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Review

Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil attributes

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ABSTRACT

This study explores agronomic management (AM) effects on soil parameters under diverse conditions. Investigating tillage practices (TP), nutrient management (NM), crop rotation (CR), organic matter (OM), irrigation management (IM), and mulching (MS), it aims to reveal impacts on soil productivity, nutrient availability, microbial activity, and overall health. Varied TP affect soil quality through compaction, porosity, and erosion risk. Proper NM is vital for nutrient cycling, preventing imbalances and acidification. CR disrupts pest cycles, reduces weed pressure, and boosts nutrient recycling. OM management enhances soil quality by influencing organic carbon, nutrient availability, pH, fertility, and water retention. Optimizing IM regulates soil water content without inducing waterlogging. MS contributes to OM content, nutrient retention, soil structure, and temperature-moisture regulation, benefiting soil biota, aggregation, soil health and agricultural productivity. The review emphasizes integrated nutrient, CR, and OM management's positive impact on fertility and microbial activity. Different TP and IM variations impact soil health and crop production. Judicious implementation of these practices is essential for sustainable agriculture. This synthesis identifies uncertainties and proposes research directions for optimizing productivity while ensuring environmental sustainability. Ongoing inquiry can guide a balanced approach between yields and resilient soil stewardship for future generations.

1. Introduction

Agronomic management (AM) has a significant impact on soil chemical, biological, and physical properties (SCBPPs), such as soil organic matter content, nutrient availability, microbial biomass and diversity, enzyme activities, and soil pH, with various outcomes influenced by specific soil treatments (Cabrera-Pérez et al., 2023; Lal, 2016; Zhou et al., 2023a). Understanding the complicated effects of these practices on soil fertility, nutrient availability, microbial interest, and overall soil fitness is essential for sustainable agriculture. These practices are important to sustainable crop production (Zhou et al., 2023a) and ecosystem health (Six et al., 2022; Wang et al., 2021), have gained significant attention for their potential to augment soil quality and productivity (Smith et al., 2005; Wang et al., 2023c), and ultimately, improved food security for the local communities and the nation as a whole (Astapati and Nath, 2023; Lu et al., 2023b; Wudil et al., 2022). AM involves several programs, which include tillage practices (TP), nutrient management (NM), crop rotation (CR), organic matter (OM), irrigation control (IM), and mulching systems (MS) of soil (Blanco--Canqui, 2023; Bu et al., 2020; Hashimi et al., 2023; Zhang et al., 2022a), as shown in Fig. 1.

The impact of AM has a profound effect on soil ecosystems, significantly affecting their delicate balance. Recognizing these impacts is pivotal for optimizing agricultural productivity while minimizing adverse environmental outcomes. TP, CR, NM, OM, IM, and MS, significantly influence SCBPPs in agricultural systems, as seen in Figs. 1 and 3. For instance, TP involves mechanical manipulation of the soil, with intensive or conventional tillage plays a role in the OM decomposition (Palsaniya et al., 2023), enhances the rates of nutrient mineralization (Niether et al., 2023), and increases erosion risk (Zarrinabadi et al., 2023). On the other hand, reduced tillage or no-till practices have the effect of minimizing soil disturbance (Niether et al., 2023; Wuest

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et al., 2023), maintaining soil structure (Bhattacharyya et al., 2022), and enhance water infiltration (Atta-Darkwa et al., 2022; Canet-Martí et al., 2023) and retention (Wuest et al., 2023). Selecting a TP should consider soil type, crop requirements, and erosion control objectives. Moreover, the selection of suitable TP can influence soil structure, aeration, and water-holding capacity (Agbede, 2021; Canet-Martí et al., 2023; Gatea Al-Shammary et al., 2023; Li et al., 2023a). Consequently, can impact microbial communities and their functions, as shown in Fig. 2.

Judicious NM significantly affects SCBPPs by influencing nutrient availability (Nasrollahzadeh et al., 2023) and soil pH (Sun et al., 2024). Optimally integrated and balanced NM ensures that essential nutrients are available to plants, hence healthy growth and high yields (Kumar et al., 2023). Conversely, improper or excessive use of fertilizer can lead to nutrient imbalances (Shanmugavel et al., 2023), soil acidification (Agegnehu et al., 2023), and loss of nutrients through leaching or runoff (Ain et al., 2023), which may negatively impact on soil quality and environmental pollution, as shown in Fig. 3.

CR, involving the alternating of various crop species or families, offers numerous benefits for soil health and fertility (Bünemann et al., 2022; Wu et al., 2024). It disrupts pest and disease cycles (Zani et al., 2023), decreases weed pressure (Otto et al., 2023), and improves nutrient cycling (Jin et al., 2024). Different crops contribute to heterogeneous microbial communities and improved soil structure (Bai et al., 2022). Therefore, CR also mitigates soil-borne illnesses and reduces the need for chemical inputs, as shown in Fig. 3. OM management directly affects the amount of soil organic carbon (SOC), a key component of soil organic matter (Gilmullina et al., 2023). Practices such as adding organic amendments (such as compost and manure) or adopting cover cropping and crop residue retention techniques can increase soil organic carbon (Duan et al., 2022). Higher SOC levels enhance soil fertility (Fontúrbel et al., 2023), nutrient availability (Feng et al., 2023), water-holding capacity (Inagaki et al., 2023), microbial diversity (Man et al., 2023), and soil fauna activity (Hagner et al., 2023), as shown Fig. 3.

IM, the artificial application of water to crops to supplement rainfall, is crucial for maximizing soil moisture content and crop productivity (Abou Ali et al., 2023; Canet-Martí et al., 2023). The impact of IM on soil properties by influencing water availability (Severini et al., 2023), drainage (Dossou-Yovo et al., 2023), and salinity (Weldewahid et al., 2023). Over-irrigation can cause waterlogging (Khalil et al., 2021), compaction (Liu et al., 2016), and nutrient leaching (Song et al., 2022), whereas insufficient irrigation can lead to drought stress and reduced crop yields (Peymaei et al., 2024). Proper scheduling, irrigation management, and water quality management are essential for preserving soil health and reducing water-related issues (Abou Ali et al., 2023; Yang et al., 2023d) (Fig. 3).

MS impacts SCBPPs according to Yang et al. (2023a). We can broadly divide the MS into two categories: organic and inorganic mulches (Dix et al., 2024; Visconti et al., 2024). Organic mulches, such as crop residues, straw, or compost, have been found to increase soil OM (Cai et al., 2023), enhance nutrient retention (Siedt et al., 2021), water-holding capacity (Jourgholami et al., 2022), and soil structure (Liu et al.,

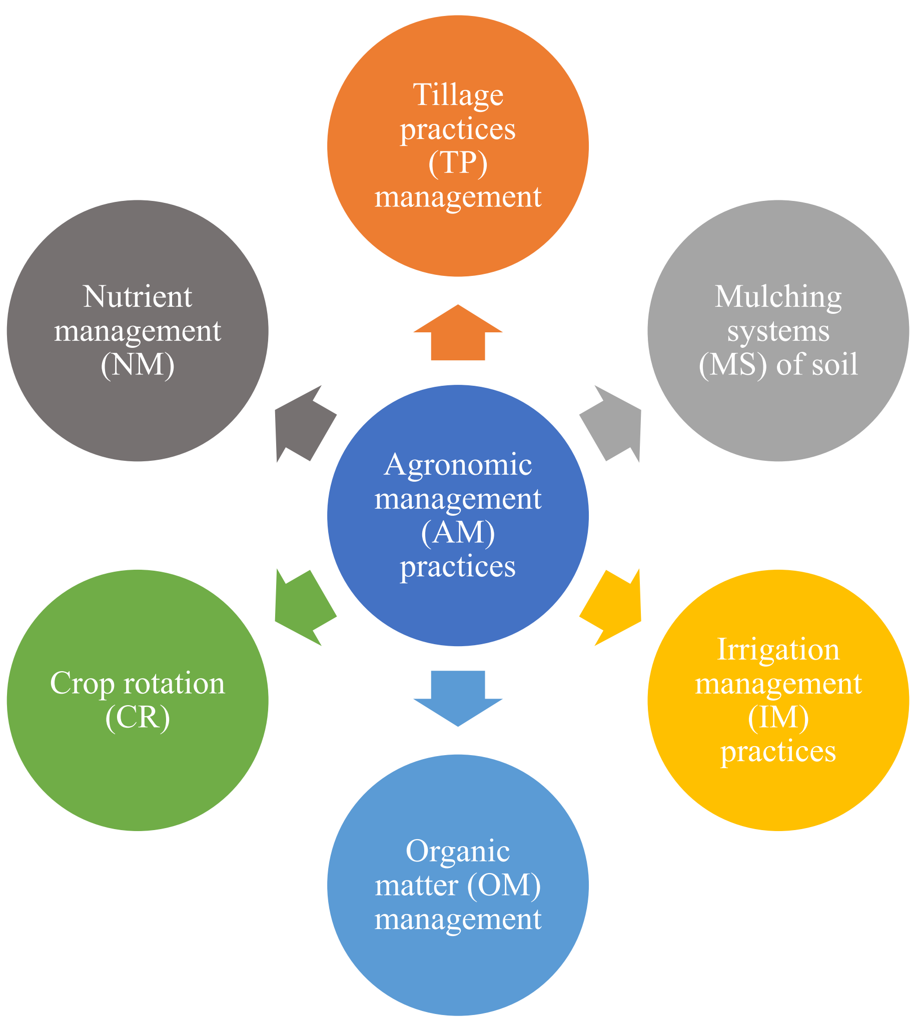

Fig. 1. Agronomic management practices under examination: A visual overview of the experimental setup and treatments.

2023g). Unlike inorganic mulches such as plastic or gravel soil, in which weeds grow, and can also help maintain moisture content, but can have little effect on soil ecosystems and biological choices, whether organic or organic, and SCBPP (Blaise et al., 2021), and thus in general. It can have a significant impact on health and productivity(Bandyopadhyay et al., 2023a; M et al., 2024).MS also regulates soil temperature (Yin et al., 2023b), water content (Gatea Al-Shammary et al., 2023; Yin et al., 2023a), and erosion of soil (Yakubu et al., 2021), providing favourable conditions for soil biota, including microorganisms, earthworms, and beneficial insects (Beriot et al., 2023). These microbes contribute to nutrient cycling, decomposition of OM (Hao et al., 2023), and soil aggregation (Liu et al., 2023f), which eventually enhances soil health and productivity (Palsaniya et al., 2023), as set out in Fig. 4.

This review aims to fully evaluate the present literature on the impact of agronomic management (AM) practices on SCBPPs under diverse conditions. The evaluation aimed to identify significant findings, unresolved questions, and promising future research directions within this domain. Specifically, consolidating what is firmly established regarding the influence of different land management techniques on soil characteristics, and processes will help find high-priority topics warranting further exploration. An in-depth comprehension of interaction pathways can ultimately optimize agricultural approaches to balance productivity, environmental protection, and long-term soil stewardship.

The value of this review stems from its systematic examination of how AM affects SCBPPs across diverse conditions. Such insights are paramount for improving sustainable agriculture via optimized land management approaches that reduce negative environmental impacts. Additionally, this paper indicates promising pathways for continued progress by describing significant findings and remaining uncertainties. Ultimately, this work contributes to academic knowledge by offering practical recommendations that foster resilient and productivity-enhancing soil stewardship worldwide.

2. Methodology

To ensure a comprehensive understanding of the impacts of AM on SCBPPs, a meticulous search of the Web of Science and Google Scholar databases was conducted. The search focused on identifying literature that explores the influence of AM on soil SCBPPs. The main sources considered were peer-reviewed journal articles and review papers, chosen for their authority and relevance to the study objectives (Rodrigo-Comino et al., 2018).

The search approach used specific words and keyword combinations pertinent to the topic, including “agronomic practices”, “mulching”, “tillage practices”, “soil chemical–biological properties”, “sustainable agriculture”, “water management”, “crop rotation”, and “soil health”.

We conducted a thorough search and assessment of several significant research papers about agronomic management strategies and their effects on soil characteristics. We conducted a thorough literature search and identified 290 high-quality, peer-reviewed sources that included the most pertinent and trustworthy material. These sources were carefully chosen and their findings were combined in this review report.

To ensure the inclusion of recent contributions within the fields of agriculture and soil science, the reference years were limited to the period from 2020 to 2024. The selected literature covered a spectrum of empirical investigations, theoretical discussions, and practical guidelines across various disciplines, including soil science, agronomy, ecology, and environmental science. This multidisciplinary approach allowed an in-depth examination of interactions and trends associated with AM practices.

The retrieved sources underwent a rigorous evaluation process, considering their quality, relevance and potential to contribute meaningfully to the comprehensive analysis (Rodrigo-Comino et al., 2020). A comprehensive and useful review was conducted to summarize the major results, knowledge, and conclusions addressing the impact of AM practices on soil parameters. Although efforts were made to reduce prejudices, it has been acknowledged that certain fundamental biases may endure. The combination of literature researched, spanning diverse disciplines, provides a robust foundation for comprehending the current status of knowledge on the topic. Additionally, it serves as a valuable resource for identifying key areas that warrant further investigation, thereby contributing to the ongoing scholarly discourse on the impacts of AM on SCBPPs.

3. How does agronomic management affect SCBPPS?

AM exert substantial impacts on SCBPPs. Notably, NM, CR, and OM management impact nutrient availability and microbial activity, whereas TP and IM play pivotal roles in shaping soil structure and pH levels. Pesticide and mulching practices further contribute to the complex dynamics of soil properties. Understanding the nuanced interactions and considering site-specific conditions are imperative for optimizing the desired effects on soil health.

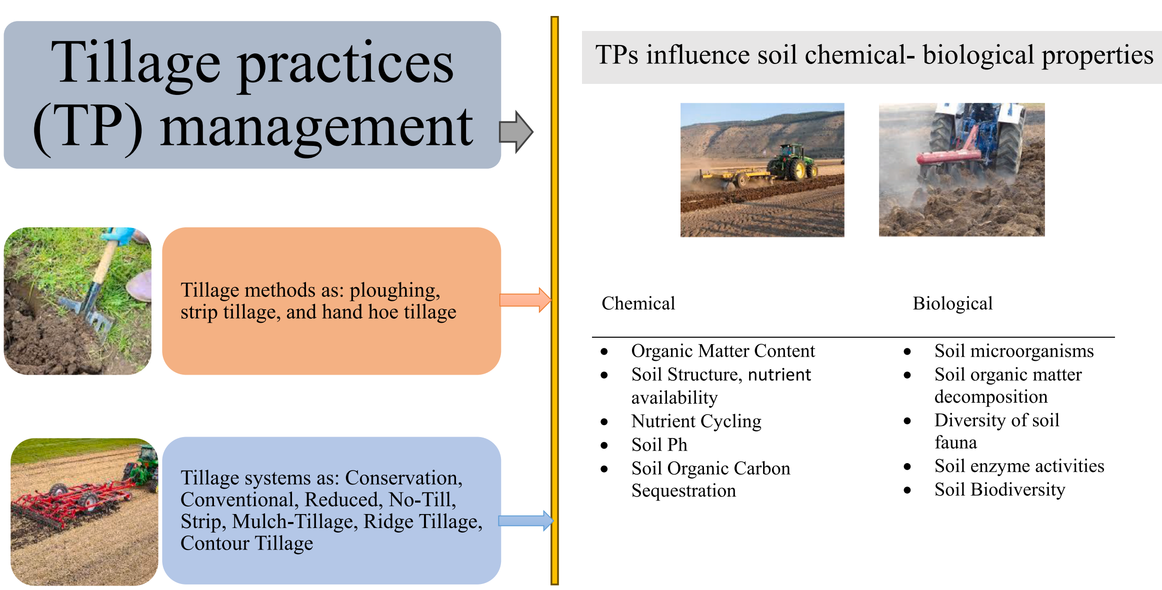

Fig. 2. Tillage methods and systems effect on soil chemical-biological properties (SCBPPs).

3.1. Tillage practices

TP have been identified as significant determinants of SCBPPs (Li et al., 2023c; Liu et al., 2022b; Sharma and Singh, 2023). As illustrated in Fig. 2 and detailed in Table 1, various tillage methods, such as ploughing, strip tillage, and hand hoe tillage, have been systematically evaluated for their impacts on SCBPPs (Badagliacca et al., 2021; Barbosa, 2020; Mihretie et al., 2022b; Nafi et al., 2020; Paye et al., 2023).

The effects of TP on chemical properties encompass soil OM content, structure, nutrient availability, nutrient cycling, pH, and SOC sequestration (Table 1). For instance, integrating ploughing with lime and phosphorus application has demonstrated notable reductions in soil pH (Njiru et al., 2023), extractable phosphorus (Pan et al., 2023), and exchangeable calcium (Sharma and Singh, 2023). Additionally, it creates no marked difference in cation exchange capacity (Özbolat et al., 2023), and reduces exchangeable magnesium, while reducing concentrations of exchangeable aluminum.

Conservation tillage (CT) practices, such as no-tillage (NT), reduced tillage (RT), mulching tillage (MT) and strip-tillage (ST), have been seen to enhance soil health and productivity (Alam et al., 2024; Pramanick et al., 2024; Verma et al., 2024), compared to conventional or traditional intensive (TT) tillage (Toth et al., 2024). These CT practices can enhance the process of soil accumulation(Liu et al., 2023d), increase the stability of soil aggregates (Zhang et al., 2024), improve water infiltration (Vlček et al., 2022), and mitigate erosion (Pi et al., 2024), hence leading to enhanced soil quality and long-term (Al-Shammary et al., 2023; Rocco et al., 2024). Furthermore, the specific effect of each of CT practices may differ based on factors like climate, soil texture, composition and other agro-management practices used (Madejón et al., 2023; Zhu et al., 2024a).

No-tillage (NT) has been found to enhance SOC and overall soil quality compared to conventional tillage (Hashimi et al., 2023; Palsaniya et al., 2023; Zhao et al., 2023b). TP useful for improving soil temperature (Islam et al., 2023), OM content (Bu et al., 2020; Niether et al., 2023; Palsaniya et al., 2023), nutrient availability (Liu et al., 2023c; Yan et al., 2023), and microbial biomass (Govednik et al., 2023; Sae-Tun et al., 2022), leading to improved soil health and crop production (Chang et al., 2023; Zhao et al., 2023b). Additionally, studies have demonstrated that long-term NT assist to conserve soil moisture, maintain or increase OM (Hashimi et al., 2023; Sharma and Singh, 2023), and improve crop production (Huang et al., 2023b) compared to CT. TP such as subsurface-sweeping, offset-disk tillage, and moldboard ploughing have been found to negatively effects soil chemical properties and reduce wheat yields, with surface soil acidification observed under certain tillage methods (Gao et al., 2023). Conservation TP is associated with favourable conditions for microbial abundance and diversity, whereas conventional TP tends to accelerate OM decomposition and might disrupt soil structure, negatively impacting biodiversity (Barbosa, 2020; Liu et al., 2023a; Sharma and Singh, 2023; Wang et al., 2020). While conventional TP exhibits higher enzymatic activity, conservation TP promotes higher biodiversity by providing suitable habitats and food sources for soil organisms (Malobane et al., 2020; Wen et al., 2023).

TP significantly influences key biological properties, including soil microorganisms, OM decomposition, soil fauna diversity (Coulibaly et al., 2022; Denier et al., 2022), enzyme activities, and overall biodiversity, as shown in Table 1. Conservation TP is associated with favourable conditions for microbial abundance and diversity, whereas conventional TP tends to accelerate OM decomposition and may disrupt soil structure (Wang et al., 2020). While conventional TP exhibits higher enzymatic activity, conservation TP promote higher biodiversity by providing suitable habitats and food sources for soil organisms (Malobane et al., 2020; Wen et al., 2023).

Despite the valuable insights provided by studies on TP, certain limitations, including variability, lack of control, time scale, observation scale, interactions with other management practices, generalizability, and absence of standardized protocols, must be considered (Table 1).

Tillage practices impact SCBPPs
1 Soil pH, phosphorus, calcium, and aluminium
2 Organic carbon and soil quality
3 Enhance soil temperature, organic matter, nutrients, microbial biomass, soil health, and crop production
4 Long-term NT conserves moisture, increases organic matter, and improves crops
5 Soil chemicals and wheat yields

Crop rotation impact on the SCBPPs
1 Enhances soil fertility and microbial diversity
2 Managing pests and diseases
3 Increase plant yields
4 Improve soil microbial diversity
5 Weed control, varying growth habits, root structures, and canopy cover
6 Soil organic matter content
8 Improves soil structure, water retention, and nutrient-holding capacity
9 Soil microbial communities, varying root exudates and residues, promoting beneficial microbial activity and nutrient cycling

Irrigation management impact on the SCBPPs
1 Soil Salinity, excessive use of water or poor drainage
2 Enzyme Activities
3 Nutrient cycling, organic matter decomposition, and soil health
1 pH, cation exchange capacity (CEC), affecting soil fertility
2 Increased levels of nitrogen (N) and phosphorus (P)
3 Use of wastewater for irrigation can introduce elements such as Na, Cl, Cu, Zn, and Cd to the soil, affecting plant growth and soil health

Nutrient management impact on the SCBPPs
1 Availability of essential nutrients for plant uptake, maintain soil fertility and affect soil pH.
2 Increase soil organic matter content
3 Microbial activity
4 Nutrient losses from the soil
5 Contributes to overall soil health
6 Maintaining soil fertility
7 Soil structure, productivity

Organic matter management impact on the SCBPPs
1 Maintaining soil fertility, a source of essential nutrients, such as nitrogen, phosphorus, and potassium, improves the cation exchange capacity (CEC)
2 A vital role in soil health and productivity
3 Enhances nutrient cycling in the soil
4 Contributes to soil structure and aggregation, soil porosity, water infiltration, drainage, promoting root growth and nutrient uptake
5 Soil microbial communities, supporting their growth and activity
6 Water-holding capacity of soils
7 Soil pH, favourable environment for nutrient availability

Fig. 3. Illustration of the influence of agronomic management practices on soil chemical and biological properties.

Fig. 4. Diagram displaying various mulching systems and their impacts on soil chemical and biological properties.

Addressing these limitations in future studies can contribute to a more comprehensive understanding of the impacts of TP on SCBPPs.

3.2. Nutrient management

NM has a significant impact on SCBPPs, playing an important role in improving soil fertility and sustainable agriculture. This comprehensive approach includes the use of implementing to manage nutrient availability (Cheng et al., 2023; Naher et al., 2021; Zhang et al., 2023d), nutrient balance (Tiemann and Douxchamps, 2023), soil pH (Kong and Lu, 2023; Zhang et al., 2023d), increase cation exchange capacity (Dey et al., 2023; Naher et al., 2021), soil salinity (Somenahally et al., 2023; Tan et al., 2023), and controls nutrient losses by leaching and runoff (Melland et al., 2022).

Table 2 provides a detailed summary of research findings on the integrated effects of NM in SCBPPs Implementing effective NM systems enables farmers and land managers to improve soil fertility, reduce environmental impacts, and promote sustainable agricultural practices (Quaye et al., 2021). Studies in various fields show that combined application of organic manure and inorganic fertilizers improves soil fertility and protects soil quality from degradation (Ejaz et al., 2022; Tomar and Saikia, 2022; Wang et al., 2023d). Integrated NM actions improve the availability of essential nutrients such as nitrogen, phosphorus, potassium, and organic carbon in soil (Madhurya et al., 2022; Tampio et al., 2022). It has been reported that high-quality organic fertilizers increase wheat yield and improve soil chemistry (Singh et al., 2020). The holistic approach of integrated NM applies especially in improving the fertility of the soil and enhancing the sustainability of agricultural production by Dhonde et al. (2022). NM practices exert significant effects on soil biological properties (Neelima et al., 2022; Su et al., 2023). They impact microbial activity (Borase et al., 2020; Zhang et al., 2023d), soil biodiversity (Köninger et al., 2021; Prack McCormick et al., 2022), OM decomposition (Fang et al., 2023; Reilly et al., 2023), nutrient mineralization (Debnath et al., 2023; Liu et al., 2023c), soil structure formation (Reilly et al., 2023; Xie et al., 2022), and soil health and resilience (Joshi et al., 2023; Neelima et al., 2022). Table 2 provides a comprehensive summary of the effects of NM on soil biological properties, highlighting the intricate connections between NM and the vitality of soil ecosystems.

3.3. Crop rotation

CR has a crucial role in influencing SCBPPs, significantly impacting soil health and productivity. This practice has played an essential part in maintaining and enhancing soil chemical properties by optimizing nutrient availability (Yang et al., 2023c), OM content (Liu et al., 2023e; Niether et al., 2023; Zheng et al., 2023), pH balance (Sun et al., 2022; Wu et al., 2024), nutrient balance (Hanrahan et al., 2023; Jahan et al., 2016), and pest control (Mwenda et al., 2023; Orek, 2024). Refer to Table 3 for a comprehensive overview of the research findings on the positive effects of CR on soil chemical properties.

CR exhibits a notable effect on soil biological properties, fostering enhanced soil fertility and microbial community diversity (Ansari et al., 2024; Li et al., 2023b). CR stimulates the activity of beneficial microorganisms in the soil (Ma et al., 2024), as demonstrated by the symbiotic relationships formed between legumes (e.g., peas and beans) and nitrogen-fixing bacteria (rhizobia) (Ma et al., 2024). Compared to monoculture systems, CR influences both the quantity and quality of OM inputs to the soil (Liu et al., 2023e; Theron et al., 2023), reduces disease incidence (Theron et al., 2023), increases plant yields (Wu et al., 2024), and improves soil microbial diversity (Ansari et al., 2024; Liu et al., 2023b). CR, when effectively implemented, aids in restoring soil fertility and health by mitigating the potential unilateral influence of plants on the soil (Ma et al., 2023; Wang et al., 2024; Zheng et al., 2024).

Moreover, CR practices involving cover crops or green manure contribute to an increase in earthworm populations (Denier et al., 2022). Long-term studies highlight the positive impact of CR, especially when coupled with the addition of organic fertilizers like poultry litter, on soil

Table 1
Influence of tillage practices (TP) management on soil chemical and biological properties.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Organic Matter Content	Conventional intensive tillage accelerates organic matter decomposition	Reduced disturbance tillage conserves or raises levels. No-till and strip-till mitigate disturbance, enabling crop residues to accumulate and slowing decomposition, maintaining or boosting organic matter in the long-term	(Bu et al., 2020; Hashimi et al., 2023; Niether et al., 2023; Palsaniya et al., 2023)	➢ Long-term studies are needed to capture the slow changes in organic matter content ➢ Diverse methods of measuring organic matter content can yield slightly different results
	Soil Structure, nutrient availability	TP affect soil structure, which in turn impacts soil chemical properties	- Negatively affect the movement of water, air, and nutrients in the soil. Intensive TP can disrupt soil aggregates, leading to the breakdown of soil structure and increased soil compaction - Conservation TP, on the contrary, promote the formation and stability of soil aggregates, improving soil porosity, water infiltration, and nutrient availability	(Barbosa, 2020; Liu et al., 2022b; Sharma and Singh, 2023)	➢ The influence of tillage practices on soil structure and chemical properties can be confounded by other management practices and environmental factors ➢ Results may vary across different soil types and climates
	Nutrient Cycling	TP influence nutrient cycling processes in the soil	- Intensive TP can increase nutrient mineralization rates by enhancing microbial activity and exposing organic matter to decomposition. It can also lead to nutrient losses through accelerated erosion and leaching - Conservation TP can help retain nutrients in the soil by reducing erosion and improving nutrient-use efficiency	(Liu et al., 2023b; Niether et al., 2023; Yan et al., 2023)	➢ TP can contribute to nutrient losses through erosion and leaching, which may not be fully accounted for in studies ➢ Long-term effects on nutrient cycling may not be fully captured
	Soil pH	TP can influence soil pH	lime incorporation through tillage can be used to raise soil pH in acidic soils	(Gao et al., 2023; Njiru et al., 2023)	➢ Results may vary depending on soil types, initial pH levels ➢ Assessing soil pH accurately can be complex and may involve various measurement methods, potentially introducing measurement variability
	Soil Organic Carbon (SOC) Sequestration	Conservation TP, such as no-till or reduced tillage, can enhance the accumulation of soil organic carbon compared to intensive TP	Reduced disturbance reduces the decomposition of organic matter and facilitates its incorporation into the soil, leading to increased carbon sequestration.	(Hashimi et al., 2023; Palsaniya et al., 2023; Zhao et al., 2023b)	Historical tillage practices and their legacy effects can impact current soil organic carbon levels, which should be considered in studies.
Biological	Soil microorganisms	TP influence the abundance, diversity, and activity of soil microorganisms	- Intensive TP disrupt the soil structure, reduce the population of beneficial microorganisms, and increase oxygen availability, promoting the growth of aerobic microorganisms - Reduced or conservation TP provide a more favourable environment for soil microorganisms, by preserving soil structure, organic matter, and moisture content	(Govednik et al., 2023; Ma et al., 2022; Sae-Tun et al., 2022; Wang et al., 2020)	➢ Legacy effects of TP on soil microorganisms should be evaluated when considering the result ➢ Different microbial groups may respond differently to TP, and studying the entire microbial community may not capture the specific responses of certain groups
	Soil organic matter decomposition	TP affect the decomposition rate of soil organic matter	- Intensive TP accelerate the breakdown of organic matter by increasing its contact with oxygen and microbial activity. Reduced TP can slow down organic matter decomposition, leading to its accumulation in the soil. This promotes the formation of stable organic aggregates and enhances the soil's capacity to store carbon	(Hashimi et al., 2023; Lv et al., 2023; Sharma and Singh, 2023; Zheng et al., 2023f)	➢ Lengthy investigations are required to capture the full effects of TP on soil organic matter ➢ TP may impact nutrient availability, which can influence the rates of decomposition pertaining to soil organic matter. Thoughtfully, considering nutrient dynamics is important for a comprehensive understanding of the process of decay
	Soil diversity fauna	The TP affect the abundance and diversity of fauna such as earthworms, insects, and other invertebrates	- Intensive TP can negatively influence soil fauna by worrying about their habitats and diminishing their food sources	(Coulibaly et al., 2022; Denier et al., 2022; Kraft et al., 2022)	➢ Long-term studies are indispensable for discerning the full effects of TP on the population levels and diversity of soil fauna

(*continued on next page*)

Table 1 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
		- Reduced TP leave the soil undisturbed, and provide a more favourable environment for soil fauna, promoting their abundance and diversity. As key contributors to nutrient cycling, soil structure formation, and organic matter decomposition		➢ When interpreting results, previous TP and their legacy effects on soil fauna communities should be considered, only through such longitudinal analyses can we hope to untangle the complex relationships between TP and the subterranean organisms that are so vital to soil welfare
Soil enzyme activities	TP influence soil enzyme activities, which are essential for nutrient cycling and organic matter decomposition.	- Intensive TP lead to increased enzyme activity due to the greater availability of incorporating organic residues and aerating the soil profile. - Reduced or conservation TP can maintain or enhance the delicate balance of soil enzyme activities by preserving organic matter and providing a stable environment conducive to the biological processes of soil.	(Liu et al., 2024b; Liu et al., 2023c; Malobane et al., 2020; Wen et al., 2023a)	➢ Long-term studies are needed to capture the full effects of TP on soil enzyme activities ➢ Understanding changes in soil enzyme activities resulting from TP requires additional investigations to assess their impact on nutrient cycling, organic matter decomposition, and overall soil health
Soil Biodiversity	TP management can impact soil biodiversity, as a variety of plant and animal species are present in the soil ecosystem	Intensive TP can reduce soil biodiversity by excessively disturbing soil habitats, diminishing organic matter, and altering soil physical and chemical properties - Conservation TP can foster soil biodiversity by minimally disturbing the soil profile and providing a more stable and diverse array of habitats for various organisms to inhabit. Furthermore, by preserving habitat complexity, reduced tillage encourages the thriving proliferation of the abundant and diverse assemblage of organisms that comprise a healthy, vibrant soil ecosystem	(Korniłłowicz-Kowalska et al., 2022; Liu et al., 2023a; Lu et al., 2022; Wang et al., 2023d)	➢ Longitudinal analyses are indispensable for capturing the full effects of TP on soil biodiversity, as changes in compositional balance and diversity can take time to manifest. To fully comprehend the ramifications of tillage-induced alterations to subterranean life, further research is warranted ➢ How changes in biodiversity feedback from TP require additional investigations to assess their impact on ecosystem processes, biogeochemical cycling, and overall soil health, of this vital yet oft-overlooked domain

fertility levels, nutrient cycling, crop yields, and soil biodiversity (Yang et al., 2022; Zhou et al., 2023b).

In conclusion, CR proves to be a crucial practice for maintaining soil health and advancing agricultural sustainability. Its multifaceted benefits underscore its importance as a strategic approach in sustainable land management. It contributes to improved food security, including increased food availability, accessibility, and utilization.

3.4. Organic matter

OM management stands as crucial determinant in shaping SCBPPs, exerting profound effects on soil health. A judicious approach to soil management strategies can significantly elevate SOC content, thereby influencing various soil chemical properties (Fontúrbel et al., 2023; Gilmullina et al., 2023; Liu et al., 2024; Malone et al., 2023; Sao et al., 2023). OM plays a pivotal role in influencing SOC content (Gilmullina et al., 2023; Urbanski et al., 2023), nutrient content and availability (Mabagala and Mng'ong'o, 2022; Prats et al., 2023), cation exchange capacity (Jeon et al., 2023), soil pH (de Santana et al., 2022; Duan et al., 2022), soil fertility (Fontúrbel et al., 2023; Mabagala and Mng'ong'o, 2022), and water-holding capacity (Inagaki et al., 2023; Védère et al., 2022), as comprehensively summarized in Table 4.

Appropriate OM management strategies hold the potential to enhance soil fertility, nutrient availability, water management, and overall soil health. Distinct tillage systems and stubble management practices significantly impact soil chemical composition (Fang et al., 2022), influencing parameters such as organic carbon (Lu et al., 2023a), phosphorus (Sharma and Singh, 2023), potassium (Lu et al., 2023a), and magnesium content (Lv et al., 2023). Practices like manure application and leaving straw in the field following OM amendment have been associated with higher organic carbon and biologically available potassium levels (Chen et al., 2023b; Farooq et al., 2022).

The influence of OM management practices extends to soil biological parameters (Feng et al., 2023; Fontúrbel et al., 2023; Védère et al., 2022), showcasing impacts on microbial (Jin et al., 2022; Miao et al., 2023) and soil enzyme activities (Fontúrbel et al., 2023; Shaaban et al., 2023), diversity (Jin et al., 2023), soil respiration (Ansari et al., 2023; Verrone et al., 2024), earthworm and soil fauna activity (Hagner et al., 2023; Wen et al., 2023), disease suppression (Dignam et al., 2019; Ogundeji et al., 2022), and mycorrhizal associations (Chen et al., 2023a; Yin et al., 2021), as summarized in Table 4. Notably, agronomic management practices, encompassing both organic and conventional approaches, can influence soil microarthropods (Hagner et al., 2023; Reilly et al., 2023), key players in nutrient dynamics and soil microbial communities (Govednik et al., 2023; Mabagala and Mng'ong'o, 2022; Zheng et al., 2022).

In summary, OM management practices wield substantial potential in improving SCBPPs, thereby contributing to sustainable agriculture practices and bolstering soil quality.

3.5. Irrigation management

IM practices have a significant impact on SCBPPs by appropriate irrigation scheduling (IS) and irrigation techniques (IT), as indicated by

Table 2
Impact of nutrient management (NM) on selected chemical and biological indicators of soil quality.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Nutrient availability	The NM is to optimize nutrient availability for plants	Fertilizers or organics boost soil nutrients, supporting plant growth and development, by increasing the concentration of essential nutrients in the soil	(Cheng et al., 2023; Ma et al., 2023; Tampio et al., 2022; Wang et al., 2023e; Zheng et al., 2024)	➢ Nutrient dynamics need detailed studies considering soil, environment, and diverse nutrients for comprehensive consideration ➢ Nutrient availability is influenced by various management practices, such as fertilizer strategies, organic inputs, crop rotation, and irrigation protocols. Ascertaining the precise influence of NM practices can be challenging due to their interactions with other factors
	Nutrient balance	Optimal nutrient balance benefits plant health, while imbalances impact productivity and health negatively	Nutrient balance is indispensable for proper NM practices and agricultural sustainability. By providing crops with a balanced supply of nutrients, nutrient deficiencies and toxicities can be prevented, promoting optimal plant nutrition, maximizing nutrient use efficiency, and supporting soil health and productivity	(Naher et al., 2021; Tiemann and Douxchamps, 2023)	➢ Different crops have varying nutrient requirements and may respond differently to nutrient imbalances. Generalizing findings across different crops can be challenging ➢ Soil characteristics, such as pH, organic matter content, and nutrient-holding capacity, can vary spatially and influence nutrient balance. Accounting for soil variability is crucial for accurate nutrient management
	Soil pH	The NM can influence soil pH levels	The use of acidic fertilizers or amendments can lower soil pH over time, while the application of alkaline materials can increase soil pH	(Kong and Lu, 2023; Zhang et al., 2023e)	➢ Soil pH affects nutrient availability and interactions. However, the relationships between pH and nutrient availability can be complex, and the effects may vary depending on soil characteristics and nutrient sources ➢ Assessing the long-term impacts of nutrient management practices on soil pH requires extended monitoring and evaluation. Changes in soil pH can occur gradually over time, and their consequences may become more evident in the long run
	Cation exchange capacity (CEC)	The NM can be significant on CEC, by affecting soil organic matter content, fertilizer, nutrient interactions, liming, and soil texture	Organic matter harbours negatively charged functional groups that readily adsorb and retain cations, thereby bolstering the soil's capacity to retain and exchange essential nutrients. Furthermore, because affects the availability and uptake of different NM. When NM are applied in balanced proportions, they can promote optimal soil pH levels, which in turn can enhance CEC.NM practices that improve soil structure and increase clay content can enhance CEC.	(Dey et al., 2023; Esfandiar and McKenzie, 2022; Madhurya et al., 2022)	➢ Soil heterogeneity, interaction with other soil properties, timeframe of the study, regional and climatic variations, variability in organic amendments, and plant and crop interactions are limitations in studying the influence of nutrient management on CEC ➢ Field-scale validation is necessary
	Soil salinity	The NM can contribute to the accumulation of salt in the soil, leading to soil salinity, through the implementation of suitable irrigation and fertilization practices.	As part of effective NM practices, monitor soil salinity levels and implement suitable irrigation and fertilization techniques to prevent the build-up of salt. improper NM practices, such as inadequate irrigation and fertilization, can lead to salt accumulation in the soil. This, in turn, can result in the concentration of salts through evaporation, contributing to salt buildup. Ultimately, this negatively impacts plant growth and agricultural productivity	(Somenahally et al., 2023; Tan et al., 2023)	➢ Soil salinity is a complex issue with various factors and limitations. For example, soil texture variations, measurement challenges, management strategies, soil remediation, environmental impacts, and economic considerations all contribute to the complexity of managing soil salinity effectively, associated with soil salinity that should be considered
Biological	Microbial activity	The NM practices can have a significant impact on microbial activity in the soil	By harnessing beneficial soil microorganisms, which can enhance soil health, nutrient cycling, and plant productivity. Different microbial groups have unique metabolic capabilities and ecological roles, allowing us to	Zhang et al. (2023e)	➢ It is important to acknowledge the complexity and challenges in studying soil microbial communities. Factors such as community complexity, spatial and temporal variability, measurement techniques, linking microbial activity to soil health, long-term effects, and scale-

(continued on next page)

Table 2 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
		target specific soil processes for sustainable agriculture		related issues all contribute to limitations in understanding the impact of NM practices on soil microbial activity
Soil biodiversity	The NM practices can have both positive and negative impacts on soil biodiversity. The specific effects depend on the type and intensity of the NM practices implemented	The impact of NM practices on soil biodiversity depends on various factors, including soil type, climate, crop management, and specific NM techniques. Sustainable NM practices like organic amendments, crop diversification, reduced tillage, and integrated nutrient management can enhance soil biodiversity, promoting microbial diversity and abundance while maintaining soil fertility and productivity	(Köninger et al., 2021; Prack McCormick et al., 2022)	➢ NM practices can have both positive and negative impacts on soil biodiversity. Organic amendments and crop rotation enhance biodiversity, while pesticide use can be detrimental. However, studies have limitations: generalization, short-term focus, specific group emphasis, interactions with other factors, lack of standardized methodologies, and insufficient attention to below-ground biodiversity. Future research should address these limitations for a comprehensive understanding of soil biodiversity dynamics
Organic matter decomposition	The NM practices can have significant impacts on organic matter decomposition in the soil	The impact of NM practices on organic matter decomposition depends on factors like organic matter quality, quantity, soil conditions, climate, and management. Sustainable NM practices emphasizing organic matter addition, balanced nutrient management, and soil health enhancement can enhance organic matter decomposition, nutrient cycling, and soil fertility	(Fang et al., 2023; Reilly et al., 2023)	➢ The impact of NM on organic matter decomposition is complex, influenced by biology, environment, organic matter quality, timing, and site-specific conditions. Long-range impacts and uncertainty pose challenges in predicting and optimizing decomposition. Continued rigorous investigation should deepen our understanding of these interactions to develop effective and sustainable strategies for soil health, biogeochemical cycling, and agricultural productivity in a balanced, enduring manner aligned with ecological stewardship objectives
Nutrient mineralization	The NM practices on nutrient mineralization is an increased availability of plant-accessible nutrients in the soil	By judicious stewardship of the nutrient cycle that converts organic sources into plant-available inorganic forms, NM practices contribute to sustained soil fertility, agronomic productivity, and environmental sustainability when implemented prudently. By strategically facilitating nature's processes of mineralization and immobilization, balanced NM practices hold potential to enhance nutrient availability and cycling in a way supportive of both agricultural and ecological priorities over the long term	(Debnath et al., 2023; Liu et al., 2023b)	➢ The innate diversity of soil conditions and intricate web of interdependencies surrounding nutrient management protocols do indeed complicate the rigorous study of nutrient mineralization dynamics. To surmount such obstacles demands a nuanced examination of edaphic particularities, microbial consortia, climatic influences, organic substrate traits, and application of sophisticated simulation techniques. A deeper dive into these intricacies holds promise to refine our comprehension of mineralization mechanisms at play within and across sites. Only through such diligent, multifaceted investigation can more informed strategies be developed to optimize nutrient mineralization processes in a manner aligned with agricultural productivity and environmental protection objectives alike
Soil structure formation, soil health	The NM practices on soil structure formation is the improvement of soil aggregation and stability	The impacts of NM practices upon soil structural vary based on soil type, climate regime, organic matter quality, and management practices. NM practices are able to stimulate organic matter dynamics, microbial activity, and carbon sequestration, leading to the formation and stability of soil aggregates, which contribute to soil structure formation	(Joshi et al., 2023; Reilly et al., 2023; Xie et al., 2022)	➢ Indeed, the inherent soil variations and complex interactions pose challenges when studying the influences of NM practices on soil structure formation. To overcome these challenges, it is crucial to examine soil-specific factors, microbial dynamics, water management, nutrient equilibrium, and organic matter decomposition. A deeper involvement into these features, we can improve our considerate of soil structure formation and optimize NM practices consequently. This will enable us to develop effective

(continued on next page)

Table 2 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
				strategies for promoting healthy soil structure and enhancing overall soil health

various studies conducted in this field (Abad et al., 2023; Ball et al., 2023; Díaz et al., 2021; Wang et al., 2023b; Zhang et al., 2023e). For example, with drip irrigation or deficit irrigation, the IT play an essential in determining soil chemical properties, with substantial impacts on soil salinity (Weldewahid et al., 2023; Zhang et al., 2023b), pH (Ewald et al., 2022; Kama et al., 2023; Weldewahid et al., 2023), nutrient leaching (Rath et al., 2021; Song et al., 2022), nutrient availability (Bao et al., 2023; Majumdar et al., 2023; Moulia et al., 2023), soil erosion (Chen et al., 2023c; Zhu et al., 2024b), and waterlogging (Nóia Júnior et al., 2023; Zhang et al., 2022b). Additionally, IS or well-managed irrigation can help mitigate nutrient losses that may occur through processes like leaching or surface runoff (Mañas and De las Heras, 2024; Zang et al., 2024), as summarized in Table 5.

Prudent implementation of IM, such as efficient water application, adequate drainage, and timely scheduling, is pivotal for sustaining optimal conditions that support agricultural viability(Wudil et al., 2022). Notably, studies underscore the potential risks associated with the use of unconventional water resources, like treated wastewater, for irrigation. Such practices have been linked to elevated soil salinity (Gao et al., 2021; Zhang et al., 2023c) and inhibited enzyme activities (Ben Hassena et al., 2022; Nemera et al., 2023), posing threats to soil health and accelerating degradation (Mishra et al., 2023; Zhou et al., 2023c).

Furthermore, IM have visible effects on properties such as pH (Kama et al., 2023), cation exchange capacity (Ibrahimi et al., 2022; Werheni Ammeri et al., 2023), and OM content (Chen et al., 2023d). The use of wastewater for IM purposes introduces complexities in nutrient levels, including nitrogen and phosphorus (Bao et al., 2023; Moulia et al., 2023), as well as elements like sodium, chloride, copper, zinc, and cadmium (Ma et al., 2021a; Simhayov et al., 2023; Zhou et al., 2023c). The potential for heavy metal accumulation poses a risk to soil quality, highlighting the need for careful consideration and management.

In addition to its impact on soil chemical properties, IM also significantly influence biological properties(Haoyu et al., 2023; Omer et al., 2023). This includes effects on microbial activity (Haoyu et al., 2023) and diversity (Majumdar et al., 2023), OM decomposition (Núñez and Schipanski, 2023; Weldewahid et al., 2023), fauna activity (Benjlil et al., 2024; Ewald et al., 2022; Radini et al., 2023), mycorrhizal associations (Aganchich et al., 2022; Das et al., 2022), and disease dynamics (Mihretie et al., 2022a; Romero et al., 2022; Schattman et al., 2023). Therefore, adopting prudent IM practices is paramount to maintaining soil health, preventing deterioration, and ensuring sustainable agricultural practices.

3.6. Mulching systems

MS exerts a profound influence on SCBPPs through a myriad of mechanisms. There are two types of MS of soil: Organic (MS $_{organic}$), and inorganic materials (MS $_{inorganic}$).The MS $_{organic}$ extends to significant effects on soil chemical properties (Biswas et al., 2022; Palsaniya et al., 2023), when incorporated into soils as plant residues, wood chips, or compost (Cai et al., 2023). contribute to the enhancement of soil OM (Yang et al., 2023a, 2023b), leading to improved nutrient availability (Biswas et al., 2022; Yang et al., 2023a; Zhang et al., 2023b), even can have a minor influence on soil pH (Micallef et al., 2023; Zhou et al., 2023a), water conservation (Gatea Al-Shammary et al., 2023; Palsaniya et al., 2023) or improve soil water retention(Tuure et al., 2021; Wang et al., 2023a), enhance nutrient cycling, which can increase the soil's fertility and plant growth (McAmis et al., 2024), temperature regulation (Zhao et al., 2023c; Zou et al., 2021), weed suppression (Choudhary, 2023), and microbial activity (Hao et al., 2023). A comprehensive overview is provided in Table 6. Despite this, the use of MS $_{inorganic}$, for example plastic or gravel, can have different effects on the soil, although these types of mulches can effectively inhibit weed growth (Choudhary, 2023; Mairata et al., 2023; von Cossel et al., 2023), mitigate soil erosion (Carrà et al., 2022; Fan et al., 2023), and retain soil moisture (Zhao et al., 2023a), their impact on soil organic matter concentration and organic activity is often limited (Campanale et al., 2024; Ma et al., 2021b), which can indirectly influence soil productivity. Furthermore, they may not contribute directly to the improvement of SCBPPs (Bandyopadhyay et al., 2023b).

Thus, implementation of appropriate mulching emerges as a pivotal strategy to bolster soil fertility, elevate water use efficiency, and enhance overall soil health.

Moreover, MS organic engenders numerous positive effects on soil biological properties (Al-Shammary et al., 2020; Huang et al., 2023a; Tesfuhuney et al., 2022), including enhanced microbial activity (Bo et al., 2024; Han et al., 2023), increased OM (Huang et al., 2023a), improved water content and temperature conditions (Al-Shammary et al., 2020; Liu et al., 2022a), erosion control (Fan et al., 2023; Wang et al., 2023a), and heightened earthworm activity (Carpena-Istan et al., 2024; Liu et al., 2021). The incorporation of organic mulches into soils enriches them with OM, fostering robust nutrient cycling processes and water retention. MS $_{inorganic}$, though effective in influencing nutrient availability and soil temperature, might pose challenges to water infiltration under specific conditions (Fan et al., 2023; Thakur and Kumar, 2021; Xing et al., 2022).

In essence, the positive impact of mulching regimes on SCBPPs varies depending on factors such as the type and amount of mulch applied, prevailing climatic conditions, soil type characteristics, and adopted management strategies. The details regarding how different MS can influence SCBPPs are meticulously outlined in Table 6.

4. Discussion and limitations

This paper reviews the multifaceted influence of AM practices on SCBPPs across diverse soil treatments, emphasizing their pivotal role in fostering understanding on how these practices influence soil fertility, nutrient availability, microbial activity, and overall soil health for sustainable agriculture. The significance of AM such as TP, NM, CR, and IM, is emphasized, as well as the role of MS in enhancing soil quality and agricultural productivity and contributing to improve food security, including increased food availability, accessibility, and utilization (Liao et al., 2021; Zhang et al., 2023a).

The tangible impact of AM on SCBPPs is evident across various dimensions. TP intricately influences soil compaction (Barbosa, 2020), soil organic carbon (Sharma and Singh, 2023), erosion risk, water dynamics, and soil diversity fauna (Coulibaly et al., 2022). The study carried out by Barbosa (2020) efforts on the examination of soil structure and tillage techniques in agriculture, with a focus on seedbed preparation, showed that soil aggregates, which are produced by the combination of soil particles, play a crucial role in determining soil structure and performing many activities. These aggregates are affected by aspects such as soil type, moisture content, and the presence of organic matter. Sharma and Singh (2023) investigate the impact of different levels of soil ploughing and the method of keeping straw on the agricultural land on the physical features of the soil in a rice-wheat farming system in Punjab, India. The

Table 3
Impact of crop rotation (CR) upon edaphic chemical attributes and biotic activity.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Nutrient availability	CR affects nutrient availability through cycling, pest control, organic matter input, microbial interactions, and nutrient balance	CR manages nutrient-extractive and nutrient-additive cultivars by alternating nutrient-depleting and nutrient-accumulating crops, maintaining overall nutrient balance, preventing deficiencies or excesses, and ensuring optimal nutrient availability for subsequent crops. So, through judicious variation, nutrient availability remains optimized across plantings to sustain agronomic productivity, soil fertility and ecological integrity in an enduring manner	(Liu et al., 2023e; Yang et al., 2023c; Zou et al., 2023)	Implementing prudent CR can facilitate nutrient availability through balanced nutrient release and uptake, balancing demands placed upon nutrient reservoirs, but limitations persist. Future investigations would do well to illuminate nutrient cycling dynamics, crop- and site-specific nutritional necessities, soil microbial interactions, long-term repercussions, integrated methods, and site-specific factors attuned to local ecological contexts. Only through such nuanced, multifaceted inquiry can we hope to optimize nutrient stewardship and safeguard agricultural viability, and environmental protection objectives
	Organic matter content	CR influences organic matter content by adding residues, promoting decomposition, and stimulating microbial activity, leading to increased organic matter in the soil	CR increases organic matter content through residue addition, decomposition, and stimulation of microbial activity	(Liu et al., 2024a; Liu et al., 2023d; Niether et al., 2023; Zheng et al., 2023)	The CR can influence positively soil organic matter endowments and its associated benefits; limitations persist in our comprehensive grasp. Future studies should focus on quantifying organic matter contributions, elucidating long-term effects, exploring soil carbon sequestration potential, investigating CR practices, examining soil microbial communities, accounting for environmental particularities, offering a pathway to optimize the use of CR for enhancing soil organic matter content in diverse agricultural systems, only through nuanced, interdisciplinary investigation can we cultivate rotational systems attuned to safeguarding both agricultural productivity and ecological services for generations to come
	pH balance	CR impacts pH balance through acidification or alkalization, organic matter decomposition, and nutrient availability.	Different crops have varying influences on the pedogenic pH of the soil. Some crops can cause soil acidification, while others can lead to soil alkalization trajectories. By CR, agriculturalists can manage and regulate soil pH conditions to create optimal conditions for plant growth and nutrient availability	(Liu et al., 2024a; Sun et al., 2022; Wu et al., 2024)	The CR can help manage soil modulate pH conditions by considering the pH influences of different crops, limitations persist in comprehending these dynamics comprehensively. Future studies should focus on quantifying pH fluctuations induced by diverse cultivars, characterizing crop-specific pH responses, illuminating soil buffering capacity, investigating long-term effects, exploring nutrient interactions, and considering regional factors. This investigation would enhance our information on the relationship between CR and soil pH, providing valuable guidance for sustainable soil management practices
	Soil nutrient balance	CR affects soil nutrient balance, by reducing nutrient imbalances, improves nutrient cycling, and promotes sustainable nutrient management practices	The CR benefits mitigate nutrient reduction or growth in soil, and different crops have varying nutrient supplies and uptake patterns. By incorporating crops with different nutrient requests in rotation, a more stable nutrient profile is preserved, dropping the risk of deficiencies or imbalances. Additionally, CR improves nutrient cycling, as different crops contribute to organic endowments and microbial consortia central, promoting nutrient availability, and agricultural productivity	(Hanrahan et al., 2023; Jahan et al., 2016; Kaur et al., 2024)	The CR is effective in maintaining soil nutrient balance, but gaps persist in our comprehensive understanding of these systems. Future investigation should focus on nutrient cycling dynamics, crop-specific requirements, environmental particularities, site-specific factors, integrated approaches, and long-term effects. This research would enhance our knowledge of how CR optimizes soil nutrient management for sustainable agriculture and safeguarding soil fertility
	Weed and pest management	CR affects pest management, through the breakdown of pest habitat, reduction of pest pressure, beneficial	Judicious CR, offers means to disrupt pest life cycles, reduce pest pressure, help beneficial insects, and handle pest-related diseases. It breaks pest	(Mwenda et al., 2023; Orek, 2024)	CR can contribute to weed and pest management, future studies should focus on investigating pest and disease dynamics, crop-specific vulnerabilities,

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Table 3 (*continued*)

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
		insect promotion, and management of soil-borne diseases	habitats, lowers pest populations, attracts helpful insects, and prevents the persistence of pathogens. This sustainable approach minimizes pesticide use and promotes healthier crops		integrated pest management approaches, herbicide resistance and weed management, and the long-term effects of crop rotation. By conducting such studies, we can enhance our knowledge of how to optimize crop rotation to promote effective weed and pest control, reduce reliance on chemical pesticides, and foster a healthier soil environment
Biological	Soil microbial diversity	The CR on soil microbial diversity is the promotion of a diverse and balanced microbial community	Because of changing resource availability, it creates diverse soil conditions, disrupting pathogen and pest cycles, influencing nutrient cycling, and altering organic matter inputs	(Ansari et al., 2024; Li et al., 2023b)	The CR promotes greater microbial diversity in the soil, but there are limitations and gaps in our understanding. Future studies should focus on quantifying microbial diversity, characterizing functional microbial groups, assessing long-term effects, investigating crop-specific effects, and linking microbial diversity to soil health parameters. These studies would enhance our knowledge of how CR practices can cultivate microbial communities. They would also contribute to sustainable soil management
	Beneficial microbial activity	Effects of CR on beneficial microbial activity are the enhancement of microbial diversity, population size, and activity in the soil	This is because of the diverse root exudates, organic residues, and plant debris provided by different CR	(Liu et al., 2024b; Ma et al., 2024)	The CR can stimulate beneficial microbial activity in the soil, however, there are limitations and gaps in our understanding. A further study with more focus on quantifying beneficial microbial activity, exploring crop-specific effects, investigating the underlying mechanisms of microbial contribution, conducting field-scale studies, and evaluating the long-term effects are therefore suggested. These studies would enhance our knowledge of how crop rotation practices can optimize beneficial microbial interactions and contribute to sustainable soil management
	Organic matter decomposition	CR on organic matter decomposition is the stimulation of microbial activity and enhanced decomposition rates	Different CRs have varying qualities and quantities of organic matter inputs. When crops are rotated, CR supports the growth and activity of diverse microbial populations, leading to accelerated breakdown of organic materials and nutrient cycling in the soil	(Bo et al., 2024; Liu et al., 2023d)	The CR has been widely acknowledged for its positive effects on organic matter decomposition and soil health. However, limitations and gaps remain in studies on CR and organic matter decomposition. These limitations include limited long-term studies, an evolving understanding of microbial community dynamics, a lack of research on interactions with other management practices, and insufficient investigation of specific organic matter fractions
	Pest and disease suppression	CR is the suppression of pests and diseases	Because of disrupting life cycles, reducing buildup, altering habitats, promoting natural control, improving soil health, and reducing pesticide reliance	(Liu et al., 2023e; Niether et al., 2023; Theron et al., 2023)	The general benefits of CR for pest and disease management are well established. However, limitations and gaps remain in studies on CR and pest/disease management that include: limited long-term research, evolving understanding of ecological interactions, lack of standardized protocols, and the need for multi-tactic strategies
	Earthworm activity	The CR on earthworm activity is generally positive. Crop rotation can increase earthworm abundance, enhance soil structure, improve nutrient cycling, and influence soil organic matter composition	The CR causes of introduction of diverse crops, which provide a range of organic inputs, enhance soil structure, improve nutrient cycling, and influence soil organic matter composition. These factors collectively contribute to a healthier soil environment, supporting increased earthworm abundance and activity	(Denier et al., 2022; Drut et al., 2023)	The CR has positive effects on earthworm activity, though limitations and gaps remain in our understanding. Future research should focus on site-specific responses, species diversity, long-term effects, and interrelations with other soil factors. It should also include quantitative assessments. This improved understanding will help elucidate the complex relationships between crop rotation and earthworm activity. In turn, it can lead to more

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Table 3 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
				effective soil management practices and sustainable agricultural systems

study findings show that both tillage intensity and straw retention had a substantial impact on the soil characteristics under study. Conservation tillage measures, such as reduced tillage and no-tillage, often increase soil organic carbon, or SOC, levels, enhance phosphorus (P) availability, and stimulate biological activity within soil aggregates. The study conducted by Coulibaly et al. (2022) showed that the use of conservation TP, namely no-tillage methods, has the potential to augment soil biodiversity and promote soil quality and health. Nevertheless, the reaction of several soil fauna groups to mechanical disturbance of the soil indicated variation. The outcomes show the significance of taking into account the degree, frequency, and timing of tillage, as well as additional parameters including climate and crop growth stages, when evaluating the effect of tillage practices on the biodiversity of soils and the functioning of ecosystems.

NM, including fertilizers, emerges as a linchpin for maintaining nutrient balance (Cheng et al., 2023), averting acidification (Kong and Lu, 2023), and ensuring optimal nutrient availability. Cheng et al. (2023) emphasize the need of employing suitable irrigation and fertilization techniques for potato farming in sandy areas. The paper highlights the significance of managing water and fertilizer management to improve agricultural output and improve efficiency in resource utilization. The findings of this study can aid in the advancement of sustainable potato cultivation methods, especially in areas characterized by sandy soils and constrained water resources. The study executed by Kong and Lu (2023) investigates the impact of inorganic amendments on acidic paddy soils. The research especially studies alterations in soil characteristics, aluminum fractions, and microbial communities. Research findings underscore the positive impact of integrated NM on soil productivity and protection against degradation.

CR, a strategic tool for breaking pest and disease cycles, managing weeds, and enhancing soil health, significantly contributes to soil fertility and microbial diversity (Ansari et al., 2024; Li et al., 2023b; Yang et al., 2023a). Ansari et al. (2024) examined the influence of rice-wheat and sugarcane-wheat CR on microbial diversity and the presence of bacteria that promote plant development (PGPB). High-throughput sequencing and soil analysis methods were used in the study to evaluate the microbial populations. The findings showed that PGPB quantity and microbial diversity were highly impacted by CR. In comparison to the sugarcane-wheat cycle, the rice-wheat rotation showed better microbial diversity and a larger presence of beneficial PGPB. These results emphasize how crucial CR is for influencing the microbial populations in the soil and encouraging plant development.

IM plays a crucial role in shaping soil water content, drainage, pH, nutrient availability and salinity, demanding prudent management to mitigate adverse effects such as waterlogging or drought stress (Majumdar et al., 2023; Weldewahid et al., 2023; Zhu et al., 2024b). The research investigation performed by Weldewahid et al. (2023) examines the impacts of improved IM on soil quality and the levels of organic carbon and total nitrogen in the dry areas of Ethiopia. The study's findings indicate that prolonged IM had significant effects on soil quality and the levels of organic carbon and total nitrogen.MS, especially those incorporating organic materials contribute to soil OM, nutrient cycling, water-holding capacity, and temperature, thereby benefiting soil biota and overall soil health. These results match those observed by (Ball et al., 2023; Graham et al., 2022; Haoyu et al., 2023; Majumdar et al., 2023).

CR emerges as a strategic tool for enhancing soil fertility and microbial diversity(Ansari et al., 2023; Denier et al., 2022). OM management demonstrates the potential to increase SOC content and influence soil chemical composition (Duan et al., 2022; Gilmullina et al., 2023; Mabagala and Mng'ong'o, 2022). The study conducted by Gilmullina et al. (2023) investigates the impact of plant biomass input on the processes of SOC content in grassland soil under various management strategies. The study aims to compare two divergent grassland management systems: intense fertilized management (IFM) and extended unfertilized management (EUM). The study findings suggest that the amount of plant biomass added to the soil is essential in the development of soil organic matter. The researchers discovered that the IFM grasslands, which got elevated levels of fertilization and had more input of plant biomass, demonstrated higher SOC content in comparison to the EUM grasslands.

Various tillage methods exhibit differing effects on soil properties, with NT practices demonstrating benefits in terms of SOC, soil water-holding capacity, soil quality, nutrient availability, and microbial biomass (Hashimi et al., 2023; Korniłłowicz-Kowalska et al., 2022; Palsaniya et al., 2023). Hashimi et al. (2023) show that no-tillage and rye cover crop systems may enhance the ability of Andosols to retain water in regions with a humid subtropical climate. The study emphasizes the significance of increased SOC, which arises from these activities, for improving the capacity of soil to retain water. Proper IM emerges as a crucial factor for maintaining soil health, with careful monitoring required for the use of conventional and unconventional water resources for irrigation due to potential impacts on soil salinity and enzyme activities. In addition, Korniłłowicz-Kowalska et al. (2022) investigate the effect of tillage and no-tillage methods on the growth of culturable fungus populations in the rhizosphere and soil of two spelt cultivars. The study examines the influence of different tillage strategies on the incidence and variety of fungi that are connected to spelt plants.

MS, particularly those incorporating organic materials, significantly contribute to soil OM, nutrient cycling, soil structure, and favourable conditions for soil biota. The amalgamation of these agronomic practices is poised to improve SCBPPs, fostering sustainable agriculture and soil quality(Biswas et al., 2022; Bo et al., 2024; Cai et al., 2023). The study conducted by Cai et al. (2023) examines the effect of straw mulching on the composition and depletion of dissolved organic matter (DOM) in surface runoff from agricultural land. The study establishes that the use of straw mulching prevents the breaking apart of tiny macroaggregates in the soil, which in turn causes alterations in the content and depletion of dissolved organic matter in surface runoff. Biswas et al. (2022) investigate the impact of mulching and fertilizer application on the water balance of the soil and the actual evapotranspiration during the production of winter cabbage with irrigation. This study examines the effect of various mulching materials and fertilizer treatments on water availability and plant water consumption in winter cabbage production.

Acknowledging the robust findings, certain limitations in the study of AM on SCBPPs are recognized.

1. The existing literature on the impact of agronomic practices on SCBPPs might be biased towards specific countries and regions or agricultural systems. To capture the variability and generalizability of the findings, studies in diverse geographical locations are necessary.
2. A number of studies have examined the full range of effects of AM on soil microorganisms. However, the study focuses on specific soil microorganisms such as mycorrhizal fungi, nitrogen-fixing bacteria, and beneficial nematodes to further our understanding of their contributions to soil health and nutrient cycling provide knowledge of their contribution to reproduction and ecosystem function.

Table 4
Influence of organic matter (OM) management on soil chemical and biological properties.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Soil organic carbon content (SOC)	The OM management on SOC is the increase or decrease in SOC levels based on the specific OM management practices employed	OM management may promote the input, preservation, and accumulation of organic matter generally leading to an increase in SOC, while practices that result in the loss or decreased input of organic matter can lead to a decrease in SOC	(Gilmullina et al., 2023; Mabagala and Mng'ong'o, 2022; Urbanski et al., 2023)	The OM management is acknowledged to directly affect SOC content and associated benefits. However, limitations and gaps remain in our understanding. In terms of directions for future research, further work could focus on quantification and monitoring, understanding site-specific factors influencing responses, investigating the processes of SOC sequestration, studying microbial interactions, and adopting multi-faceted strategies. Addressing areas requiring further research will contribute to more effective soil management strategies that optimize SOC content and promote sustainable agricultural practices
	Nutrient content and availability	The OM management on nutrient content and availability in the soil is the overall improvement and enrichment of nutrient levels	Organic matter serves as a source of nutrients and plays a crucial role in nutrient cycling and availability in the soil	(Feng et al., 2023; Mabagala and Mng'ong'o, 2022; Prats et al., 2023)	The influence of organic matter on nutrient content and availability in soil is acknowledged. However, various areas requiring further research remain, such as nutrient release processes, organic matter quality, microbial interactions, site-specific factors influencing responses, and nutrient interrelations with organic matter management practices. Addressing these knowledge gaps will contribute to the development of more effective and sustainable soil fertility management strategies. This improved understanding can help optimize nutrient management in agricultural systems, promote sustainable crop production, and minimize environmental impacts
	Cation exchange capacity (CEC)	Effect OM management on CEC is the overall increase and enhancement of CEC in the soil	OM management practices that increase the input, accumulation, and quality of organic matter have been shown to contribute to higher CEC values. OM has a high CEC due to its anionic functional groups. When OM inputs are incorporated into the soil through management practices such as adding compost, manure, cover crops, or crop residues, it augments the overall CEC of the soil	(Jeon et al., 2023; Mabagala and Mng'ong'o, 2022)	This establishes the relationship between OM and CEC, with various areas requiring further elucidation including: soil mineralogy, organic matter quality and biochemical components, temporal dynamics, and the nuanced nature of accurately measuring CEC. The effect of OM management practices on CEC can also vary depending on site-specific factors influencing responses. Addressing these knowledge gaps can inform soil management practices aimed at optimizing nutrient availability, improving soil fertility, and promoting sustainable agricultural systems
	Soil pH	OM management affects soil pH by pH buffering	OM management practices that increase the input, accumulation, and quality of organic matter have been shown to augment pH buffering, thereby facilitating the preservation of a favourable pH range for plant growth and nutrient availability conducive to crop needs	(de Santana et al., 2022; Duan et al., 2022)	OM management has been shown to impact soil pH. However, various areas requiring elucidation remain, including understanding soil buffering capacity, the specific biochemical constituents of amendments, long-term influences on pH, interactions with soil properties, and crop-specific pH requirements. Addressing these knowledge gaps can contribute to more informed and targeted OM management practices that optimize pH conditions to support plant growth and nutrient availability
	Soil fertility	The effects of OM management on soil fertility is the improvement of nutrient content and availability in the soil	The OM is a rich source of nutrients and plays a vital role in nutrient cycling and availability. When organic matter is managed effectively, it can lead to improving soil structure and water-holding capacity and promoting optimal pH conditions. These improvements create a fertile soil environment that supports healthy plant growth and sustainable agricultural practices	(Fontúrbel et al., 2023; Liu et al., 2024a; Mabagala and Mng'ong'o, 2022)	Various aspects meriting additional research remain in our understanding of organic matter's role in soil fertility. Nutrient release dynamics from organic matter present challenges for accurately predicting and managing nutrient availability. Elucidating complex nutrient interactions resulting from organic matter management practices also warrants investigation. The

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Table 4 (*continued*)

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
					contributions of soil microorganisms to nutrient release and cycling warrant investigation. Long-term effects of organic matter management on soil fertility merit examination. Context-specific factors also highlight the importance of accounting for site-specific factors for developing effective strategies
	Water holding capacity (WHC)	The OM management on WHC is the improvement of the soil's ability to retain and store water	OM has unique properties that enhance WHC in the soil. When OM is managed effectively, it can contribute to better water availability for plants, reduce water stress, and promote more efficient water use in agricultural and natural ecosystems	(Inagaki et al., 2023; Li et al., 2023a; Védère et al., 2022)	OM improves soil WHC, but various aspects requiring elucidation remain in our understanding. Soil structure/texture and OM content differentially impact WHC. Differential water-holding capacities exist among OM types. Soil moisture dynamics influence WHC. Dynamics over time can alter the WHC of OM via processes like decomposition. Effects on WHC can differ depending on soil/climate/management. Addressing these aspects will contribute to a more comprehensive understanding of soil water dynamics, informing practices to improve water retention/availability for plants
Biological	Microbial activity	Increased OM management enhances soil microbial activity	It provides a rich substrate for microbial growth and activity, leading to improved nutrient cycling, enhanced decomposition of organic matter, and the proliferation of beneficial microorganisms. These effects contribute to healthier soils, improved plant growth, and the overall sustainability of agricultural and natural ecosystems	(Fontúrbel et al., 2024; Man et al., 2023; Miao et al., 2023)	OM management practices have been shown to increase microbial activity in soil. However, various aspects requiring elucidation should be addressed. Future research should focus on microbial community composition, processes/functions, interactions, influences of environmental factors such as soil moisture/temperature/pH/nutrient availability, and the development of improved assessment techniques. Addressing these knowledge gaps will enhance understanding of complex relationships between OM management and microbial activity, leading to more effective soil management and improved agricultural sustainability
	Microbial diversity in soil	The OM management increases microbial diversity in the soil.	It provides a variety of carbon sources and nutrients, creating favourable conditions for the growth and proliferation of diverse microbial species	(Jin et al., 2023; Liu et al., 2024a; Man et al., 2022)	OM management can influence microbial diversity in soil. However, various features requiring elucidation need addressing. Future research should focus on identifying and quantifying diversity, understanding specific microbial group responses, investigating long-term effects, exploring interactions with soil properties, and examining functional diversity and redundancy. Addressing these knowledge gaps will contribute to a more comprehensive understanding of the relationships between OM management and diversity, leading to improved soil management and enhanced health
	Soil enzyme activity	The OM management influences soil enzyme activity	The addition of organic matter through OM management serves as a substrate and energy source for soil microorganisms. These microorganisms produce various enzymes to depolymerize complex organic compounds present in the organic matter. As a result, soil enzyme activity becomes elevated, thereby promoting the decomposition and transformation of organic matter into simpler forms	(Fontúrbel et al., 2023; Gilmullina et al., 2023; Shaaban et al., 2023)	It is well-established that OM management can influence soil enzyme activity. However, various aspects requiring additional research remain. Future research should focus on developing standardized enzyme assays/substrates, elucidating interactions between amendments/substrate availability/enzyme activity, determining connections between microbial communities/enzyme production/activity, evaluating stability/persistence of activity over time, and exploring functional implications of increased activity. Addressing these knowledge gaps will contribute to a more comprehensive

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Table 4 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
				understanding of the relationships between OM management, enzyme activity, and soil functioning
Soil respiration	Increased OM management boosts soil respiration	It provides a greater supply of carbon for soil microorganisms, stimulating their metabolic activity and leading to increased rates of soil respiration	(Ansari et al., 2023; Cucina, 2023; Verrone et al., 2024)	Soil respiration is widely recognized as an important indicator of microbial activity and nutrient cycling in response to OM management. However, various aspects requiring additional research remain. Additional research should explore spatial and temporal variability of respiration, distinguishing microbial and plant contributions, investigate effects of carbon source/quality, evaluating the role of nutrient limitations, examining long-term effects, and considering broader greenhouse gas emissions. Addressing these knowledge gaps will contribute to a more comprehensive understanding of the relationships between OM management, soil respiration, and health
Earthworm and soil fauna activity	OM management increases earthworm and soil fauna activity	It provides a favourable habitat and food resources for these organisms	(Hagner et al., 2023; Wen et al., 2023b; Xu et al., 2023)	OM management practices can stimulate earthworm and soil fauna activity. However, various aspects requiring elucidation remain. Future research should focus on understanding species-specific responses, developing standardized quantification methods, elucidating functional roles and interactions, examining long-term effects, and accounting for context dependency of responses to OM management. Addressing these knowledge gaps will contribute to a more comprehensive understanding of the relationships between OM management, activity, and soil health
Disease suppression	OM management practices enhance disease suppression.	OM management practice helps the growth and activity of beneficial microorganisms in the soil, which can out-compete and overpower harmful pathogens. Additionally, organic matter amendments can advance soil health and increase the flexibility of plants, making them more resistant to diseases. OM practices with disease suppression can be judiciously calibrated to nurture agroecosystemic equilibrium	(Deng et al., 2020; Dignam et al., 2019; Ogundeji et al., 2022)	OM management can impact disease suppression in soils, though several features merit further investigation. Future investigation should focus on clarifying the specificity of suppression, discerning dynamics and mechanisms of microbial responses, assessing influences of environmental factors, investigating long-term effects, and addressing questions regarding on-farm adoption. Addressing knowledge gaps will augment understanding of relationships between OM management, disease suppression, and agriculture sustainably
Mycorrhizal associations	OM management practices have a positive effect on mycorrhizal associations	OM practices enhance the availability of organic nutrients, providing a bolstering constitution for mycorrhizal fungi to establish and thrive. Mycorrhizal fungi form symbiotic associations with plant roots, facilitating nutrient uptake and enhancing plant growth and resilience. OM management practices can contribute to the enrichment of soil organic matter, which supports the establishment and activity of mycorrhizal associations, leading to improved nutrient acquisition and overall plant health	(Chen et al., 2023a; Jin et al., 2022; Yin et al., 2021)	OM management positively influences mycorrhizal associations, enhancing nutrient uptake and promoting plant growth. However, various aspects warrant further investigation. Future research should focus on elucidating the specificity of responses, discerning mechanisms/nutrient dynamics, evaluating the influence of soil conditions and tillage practices/plant responses, examining long-term effects, and accounting for synergies with other agricultural practices. Addressing these knowledge gaps will enhance understanding of relationships between OM management, associations, and plant nutrient acquisition

3. The lack of standardized protocols and methodologies for assessing soil properties under agronomic practices hinders result comparability. Creating such standards is vital for reliable and robust future studies, ensuring consistency in evaluating agronomic impacts on soil. This lack impedes meaningful comparisons, underscoring the need for uniformity to advance precision in research findings.
4. Further investigation is needed to understand the effects of AM on soil water dynamics, encompassing infiltration rates, water-holding capacity, and water availability for plant uptake. Investigating

Table 5
Influence of Irrigation management (IM) practices on soil chemical and biological properties.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Soil Salinity	IM practices directly influence soil salinity levels	IM practices control the amount and distribution of water applied to the soil, which directly affects the movement and concentration of salts within the soil profile. Improper IM practices can lead to the accumulation of salts in the root zone, resulting in increased soil salinity levels. Conversely, appropriate IM practices can help prevent salt buildup and maintain optimal soil salinity levels for plant growth	(Weldewahid et al., 2023; Zhang et al., 2023d; Zheng et al., 2023g)	The negative impacts of soil salinization and the importance of proper IM practices are recognized, though various aspects merit additional investigation. Future research should evaluate the role of site-specific factors, undertake long-term monitoring, elucidate the potential of integrated approaches, and discern ecological consequences of soil salinity under IM. Addressing knowledge gaps will contribute to more effective salinity management and sustainable agricultural practices
	pH	IM practices have been shown to impact soil pH	IM practices can introduce water with different pH levels to the soil, which can alter the pH of the soil over time. The pH of irrigation water, along with the choice of fertilizers and amendments used during irrigation, can contribute to changes in soil pH. Proper IM practices can help maintain the desired pH range for optimal plant growth and nutrient availability	(Ewald et al., 2022; Kama et al., 2023; Weldewahid et al., 2023; Zong et al., 2023)	The impact of IM practices on soil pH is recognized, though various aspects merit additional elucidation. Future research should evaluate the influence of regional/water variability, examine long-term effects, elucidate soil buffering capacity, discern crop-specific responses, and elucidate interactions regarding nutrient availability and pH. Addressing knowledge gaps will contribute to more effective water management and sustainable systems
	Nutrient leaching	IM practices on soil nutrient leaching are that they can either increase or decrease the leaching of nutrients from the soil	Water application rates, timing of irrigation, and choice of method can impact the movement of water and nutrients within soil. Improper practices can lead to excess leaching, resulting in nutrient loss beyond the root zone. Conversely, proper management can mitigate leaching by optimizing the application, aligning with plant demands, and selecting appropriate methods	(Graham et al., 2022; Rath et al., 2021; Song et al., 2022)	The impacts of IM practices on nutrient leaching are recognized, though various aspects merit additional investigation. Future research should evaluate through quantification, assess the influence of site factors, discern impacts of nutrient sources/forms, elucidate the potential of integrated approaches, and determine environmental impacts. Addressing knowledge gaps will optimize nutrient/IM practices and sustainability
	Nutrient Availability	IM practices on nutrient availability are that they can either enhance or reduce the availability of nutrients in the soil	By facilitating nutrient movement, incorporation, and release, as well as supporting microbial activity, proper irrigation practices optimize nutrient cycling and availability for plants. However, improper practices can lead to nutrient losses, uneven distribution, and water stress, reducing availability	(Bao et al., 2023; Majumdar et al., 2023; Moulia et al., 2023)	IM practices influence nutrient availability, various aspects merit additional investigation. Further research should evaluate dynamics through quantification, assess the influence of soil heterogeneity, discern impacts of crop-nutrient interactions, determine sources and magnitude of losses, and incorporate factors relating to water quality. Addressing knowledge gaps will optimize practices and strategies for sustainable agriculture
	Soil Erosion	The effect of IM practices on soil erosion is that they can either mitigate or exacerbate erosion processes	Proper IM practices such as effective management, erosion structures, maintaining cover, conservation practices and drainage can reduce the potential for erosion. These practices regulate application, diminish runoff, promote deposition, safeguard the surface and maintain structure. However, poor practices including over-irrigation, improper distribution and inadequate control measures risk exacerbating erosion through excessive runoff, waterlogging and lack of safeguards	(Chen et al., 2023b; Zhu et al., 2024)	The impacts of IM practices on erosion are recognized, but various aspects merit additional investigation. Future research should evaluate through quantification, assess the influence of site factors, incorporate control measures, examine long-term effects, and incorporate socioeconomic considerations. Addressing knowledge gaps will optimize conservation efforts and sustainable practices
	Waterlogging	IM practices on waterlogging in soil is that they can either mitigate or exacerbate the issue	Proper IM management, effective drainage, appropriate scheduling and attention to structure/permeability can reduce the potential for waterlogging. Conversely, over-irrigation, inadequate drainage and	(Nóia Júnior et al., 2023; Prajapati et al., 2021; Zheng et al., 2022)	The impacts of IM on waterlogging are recognized, but various aspects merit additional investigation. Future research should evaluate through quantification of effects, assess the influence of site factors, elucidate

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Table 5 (*continued*)

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
			improper grading can heighten risks. It is important to incorporate practices that facilitate the maintenance of optimal moisture, efficacious drainage and healthy conditions to minimize waterlogging risks		redox/nutrient dynamics, discern plant responses, and appraise integration of approaches. Addressing knowledge gaps will optimize prevention strategies and soil management sustainability
Biological	Microbial activity	IM practices can either enhance or inhibit soil microbial activity.	IM practices have the potential to influence soil moisture levels, nutrient availability, and organic matter decomposition, and can introduce substances that may be beneficial or detrimental to microbial populations	(Haoyu et al., 2023; Omer et al., 2023; Zong et al., 2023)	While IM practices influence microbial activity are recognized, various aspects merit additional investigation. Future research should evaluate through quantification, elucidate community dynamics, discern impacts on nutrient cycling, examine influences on oxygen limitations, and appraise long-term effects on communities. Addressing knowledge gaps will contribute to understanding irrigation, activity and soil health relationships
	Microbial diversity	IM practices can significantly impact microbial diversity in the soil, either positively or negatively	Because they influence soil moisture levels, nutrient availability, organic matter inputs, water quality, and pesticide use, all of which can directly affect the composition and abundance of microbial communities	(Haoyu et al., 2023; Majumdar et al., 2023; Zong et al., 2023)	The impact of IM practices on microbial diversity is recognized, various aspects merit investigation. Future research should assess through standardizing methods, undertaking long-term studies, elucidating connections between diversity and function, examining the influence of soil properties, and incorporating factors relating to water quality. Addressing gaps will enhance understanding of relationships between IM practices, microbial diversity and ecosystem functioning
	Organic matter decomposition	IM practices on organic matter decomposition in the soil is that they can either enhance or inhibit the process	Because they directly influence factors such as soil moisture levels, nutrient availability, oxygen levels, temperature regulation, and the incorporation of organic matter, which can either promote or hinder the activity of microbial decomposers responsible for organic matter breakdown	(Ball et al., 2023; Núñez and Schipanski, 2023; Weldewahid et al., 2023; Zong et al., 2023)	The effect of IM on decomposition is acknowledged, but various aspects merit investigation. Future examination should evaluate through quantification, elucidate microbial contributions, examine impacts on nutrient release, discern feedback effects, and incorporate factors specific to crops. Addressing knowledge gaps will contribute to understanding the relationships between management, decomposition and soil fertility
	Soil fauna activity	IM practices on soil fauna activity are that they can either enhance or inhibit the activity of soil fauna	IM practices have the potential to shape factors like moisture, habitat, nutrients, inputs and pesticide use, which potentially facilitate or impede faunal activity. Proper practices that help sustain beneficial moisture and offer conducive habitats with adequate nutrients/inputs can enhance activity. Conversely, improper practices risk-reducing activity through waterlogging, imbalances or contamination by influencing conditions for fauna to thrive. Specific effects depend on practices and ecological impact	(Benjlil et al., 2024; Ewald et al., 2022; Radini et al., 2023; Santana et al., 2021)	While most studies examine impacts of IM practices on soil fauna activity, various aspects merit investigation. Future research should assess through quantification, elucidating species-specific responses, undertaking long-term studies, examining the influence of soil properties, and appraising ecosystem-level impacts on fauna-mediated processes. Addressing gaps will enhance understanding of relationships between management, fauna and ecosystem functioning
	Mycorrhizal associations	IM practices on mycorrhizal associations is that they can either promote or hinder the establishment and functioning of mycorrhizal symbiosis in plants	Due to their direct impact on factors such as soil moisture, timing, water quality, fertilizer use, and pesticide application.	(Acharya et al., 2024; Das et al., 2022; Lü et al., 2020)	While IM influence on mycorrhizal associations is recognized, various aspects merit investigation. Future research should assess through quantification, elucidating responses of types, examining the influence of properties, discerning plant-mycorrhizal feedbacks, and incorporating factors specific to crops. Addressing gaps will enhance understanding of relationships between management, associations, and nutrient acquisition.

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Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
Disease dynamics	IM practices on disease dynamics in plants is that they can either promote or reduce the incidence and severity of diseases.	Due to their scope to shape conditions impacting factors such as moisture, pathogen dispersal, plant health/resistance, conduciveness to disease, and nutrient availability.	(Mihretie et al., 2022; Romero et al., 2022; Schattman et al., 2023)	Distinct responses to IM practices are recognized, though various aspects merit investigation. Future research should assess through examination of pathogen-specific responses, fluctuating pathogen properties, interplay with microbiota, holistic prevention approaches, and investigations at the field level. Addressing gaps will enhance understanding of relationships between IM practices, diseases, and effective strategies.

these aspects can optimize irrigation strategies, enhance water use efficiency, and bolster drought resilience in agricultural systems. This research avenue is crucial for advancing sustainable water management practices in agriculture.

5. Despite the existing research on AM effects on soil greenhouse gas emissions, including carbon dioxide, nitrous oxide, and methane, uncertainties persist. Further studies are warranted to precisely quantify emission levels associated with diverse land management approaches. Identifying practices that minimize agricultural soil's greenhouse gas output remains an important avenue for future research. Quantifying mitigation potentials holds the key to optimizing agricultural productivity while reducing atmospheric contributions to climate change. Continued exploration of interaction pathways shows promise for refining best practices that balance the environmental, economic, and social imperatives of sustainable food production.
6. Longitudinal investigations are essential for revealing the cumulative and enduring influences of AM on soil characteristics over extended timeframes. Unfortunately, the current lack of long-term experimentation limits our understanding of these critical dynamics. Sustained primary research initiatives employing multiyear experimental designs offer promising avenues to address this gap and enhance predictive understanding of soil-agriculture systems' responses to land management under changing conditions. Retrospective analyses of legacy datasets hold complementary potential to glean insights from historical practices. Prioritizing both new long-term studies and mining older records are strategic means of accelerating progress toward optimized, resilient soil stewardship for generations to come.
7. While much-existing research has focused on specific soil characteristics like nutrient cycling, OM levels, and microbial activity, a more holistic evaluation is essential. Specifically, AM influencing physical properties that regulate aeration, drainage, and water movement deserve closer examination. For instance, exploring hydraulic conductivity and aggregate stability can shape resilience to compaction and erosion. Additionally, delving deeper into microbial assemblage dynamics beyond bulk activity stands to enrich our understanding of interaction pathways and feedback mechanisms. Adopting a systems approach that incorporates linkages among CBP domains holds promise for optimizing agronomic management across diverse soil contexts and climatic conditions.
8. Agronomic management practices do not operate in isolation; they intertwine with various factors like soil composition, climate, and cultivation techniques. The interplay between these influences and their collective impacts on the land is not entirely understood, nor is their coordinated influence on the well-being of the soil, nutrient cycling, and bountiful harvests fully known. This line of inquiry can help develop agricultural methods tuned to our changing climate and enhance resilience against its variations; it deserves deeper investigation.
9. Integrating precision agriculture technologies, like remote sensing, Geographic Information Systems, and sensor-based management, with AM will likely optimize use efficiency and enhance soil health and food security.

Some constraints in this analysis must be recognized. First, the available literature exhibits variations in experimental design, soil types, climate conditions, and crop management practices, potentially influencing outcomes. Hence, caution is advised when generalizing findings across diverse agricultural systems. Additionally, the review may not encompass every possible conceivable agronomic practice due to the wide array used in different regions. Furthermore, its reliance on existing studies means it might not incorporate the latest findings beyond the knowledge cutoff date.

5. Knowledge gaps and future research directions

Future research in these areas will deepen our understanding. Our findings indicate that the main gaps can be identified in the following fields.

10. Integrating multiple soil properties and their interactions when assessing the effects of AM and mulching. This holistic approach would provide a more comprehensive understanding of soil health and functionality.
11. Evaluate the effects of AM on soil ecosystems, including macrofauna, microorganisms and microorganisms. Understanding how these processes affect soil ecosystems and their functional activities is important for sustainable soil management.
12. Investigating AM contribution to climate change adaptation and mitigation. It evaluates the possibility of storing carbon, a decrease in greenhouse gas emissions, and making the land more resilient to climate change.
13. Assessing the economic viability and social acceptance of AM, including mulching techniques. An examination of the costs, benefits, and barriers to adoption from the perspective of farmers and other stakeholders would provide insights into the practical feasibility of these practices.
14. Focusing on long-term studies and CR effects.
15. Conducting a comprehensive comparison of various mulches materials and techniques, including both organic and inorganic options like plastic, straw, and living mulches, can provide a deeper understanding of their effects on soil properties This research can elucidate the advantages and constraints of alternative mulching solutions, enabling agriculturalists and land stewards to make well-informed decisions based on their specific objectives and surrounding environmental circumstances. Undertaking such studies is essential to optimize land management practices and promote informed decision-making in agriculture.

Table 6
Influence of Mulching systems (MS) on soil chemical and biological properties.

Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
Chemical	Soil organic matter content	MS on soil organic matter content is that they can increase the accumulation of organic matter in the soil	MS introduce organic materials to the soil surface, such as plant residues, compost, or mulch materials. These organic materials gradually decompose over time, adding organic matter to the soil. As a result, the main effect of MS is an increase in soil organic matter content	(Cai et al., 2023; Hu et al., 2024; Yang et al., 2023b; Zhang et al., 2023b)	The MS contributions to organic matter are recognized, and various aspects merit investigation. Future research should evaluate through quantification, elucidate impacts of mulch type/decomposition, examine the effect of properties, incorporate long-term effects, and appraise ecosystem-level impacts. Addressing gaps will enhance understanding of relationships between MS, organic matter dynamics and sustainable management
	Nutrient availability	The MS on nutrient availability in the soil is that they can enhance nutrient recycling and retention, leading to increased nutrient availability for plants	because MS incorporate organic residues at the soil surface which undergo decomposition over time, releasing nutritional elements into the soil. This process potentially enriches nutritional content, enhancing availability for plant uptake. Additionally, MS serve to curtail losses of nutrients by reducing leaching and runoff, helping nutrients remain within the root zone for plant utilization. These combined effects of element release and retention represent the primary mechanisms by which MS may influence nutrient availability	(Biswas et al., 2022; Palsaniya et al., 2023; Yang et al., 2023a; Zhang et al., 2023a)	While the effects of MS on nutrient availability are recognized, various aspects merit investigation. Future research should evaluate through examination of release dynamics, interplay between elements, cultivar-specific demands, and losses/leaching. Addressing gaps will enhance understanding of relationships between MS, availability, and effective management in agricultural systems
	Soil Moisture Retention	The MS on soil moisture retention is that they help to reduce evaporation and maintain higher levels of soil moisture	The use of MS has the potential to diminish evaporation, help retain moisture within the soil, and curtail losses via runoff, conferring potentially enhanced moisture retention. This confers a favourable influence on plant water availability and may contribute to improved growth, health and productivity	(Tuure et al., 2021; Wang et al., 2023a; Wang et al., 2023c; Yin et al., 2022; Zhang et al., 2023c)	The MS with moisture conservation is recognized, but various aspects warranting additional investigation remain. Addressing aspects of the interplay between organic content and retention potential will contribute to an enhanced comprehension of water dynamics. This improved knowledge can inform practices aimed at optimizing retention, curtailing losses via evaporation/runoff, and maximizing plant water availability
	Soil temperature	The MS on soil temperature is the moderation of temperature fluctuations	Because the MS offer an insulating layer, deflect solar radiation, and help retain soil moisture. This potential amelioration of temperatures may confer a growing environment more conducive to plant growth and help mitigate stress from extreme variances in temperature	(Yang et al., 2023a; Zhao et al., 2023a, 2023c; Zou et al., 2021)	The ability of MS to moderate soil temperature fluctuations is recognized, and various aspects merit investigation. Future research should evaluate through examination of temperature dynamics, materials/attributes, Tillage depth/placement effects, region- and climate-dependent factors, and cultivar-level reactions. Addressing gaps will enhance understanding of relationships between MS, temperature dynamics and effective management in agricultural systems
	Weed Control	The MS contribute to weed control	They provide mechanisms that impede weed seed germination, curtail weed development, diminish competition for nutrients/water, and ease weed extraction. This may engender conditions more conducive for desired plants, lessen the need for herbicides/manual weeding, and promote healthier, more productive plant growth	(Choudhary, 2023; Mairata et al., 2023; Rhioui et al., 2023; von Cossel et al., 2023)	The weed suppression capabilities of mulching systems are acknowledged, limitations and gaps in our understanding. Future work should focus on weed species and diversity, mulch type and weed suppression, mulch persistence and weed resurgence, weed management integration, and the economic and environmental impacts of mulching systems. Addressing these knowledge gaps will contribute to a better understanding of the relationships between mulching systems, weed control, and sustainable weed management practices in agricultural systems

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Soil chemical and biological properties		Main effect	Reasons	References	Study limitations
	Soil Erosion Control	Effect of MS is soil erosion control	Because they create a physical barrier, encourage water infiltration and reduce runoff, preserve soil structure, and contribute to long-term erosion control. By implementing MS, the risk of soil erosion can be significantly reduced, helping to maintain soil health, fertility, and productivity	(Carrà et al., 2022; Fan et al., 2023; Wang et al., 2021)	The contribution of MS to soil erosion control is recognized, but there are limitations and gaps in our understanding. Future research should focus on quantifying erosion control, investigating mulch type and erosion control, exploring mulch coverage and placement practices, understanding interactions with rainfall characteristics, and considering the long-term effects of MS on erosion dynamics. Addressing these knowledge gaps will contribute to a better understanding of the relationships between MS, soil erosion control, and sustainable soil management in agricultural systems
	Soil pH	MS can have an indirect influence on soil pH	MS may stimulate microbial activity in the soil, with the potential for oblique influences on pH via metabolic residues affecting balances. Importantly, impacts are typically subtle, developing incrementally. Unlikely to prompt significant shifts unless large, highly acidic/alkaline materials utilized or conditions particularly conducive to change exist	(Micallef et al., 2023; Wang et al., 2023c; Zhou et al., 2023)	While varying effects of MS on soil pH are recognized, various aspects merit investigation. Future research should evaluate through examination of enduring pH impacts, material types/pH alteration, degradation processes, soil's stabilizing potential, and pH fluctuations from MS. Addressing gaps will enhance understanding of relationships between MS, pH dynamics and effective management in agricultural systems
Biological	Microbial activity	The MS on microbial activity in the soil is to enhance and promote microbial populations and their functions	MS has the potential to stimulate microbial growth and metabolism, with the potential for elevated levels of biomass and processes, conferring potentially improved health/fertility. Microorganisms facilitate nutrient cycling, organic matter decomposition, disease control, and ecosystem functioning. MS may optimize soil structure, nutrient availability, and overall health	(Bo et al., 2024; Hao et al., 2023; Liu et al., 2022a; Liu et al., 2022b; Tesfuhuney et al., 2022)	While previous studies have shown that mulching enhances microbial activity in soil by providing nourishment for microorganisms, there are limitations and gaps in our understanding of this topic. Further investigation is needed to determine the specific microbial groups influenced by different types of mulch, quantify the extent of microbial activity increase due to mulching, assess the long-term sustainability of these effects, understand the impact of mulching on microbial functional diversity, and conduct larger field-scale studies to validate findings from smaller-scale studies and make them more applicable
	Soil organic matter	MS on soil organic matter is the increase in organic matter content	This potential arises as mulching introduces organic materials, thereby potentially contributing to the accrual of organic matter through the introduction, potential stimulation of decomposition processes, support of microbial communities, enabling biogeochemical fluxes, and securing carbon within the system. Thus, mulching regimes exert direct, beneficial influences on elevating soil organic matter content	(Al-Shammary et al., 2020; Huang et al., 2023; Mo et al., 2020)	MS have been shown to contribute to the decomposition of organic matter and support of microbial communities. There are still limitations and gaps in our understanding, there is a need for more research to understand the specific microbial communities and their activities involved in the breakdown of mulch materials and the subsequent effects on soil organic matter
	Soil moisture and temperature	MS play a crucial role in regulating soil moisture and temperature, creating an environment that promotes the activity of soil microorganisms	MS regulate soil moisture and temperature by conserving moisture, enhancing water infiltration, moderating temperature fluctuations, and providing protection from extreme conditions. This creates a favourable microenvironment that promotes the growth, metabolic activity, and nutrient cycling of soil microorganisms, ultimately contributing to improved soil health and fertility	(Hao et al., 2023; Liu et al., 2022b; Liu et al., 2022a; Liao et al., 2021a; Xing et al., 2022)	Prior work has demonstrated MS's potential to help regulate soil moisture and temperature and may stimulate microbial activity levels. More research is needed to elucidate compositional shifts and functional diversity influenced by MS. Much analysis of moisture/temperature modulation has involved abbreviated timescales. Enduring assessments are merited to appraise the persistence of observed benefits over longer periods. Such investigations may furnish novel perspectives on

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Table 6 (*continued*)

Soil chemical and biological properties	Main effect	Reasons	References	Study limitations
				mechanisms linking MS to microbial-mediated processes and biogeochemical cycling
Soil erosion control	The MS positively influence soil erosion control and promote the activity of soil microorganisms	The primary functions of mulching systems involve providing a protective layer, surface protection, potentially diminishing runoff, and controlling wind erosion. Simultaneously, they may stimulate soil microbial activity levels by supplying organic inputs, facilitating moisture conservation, tempering temperature fluctuations, and offering shelter from harsh edaphic stresses	(Carrà et al., 2022; Fan et al., 2023; Wang et al., 2021, 2023b)	MS effectively control soil erosion but merits further study. Mulch effectiveness fluctuates with material, slope, rainfall, and soil properties. MS techniques also impact erosion control. Long-term persistence and prevention of erosion require more evidence. Additional research should evaluate mulch's comprehensive soil impacts beyond erosion alone. Effectiveness varies by land use, climate, and vegetation. More information is needed on environments factors influencing mulching performance in specific settings. This knowledge can help mitigate soil loss, preserve soil fertility, and protect the overall health and sustainability of agricultural and natural ecosystems
Earthworm activity	MS have a positive influence on earthworm activity	Mulch benefits soil through several mechanisms. It offers habitat, and organic matter as nutrition, and promotes nutrient cycling. This enhances soil conditions, stimulating earthworm activity. In turn, earthworms improve structure, boost nutrient availability, and elevate overall health via their workings. As indicators of quality, earthworm presence and industry advantageously support sustainable agriculture and ecosystem functioning through aeration, incorporation of amendments, and development of fertile composition	(Carpena-Istan et al., 2024; Cheng et al., 2020; Jones et al., 2020; Liao et al., 2021b; McTavish and Murphy, 2022; Xu et al., 2023)	Previous studies show MS enlivens earthworms and enriches soil, though limitations remain. More study explores diverse MS ' impacts on earthworm populations over time and contributions to soil health. Examining earthworm diversity and roles under various MS requires more scrutiny. Clarifying the long-term sustainability of benefits to earthworm activity is key. Addressing constraints and filling knowledge gaps strengthens comprehension of MS linkage to earthworm activity and soil welfare, culminating in effective practices and sustainable agriculture. Such insights optimize soil relationships and services for generations

16. Identifying effective combinations of AM for diverse soil types, crops, and environmental conditions. This would facilitate the development of tailored management strategies that maximize soil health and productivity.
17. Exploring alternative mulching substances, such as biodegradable polymers, biochar, or cover crops and their effects on soil properties. Comparative studies can help identify innovative soil MS with environmental benefits and AM advantages.
18. Investigating the synergistic benefits of precision agriculture technologies with AM practices to improve soil management and crop production.

Addressing these constraints and gaps will advance our comprehension of AM consequences for SCBPPs, fostering sustainable and resilient agricultural systems.

6. Conclusions

This comprehensive review accentuates the substantial impact of agronomic management (AM) on soil chemical, biological, and biological properties (SCBPPs) across varied soil treatments. This study underscores the pivotal role of these practices in advancing sustainable agriculture and ensuring soil health. Key practices, including tillage (TP), nutrient management (NM), crop rotation (CR), organic matter (OM), irrigation (IM) management, and soil mulching systems (MS), manifest significant influence on SCBPPs by altering soil compaction, porosity, erosion risk, nutrient availability, and microbial activity.

Properly executed AM emerges as a potent tool for enhancing soil fertility, nutrient cycling, and overall soil health. MS, in particular, plays a crucial role in augmenting soil OM content, nutrient retention, water-holding capacity, and soil structure. It exerts control over soil temperature, moisture levels, and erosion and creates favourable conditions for soil biota, fostering nutrient cycling and soil aggregation.

Integrated NM, CR, and OM management is recognized as a very successful approach for bolstering soil fertility and microbial activity. The integration of these complementary strategies was shown to have substantial effects, leading to significant improvements in SCBPPs. In particular, the adoption of NM balanced, diverse CR and the incorporation of OM collectively contributed to increase the soil organic matter, nutrient availability, microbial activity, and overall soil health. Nevertheless, the important of considering site-specific conditions and customizing these practices is underscored. Through the synthesis of existing research, this review not only delineates the current landscape but also identifies gaps for future exploration. It stresses the imperative of developing a comprehensive understanding of the impacts of AM on SCBPPs to optimize agricultural productivity while mitigating environmental consequences.

CRediT authorship contribution statement

Ahmed Abed Gatea Al-Shammary: Writing – original draft, Visualization, Software, Resources, Project administration, Methodology,

Investigation, Funding acquisition, Formal analysis, Conceptualization. **Layth Saleem Salman Al-Shihmani:** Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis. **Jesús Fernández-Gálvez:** Writing – review & editing, Validation, Methodology, Data curation, Conceptualization. **Andrés Caballero-Calvo:** Writing – review & editing, Validation, Supervision, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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