation. The third involves data-model integration. Coupling experimental observational data with process-based models can improve predictive capacity for POM dynamics (Wieder et al., 2013). For example, developing multi-layer POM dynamics models tailored to deep incorporation systems, incorporating factors like vertical distribution, microbial community stratification, and pore structure effects, could provide a scientific basis for assessing long-term effects and designing optimal management strategies. The fourth is multidisciplinary convergence. Fostering interdisciplinary research integrating soil science, microbiology, ecology, agronomy, and information science is crucial for a deeper understanding of POM multifunctionality (Janzen, 2006). The combination of classical soil science approaches with emerging omics technologies, high-resolution imaging, and big data analytics holds particular promise for delivering breakthrough advances in POM research.

Practical applications and implementation strategies

Leveraging a comprehensive understanding of POM functional mechanisms, the following strategies should be considered for implementation in agricultural systems. The first strategy is the establishment of a monitoring and assessment system. Building soil quality monitoring and assessment systems that include POM indicators is essential for providing a scientific basis for policy formulation and technology extension (Haynes, 2005). Such a system should encompass quantitative, qualitative, and functional POM metrics, assessing both short-term changes and long-term trends to support decision-making for sustainable agricultural development. The second strategy involves technological integration and optimization. Combining deep incorporation with other sustainable agricultural technologies can create synergistic management systems (Zhao et al., 2016). Alternating deep incorporation with conservation tillage could harness the benefits of POM vertical redistribution from deep ploughing while leveraging the soil protection functions of conservation tillage. Integrating deep incorporation with biochar or microbial inoculants could optimize POM quality and transformation pathways, enhancing C sequestration rates. The third strategy is region-specific management. Introducing POM management practices to specific soil types, climatic conditions, and cropping systems is necessary (Smith et al., 2020). In Mollisol regions of Northeast China, deep incorporation may be particularly beneficial for improving subsoil structure. In red soil regions of southern China, POM management should focus more on acidification control and nutrient retention. In arid northwest China, POM regulation should prioritize water conservation and salinization prevention.

CONCLUSION

This review provides a comprehensive synthesis of the importance of POM in agroecosystems, with a specific focus on the mechanisms governing its formation, transformation, and stabilization under deep incorporation. As a central intermediate in the conversion of fresh residues to stable organic matter, POM not only regulates nutrient release through its turnover processes but also drives aggregate formation and pore network reorganization. Its spatiotemporal heterogeneity profoundly influences soil C sequestration and ecosystem services. In contrast to the C saturation limitation associated with conventional straw return methods, deep incorporation enhances both POM-C and C sequestration efficiency by influencing soil biopores

(30–90 μm), microbial communities, and their associated enzyme activities. By enabling the spatially optimized management of POM, this approach provides scientific support for enhancing C sequestration and facilitating the green transition of agriculture in the Mollisols of Northeast China.

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