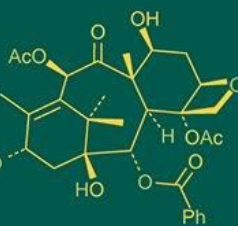
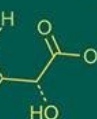


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; 10(2): 776-783
www.biochemjournal.com
Received: 02-12-2025
Accepted: 06-01-2026

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Insects and soil health: The overlooked role of ground-dwelling arthropods in agroecosystems

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i2j.7722>

Abstract

Agricultural sustainability depends on healthy soil, yet ground-dwelling arthropods' influence on soil processes has frequently been overlooked. These species, which include termites, beetles, ants, springtails, and other invertebrates, carry out vital ecological tasks such as soil aeration, nutrient cycling, organic matter decomposition, and natural pest control. Arthropods impact mycorrhizal and bacterial connections, boost microbial activity, and improve soil fertility, resilience, and biodiversity through their interactions with the soil microbiota. They are also sensitive bioindicators of soil quality due to their diversity and abundance. Arthropod populations are threatened by contemporary agricultural methods such as excessive tillage, pesticide use, and a strong reliance on chemical inputs, while climate change further alters the ecological roles and community makeup of these organisms. On the other hand, it has been demonstrated that biodiversity-friendly techniques including agroforestry, mulching, cover crops, organic farming, conservation agriculture, and organic farming promote arthropod diversity and improve soil ecosystem services. The diversity, roles, and ecological relevance of soil-dwelling arthropods, as well as their reactions to climate change and agricultural intensification, are summarized in this review along with their contributions to the sustainability of agroecosystems. Along with highlighting research gaps that need to be filled, it also discusses conservation and management initiatives that incorporate arthropods into frameworks for soil health. In addition to being essential for preserving soil quality, ground-dwelling arthropods have the potential to promote climate-resilient, sustainable agriculture.

Keywords: Ground-dwelling arthropods, soil health, microbiota, climate change, sustainability

Introduction

Because it has a direct impact on crop productivity, ecosystem stability, and environmental quality, soil health is essential to sustainable agriculture. According to Doran and Zeiss (2000) [20], a healthy soil is defined by its capacity to support biological activity, preserve environmental quality, and advance the health of plants and animals. According to Lehmann *et al.* (2020) [39], it is a dynamic living system that controls pollution buffering, organic matter decomposition, water retention, and nutrient cycling. Soil health has become a crucial factor in determining agricultural sustainability as a result of the growing problems of climate change, land degradation, and the need for food security worldwide. Therefore, to guarantee resilience and production over the long term, it is crucial to comprehend the biological foundations of soil systems.

Microbes, mesofauna, and macrofauna are all examples of soil biodiversity, which is essential for regulating ecological processes. By preserving soil structure, regulating nutrient cycles, and fostering resistance to stresses like drought or pest outbreaks, biodiversity improves soil resilience (Bardgett & van der Putten, 2014) [4]. Within the soil food web, many soil creatures play complementary roles: macrofauna, such as insects and earthworms, construct soil conditions, mesofauna control microbial populations, and microorganisms break down organic matter (Briones, 2014) [11]. Since the loss of some taxa might interfere with vital functions like carbon sequestration, pest control, and nutrient availability, this diversity guarantees the soils' multifunctionality (Wall *et al.*, 2015) [62]. Therefore, maintaining ecosystem services that support agricultural output requires preserving soil biodiversity.

Ground-dwelling arthropods continue to be a neglected aspect of soil biodiversity in agroecosystem studies, despite their ecological importance. According to Lavelle *et al.* (2006) [38], these organisms—which include termites (Isoptera), beetles (Coleoptera), ants (Formicidae), springtails (Collembola), and others—play a significant role in soil aeration, organic matter breakdown, nutrient cycling, and natural pest control. Their actions improve soil functioning by interacting with microbial communities in addition to influencing soil fertility and structure. Furthermore, due of their sensitivity to agricultural practices including tillage, pesticide usage, and monoculture, several arthropod groups serve as bioindicators of soil health (Parr *et al.*, 2016) [49]. It is possible to incorporate ground-dwelling arthropods into soil health frameworks and agroecological management strategies by acknowledging their underappreciated importance. Thus, the purpose of this review is to emphasize their ecological roles, reactions to farming methods, and potential for advancing sustainable soil management.

Diversity and Functional Groups of Ground-Dwelling Arthropods

One of the most taxonomically varied groups in terrestrial ecosystems are ground-dwelling arthropods, which include insects, arachnids, myriapods, and crustaceans that live on the surface and beneath the soil. With families like the Carabidae (ground beetles) and Staphylinidae (rove beetles) serving as both scavengers and predators, beetles (Coleoptera) are the most prevalent insect group (Lövei & Sunderland, 1996) [41]. By constructing nests and redistributing nutrients, ants (Formicidae) are common ecological engineers that affect soil structure (Folgarait, 1998) [22]. Termites (Isoptera) are important decomposers in many areas, particularly in tropical and subtropical soils, where they improve nitrogen cycling and break down a lot of organic matter (Jouquet *et al.*, 2011) [35]. Despite their small size, springtails (Collembola) are common soil arthropods that aid in the decomposition process by feeding on fungi and decomposing organic debris (Hopkin, 1997) [30]. Spiders (Araneae), centipedes (Chilopoda), and isopods (Oniscidea) are other significant taxa that all contribute to the dynamics of predator-prey relationships and the turnover of organic matter. The diverse ecological roles that arthropods perform in agroecosystems are supported by their enormous taxonomic diversity.

- Functional responsibilities, not taxonomic identification, are the best way to understand the ecological significance of soil arthropods. They fall under the following general categories:
Termites, springtails, isopods, and certain beetle larvae are examples of detritivores, which consume dead plant and animal debris. They improve microbial breakdown and nutrient release by breaking up organic wastes (Culliney, 2013) [17].
- Predators: Natural enemies of soil-dwelling and above-ground pests include centipedes, rove beetles, spiders, and carabid beetles. In agricultural systems, they help with biological control and pest population regulation (Symondson *et al.*, 2002) [57].
- Termites and ants are two excellent examples of ecosystem engineers. They affect soil structure and fertility by changing soil porosity, water infiltration, and nutrient distribution through the construction of

nests and galleries (Jones *et al.*, 1994; Lavelle *et al.*, 2006) [33, 38].

- Mutualists: A few arthropods that live on the ground have symbiotic relationships. For instance, termites harbor symbiotic gut bacteria that facilitate nitrogen fixation and cellulose digestion, while ants provide honeydew to aphids in return for protection, thereby affecting soil nutrient cycling (Brune, 2014) [13].

The direct and indirect contributions that soil arthropods provide to soil ecosystem services are highlighted by these functional classifications.

Because they connect primary producers, decomposers, and higher trophic levels, ground-dwelling arthropods are essential parts of the soil food web. Microbivores like mites and springtails are supported by detritivores, which break down organic materials and increase its accessibility to microbes and fungus (Moore *et al.*, 2005) [45]. In order to prevent outbreaks that could upset the ecology, predators like carabids and spiders control the numbers of herbivores and detritivores (Scheu, 2002) [53]. Termites, ants, and other ecosystem engineers alter the soil environment by forming microhabitats that affect the distribution of other arthropods and the makeup of the microbial community. These interrelated trophic interactions create intricate networks that improve soil resistance to perturbations and maintain nitrogen cycle (Wardle *et al.*, 2004) [63]. administration. The necessity for biodiversity-friendly management is highlighted by the fact that extensive tillage or the use of pesticides can disrupt agroecosystem networks, weaken natural regulation and reduce soil multifunctionality.

Ecological Functions of Soil-Dwelling Arthropods

Arthropods that live in the soil play a crucial role in the breakdown of organic matter and are the main forces behind the cycling of nutrients. Plant litter and organic leftovers are broken up by detritivores such termite workers, isopods, and springtails (Collembola), which increases the surface area accessible for microbial colonization (Culliney, 2013) [17]. This fragmentation speeds up microbial breakdown, which in turn speeds up the mineralization of minerals like potassium, phosphorus, and nitrogen—all of which are essential for plant absorption (Barrios, 2007) [14]. By breaking down lignocellulosic material that would otherwise be resistant to microbial decomposition, termites—in particular—play a significant role in tropical soils (Jouquet *et al.*, 2011) [35]. Similar to this, animal waste is recycled into the soil by dung beetles (Scarabaeidae), which enriches it with organic carbon and encourages microbial activity (Nichols *et al.*, 2008) [47]. Soil arthropods facilitate nutrient turnover through various mechanisms, guaranteeing soil fertility and long-term agroecosystem productivity.

Because they dig, ground-dwelling arthropods are important ecosystem engineers that improve soil aeration and structure. Termites and ants build vast tunnels and nest systems that improve gas exchange, water infiltration, and soil porosity (Jones *et al.*, 1994; Lavelle *et al.*, 2006) [33, 38]. By increasing root penetration and soil water-holding capacity, these burrowing actions lessen erosion and runoff (Decaëns, 2010) [19]. For instance, termite mounds create nutrient hotspots that promote plant growth by redistributing soil particles and organic matter from deeper layers to the top (Jouquet *et al.*, 2011) [35]. By controlling the numbers of root-feeding pests that harm soil aggregates, carabid beetles

and other predators that live in the soil have an indirect impact on soil structure. When taken as a whole, these actions demonstrate how arthropods play a bioturbation role that promotes soil aggregation, fertility, and resilience. Because they naturally manage pests, predatory arthropods are important friends in agroecosystems. Aphids, caterpillars, root maggots, and weed seeds are just a few of the above-ground and soil-dwelling pests that are preyed upon by ground beetles (Carabidae), rove beetles (Staphylinidae), spiders, and centipedes (Symondson *et al.*, 2002) ^[57]. For example, carabids are recognized for their polyphagous feeding habits, which reduce the requirement for chemical inputs by eating both weed seeds and insect pests (Honek *et al.*, 2003) ^[28]. In manure and compost systems, rove beetles are especially crucial for controlling fly larvae (Frank & Thomas, 1999) ^[23]. These predators contribute significantly to Integrated insect Management (IPM) and the ecological intensification of agriculture by keeping insect numbers below economic thresholds. Many soil arthropods have symbiotic or mutualistic connections that improve soil and plant health in addition to their primary ecological roles. Termites are home to symbiotic gut microorganisms that help fix nitrogen and breakdown cellulose, which enriches soils with nutrients (Brune, 2014) ^[13]. In specialized gardens, some ants (such as the genus *Atta* leafcutter ants) cultivate fungus, a partnership that enriches soils with organic matter and microbial diversity (Mueller *et al.*, 2005) ^[46]. By feeding on fungal hyphae, springtails and mites engage with mycorrhizal fungi, indirectly controlling fungal populations and affecting relationships between plants and fungi (Crowther *et al.*, 2011) ^[16]. Additionally, by burying seeds inside their tunnels, dung beetles promote plant recruitment and seed germination, which aids in seed distribution (Nichols *et al.*, 2008) ^[47]. These intricate symbiotic relationships demonstrate how arthropods that live in the soil play a crucial role in mediating interactions between plants, microorganisms, and soil in agroecosystems.

Interactions between Arthropods and Soil Microbiota

Arthropods that live in the soil have a strong relationship with microbial populations and frequently act as catalysts for the turnover of nutrients. Termites, springtails, and isopods are examples of detritivores that break down organic waste, which promotes microbial colonization and enzymatic activity (Culliney, 2013) ^[17]. They accelerate decomposition and nutrient mineralization by inoculating organic waste with microbial propagules through their eating and digestive processes (Anderson, 2019) ^[1]. Because their stomach symbionts generate ligninolytic and cellulolytic enzymes that convert resistant plant residues into accessible forms of nitrogen and carbon, termites have a particularly significant impact (Brune, 2014) ^[13]. Similarly, microbial communities and organic matter are transported and buried by dung beetles, which promotes localized nutrient hotspots that improve soil fertility (Nichols *et al.*, 2008) ^[47]. As a result, arthropod activity supports the functioning of soil ecosystems by acting as a catalyst for microbially driven nutrient cycles.

Additionally, arthropods mediate important interactions between bacteria, fungus, and plants. By spreading bacterial and fungal propagules by their feces, cuticles, or nesting activity, certain ground-dwelling insects affect the composition of the soil microbial community (Barton *et al.*,

2019) ^[5]. For instance, by consuming fungal hyphae and spores, springtails help to promote plant-fungus symbioses and redistribute mycorrhizal inoculum in the rhizosphere (Lussenhop, 1992) ^[43]. When building their nests, termites and ants move organic materials and microorganisms, forming microenvironments that support the growth of bacteria and fungi (Jouquet *et al.*, 2011) ^[35]. In addition, some insect-microbe relationships are obligatory: termites digest cellulose and fix nitrogen using stomach protozoa and bacteria, whereas leafcutter ants (*Atta* spp.) cultivate fungal gardens as their main food source (Mueller *et al.*, 2005) ^[46]. These examples underline the importance of arthropods as carriers and facilitators of microbial symbioses in soils.

Arthropod activity has a significant impact on the metabolic activity and variety of soil microbes. Arthropods like collembolans and mites preserve the balance of the microbial community and avoid a single taxon's dominance by controlling bacterial populations and fungal biomass through grazing (Crowther *et al.*, 2011) ^[16]. According to Lavelle *et al.* (2006) ^[38], their bioturbation also modifies the moisture and aeration of the soil, resulting in heterogeneous microhabitats that sustain a variety of microbial assemblages. Indirect contributions are also made by predator-prey dynamics, which alter root exudation and microbial recruitment in the rhizosphere by lowering herbivore concentrations (Wardle *et al.*, 2004) ^[63]. Furthermore, the corpses and frass of arthropods offer nutrient-rich microsites that improve soil enzymatic processes and promote microbial activity (Frouz, 2018) ^[24]. With important ramifications for soil health and the sustainability of agroecosystems, these interactions show that soil arthropods are active regulators of the composition and function of microbial communities rather than just consumers.

Contribution to Soil Health Indicators

Because of how sensitive their abundance, variety, and community composition are to changes in land use, agricultural management techniques, and environmental stresses, ground-dwelling arthropods are becoming more widely acknowledged as trustworthy bioindicators of soil quality (Paoletti, 1999) ^[48]. For instance, because of their quick reactions to tillage, pesticide application, and organic matter inputs, carabid beetles and ants are frequently utilized in agroecological studies to evaluate habitat disturbance and soil degradation (Rainio & Niemelä, 2003) ^[51]. Diverse arthropod populations are a sign of ecological stability, but losses in certain groups are frequently interpreted as a symptom of decreased biological activity or soil stress. Therefore, adding arthropod monitoring to frameworks for evaluating soil health offers an ecologically significant way to gauge the sustainability of agroecosystems.

Through their bioturbation activities, which improve aggregation, porosity, and soil aeration, soil arthropods directly contribute to the structural integrity of the soil. Isopods and springtails are examples of detritivores that break up litter, increasing the surface area available for microbial breakdown and speeding up the turnover of carbon (Chauvat *et al.*, 2003) ^[15]. As ecosystem engineers, termites and ants build mounds and tunnels to redistribute organic matter and minerals, increasing soil variability and nutrient availability (Jouquet *et al.*, 2011) ^[35]. These practices enhance water infiltration and soil aggregate

stability; two important characteristics associated with resistance to erosion and compaction. Additionally, the integration of organic matter into deeper soil layers by arthropods supports fertility and climate regulation functions by contributing to the long-term retention of soil organic carbon (Frouz, 2018) [24].

Indicators of soil fertility, including crop yield, organic matter content, and nutrient availability, are intimately related to the variety and abundance of ground-dwelling arthropods. In order to maintain soil fertility, high arthropod diversity is linked to balanced trophic interactions, quicker nutrient cycling, and effective litter decomposition (Birkhofer *et al.*, 2015) [8]. For example, predator arthropods limit herbivorous pest populations, thereby safeguarding plant yield, whereas detritivores and mutualists increase nutrient mineralization (Snyder & Wise, 2001) [56]. On the other hand, decreased soil fertility and fewer ecosystem services sometimes accompany decreases in arthropod diversity brought on by intense tillage, monocultures, or heavy pesticide use. Thus, one crucial tactic for preserving and enhancing soil fertility throughout time is managing agricultural landscapes to preserve arthropod communities.

Impacts of Agricultural Practices on Ground-Dwelling Arthropods

Ground-dwelling arthropods are significantly impacted by tillage and mechanization activities, mostly due to habitat disruption, soil compaction, and microhabitat destruction. The habitat variability that many arthropods depend on for refuge, feeding, and nesting is diminished by conventional plowing, which breaks up soil aggregates and litter layers (Kladivko, 2001) [36]. In addition to lowering soil moisture and organic matter availability, frequent tillage operations can directly kill soil-dwelling insects and their juvenile stages (Briones & Schmidt, 2017) [12]. Research has demonstrated that by preserving soil structure and organic residues on the surface, decreased or no-tillage regimes promote higher abundances of predatory beetles, springtails, and other beneficial arthropods (House & Parmelee, 1985) [31]. Therefore, it is commonly acknowledged that conservation tillage improves the ecosystem services mediated by arthropods in agroecosystems.

The composition and activity of arthropod communities in soils are drastically changed by the application of synthetic fertilizers and pesticides. According to Geiger *et al.* (2010) [26], broad-spectrum insecticides frequently directly kill non-target arthropods, such as predators and detritivores, which has a domino effect on soil food webs. For example, ants and ground beetles are adversely affected by neonicotinoids and pyrethroids, which lowers their abundance and efficiency of predation (Pisa *et al.*, 2015) [50]. Likewise, overuse of chemical fertilizers alters the pH, salinity, and nutritional balance of the soil, which has an indirect impact on the diversity of arthropods (García-Palacios *et al.*, 2015) [25]. By creating ideal soil conditions and microbial communities that indirectly support arthropod populations, integrated nutrient management and a reduced need on chemical inputs, on the other hand, typically support higher biodiversity.

Another important element affecting the activity and survival of ground-dwelling arthropods is water management. Since water availability influences foraging behaviour, reproduction, and survival, many arthropod taxa, including termites, ants, and springtails, show robust

reactions to soil moisture gradients (Lavelle *et al.*, 2006) [38]. By keeping soil moisture levels higher, irrigation techniques can foster an environment that is more conducive to microbial feeders and detritivores by accelerating nutrient turnover and litter decomposition (Bardgett, 2005) [3]. However, by displacing oxygen-dependent species and producing anoxic conditions, excessive irrigation or inadequate drainage may decrease arthropod diversity (Birkhofer *et al.*, 2015) [8]. Thus, maintaining arthropod biodiversity requires adjusting irrigation schedules to balance soil moisture without waterlogging.

Ground-dwelling arthropods benefit greatly from diverse cropping systems that include rotations, cover crops, and organic amendments. Crop rotation increases habitat heterogeneity and resource diversity, which supports functional groups like predators and detritivores (Lemessa *et al.*, 2015) [40]. Organic amendments, like compost and manure, enrich soil organic carbon and microbial activity, which indirectly increases populations of soil fauna like collembolans, mites, and beetles (Sánchez-Moreno *et al.*, 2006) [52]. These practices not only increase soil arthropod diversity, but also strengthen their ecological roles in nutrient cycling, pest control, and soil structure improvement, making them essential strategies for agroecosystem sustainability.

Climate Change and Soil Arthropods

Temperature extremes and precipitation patterns are predicted to shift due to climate change, which would directly affect soil arthropod communities. Arthropod activity, reproduction, and metabolic rates are all significantly impacted by temperature; warming can quicken decomposition processes that are mediated by detritivores such mites and collembolans (Blankinship *et al.*, 2011) [9]. Extreme heat episodes, however, have the potential to surpass physiological thresholds, which would decrease the survival of species that are susceptible (Bale *et al.*, 2002) [2]. Arthropod distribution is also significantly influenced by soil moisture, since many species rely heavily on water availability for reproduction and feeding. While excessive rainfall can cause flooding and hypoxic soils, which can negatively affect oxygen-dependent arthropods, drought conditions can significantly lower the quantity of mesofauna and macrofauna (García-Palacios *et al.*, 2015) [25]. Therefore, arthropod-mediated soil functions are directly regulated by variations in the soil microclimate brought on by climate variability.

The dominance and composition of ground-dwelling arthropod populations are frequently changed by climate stresses. For example, in arid environments, water-dependent taxa like springtails may become less common, while drought-tolerant taxa like ants and certain beetles may become more prevalent (Siepel, 1996) [54]. Arthropod distributions have also been seen to migrate northward or altitudinally in response to warming, which can have a domino effect on nutrient cycling and soil food webs (IPCC, 2022) [32]. Because declines in detritivores or predators may impair decomposition and pest regulatory services, such changes have the potential to upset ecological equilibrium. Furthermore, long-term shifts in the composition of arthropod communities may modify the dynamics of soil carbon, which could have feedback consequences that worsen climate change (de Vries *et al.*, 2012) [18].

In order to protect soil systems from stress brought on by the climate, biodiversity is essential. By guaranteeing that several groups may carry out overlapping ecological roles under varying circumstances, functionally diversified arthropod communities improve ecosystem resilience (Hooper *et al.*, 2005) ^[29]. For instance, continual litter processing across moisture gradients is ensured by the coexistence of various detritivores, such as termites, beetles, and isopods. Even when some taxa experience a drop in pest control, predatory arthropods like spiders and carabid beetles maintain pest control stability (Birkhofer *et al.*, 2015) ^[8]. Therefore, in the face of climate unpredictability, protecting arthropod variety provides a natural insurance mechanism that improves soil health and agricultural sustainability. Important tactics for maintaining this resilience potential include agroecological techniques that preserve habitat variability, organic matter inputs, and low disturbance (Tsiafouli *et al.*, 2015) ^[61].

Ground-Dwelling Arthropods and Agroecosystem Sustainability

Arthropods that live on the ground are essential for increasing the soil's resistance to biological, chemical, and physical deterioration. They preserve soil porosity, structure, and organic matter content through their operations, which include litter fragmentation, bioturbation, and soil mixing. These elements are essential for preventing erosion and compaction (Six *et al.*, 2004) ^[55]. As ecosystem builders, arthropods like termites, ants, and beetles build stable microhabitats that protect soil organisms from environmental stresses including temperature changes and drought (Jouquet *et al.*, 2011) ^[35]. They aid in the quicker recovery of soils following disturbances like tillage or severe weather events by encouraging nutrient redistribution and preserving soil biodiversity (Bardgett & van der Putten, 2014) ^[4]. Therefore, the ability of agroecosystems to respond to degrading stresses is increased when varied arthropod groups are present.

Arthropods in the soil play an important role in sequestering carbon and, as a result, reducing the effects of climate change. Detritivores like collembolans and isopods speed up the breakdown of litter, increasing the accessibility of organic wastes for humus formation and microbial decomposition (Frouz, 2018) ^[24]. Through tunneling and mound-building, termites and ants add carbon from plants to deeper soil layers, stabilizing organic matter and preventing it from decomposing too quickly (Jouquet *et al.*, 2011) ^[35]. The organic carbon pools in the soil, which are important markers of soil fertility and long-term carbon storage, are improved by these activities. Furthermore, arthropods' indirect involvement in regulating the climate is highlighted by the way they control decomposition rates, which affects greenhouse gas fluxes, especially carbon dioxide and methane (Lubbers *et al.*, 2017) ^[42]. Conservation of arthropod diversity in agricultural landscapes is therefore an important strategy for aligning food production with climate mitigation goals.

Utilizing ecosystem services to lessen reliance on outside inputs while preserving or increasing production is the focus of ecological intensification. This idea is supported by the several ecosystem services that ground-dwelling arthropods provide, such as improving soil fertility, regulating pests, and cycling nutrients (Bommarco *et al.*, 2013) ^[10]. Predatory beetles, for instance, reduce the demand for chemical

pesticides by suppressing pest populations, and detritivores help recycle organic materials, which lessens the requirement for artificial fertilizers. Arthropod biodiversity is increased and their ecological roles are optimized by implementing techniques including conservation tillage, crop variety, cover crops, and organic amendments (Kremen & Miles, 2012) ^[37]. Furthermore, monitoring soil health with arthropod-based bioindicators offers a useful tool for directing decisions about sustainable management. Ground-dwelling arthropods can be included into ecological intensification frameworks to improve environmental sustainability, production, and resilience in agroecosystems.

Conservation and Management Strategies

Maintaining diverse arthropod communities that support soil health requires effective habitat management. Ground-dwelling arthropods can find refuge and alternate food sources when habitat variety is created through techniques like buffer strips, field borders, and hedgerows (Bianchi *et al.*, 2006) ^[6]. Maintaining natural vegetation and retaining crop residues around farmlands improves microhabitats and shields soil fauna from environmental stresses (Tsiafouli *et al.*, 2015) ^[61]. In addition to increasing the number of detritivores and predators, habitat complexity also improves trophic interactions, which maintain the functioning of agroecosystems (Gurr *et al.*, 2017) ^[27]. Therefore, maintaining arthropod-mediated soil functions requires managing agricultural landscapes with designs that promote biodiversity.

It has been demonstrated that soil arthropod populations benefit from conservation agriculture (CA), which is defined by permanent soil cover, crop variety, and less tillage. By minimizing the physical disruption of soil habitats, reduced or zero tillage preserves organic matter pools, microbial interactions, and arthropod nesting sites (Kladivko, 2001) ^[36]. Research continuously shows that, in comparison to traditional tillage, carabid beetles, collembolans, and mites are more abundant in CA systems (Briones & Schmidt, 2017) ^[12]. Crop leftovers provide permanent cover, which increases soil microclimate stability and detritivores' access to food. Thus, implementing CA techniques has two advantages: preserving soil biodiversity and preserving soil fertility.

By combining crops and trees, agroforestry systems provide habitats that are architecturally complex, supporting a variety of arthropods and enhancing soil function (Jose, 2009) ^[34]. According to Torralba *et al.* (2016) ^[60], soil arthropod richness is increased by shade, organic matter intake from leaf litter, and root variety in agroforestry, especially for decomposers and ecosystem engineers. According to El-Beltagi *et al.* (2022) ^[58], mulching with organic residues enhances soil moisture retention, reduces temperature swings, and offers food substrates for termites and isopods, two detritivores. Due to increased soil organic matter and microbial activity, organic farming—which eschews industrial pesticides and fertilizers—generally supports higher arthropod abundance and diversity than conventional systems (Mäder *et al.*, 2002) ^[44]. When combined, these methods promote synergies between sustainable production and biodiversity protection.

In order to convert ecological knowledge into the broad acceptance of biodiversity-friendly practices, policy frameworks and extension initiatives are essential. Initiatives supporting ecosystem services, agroecology, and

climate-smart agriculture subtly help arthropod conservation, even if agricultural policies rarely specifically emphasize the conservation of soil biodiversity (FAO, 2020) [21]. Farmers can be encouraged to conserve soil fauna by offering incentives including compensation for ecosystem services, certification programs for products that support biodiversity, and subsidies for conservation agriculture (Tuttonell, 2014) [59]. Given the low level of farmer understanding regarding the ecological significance of soil arthropods, extension services and participatory initiatives are equally crucial. Arthropod diversity in agroecosystems can be preserved over the long run by bridging the gap between scientific study and real-world management through knowledge sharing platforms and training initiatives.

Conclusion

Although soil health is essential to agroecosystem productivity and sustainability, agricultural research and management have traditionally ignored its reliance on belowground biodiversity, especially ground-dwelling arthropods. This review emphasizes the critical roles that soil arthropods play in a variety of ecosystem processes, such as the breakdown of organic matter, the cycling of nutrients, the construction of soil structure, the control of pests, and symbiotic relationships with plants and microbes. These organisms function as essential elements of the soil food web and are trustworthy bioindicators of soil fertility and quality by maintaining soil processes. Ground-dwelling arthropod groups are extremely susceptible to human activities, notwithstanding their significance. Reduced soil resilience and fertility are frequently the result of conventional agricultural methods that damage arthropod habitats and interfere with trophic interactions, such as intense tillage, pesticide usage, and an over-reliance on chemical fertilizers. Similar to this, climate change creates new difficulties by changing the temperature and moisture regimes of soil, which results in changes in the functional variety and composition of communities. However, biodiversity itself acts as a buffer against these disruptions since a variety of arthropod assemblages improve the stability and stress-adaptiveness of soil systems. It has been demonstrated that a number of agroecological practices, including as organic farming, mulching, cover crops, agroforestry, decreased tillage, and organic additions, preserve and enhance arthropod diversity. These methods promote healthy soil biotic ecosystems by increasing soil organic matter, preserving ideal microclimates, and increasing food supplies. Soil arthropod conservation must be integrated into sustainable agriculture frameworks on a larger scale through habitat management at the landscape level, regulatory incentives for ecosystem service protection, and farmer education through extension programs.

In order to capture their intricate ecological roles, future research should concentrate on incorporating soil arthropods into soil health assessment systems using cutting-edge techniques including molecular markers, isotopic tracing, and long-term monitoring. Additionally, to fully exploit the promise of soil biodiversity in addressing the global concerns of food security, climate change, and ecosystem restoration, interdisciplinary approaches that span soil ecology, agronomy, and socioeconomics will be crucial. In summary, ground-dwelling arthropods are active contributors to the resilience and functionality of

agroecosystems rather than just passive soil residents. Current agricultural systems can be transformed into more sustainable, biodiversity-rich landscapes that can guarantee food production and environmental health for future generations by acknowledging and preserving their ecological responsibilities.

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