

Millipedes as ecosystem engineers: Their role in nutrient cycling, soil health and biotechnological significance

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Abstract

Millipedes (Diplopoda) play a crucial role in terrestrial ecosystems as detritivores, contributing to the decomposition of organic matter, nutrient cycling, and soil health. This review examines their diversity, ecological importance, and habitat preferences in the Marathwada region of Maharashtra, India. Marathwada's unique topography, including forests, grasslands, and agricultural lands, supports diverse millipede species such as Julidae, Spirostreptidae, and Polydesmidae. Adapted to the region's semi-arid to tropical climate, millipedes enhance soil fertility, aeration, and water retention while supporting crop productivity by decomposing organic residues. However, they face significant threats from habitat loss, climate change, pollution, and unsustainable agricultural practices. Despite their ecological importance, millipedes in Marathwada remain understudied, and conservation efforts are limited. This review emphasizes the need for further research to explore their biodiversity, genetic diversity, interactions with soil microorganisms, and resilience to environmental changes. Such studies can guide sustainable agricultural practices and conservation strategies to protect these ecologically valuable invertebrates. Understanding millipede dynamics is critical to maintaining biodiversity, ecosystem services, and soil health in Marathwada's varied landscapes. Beyond their environmental contributions, millipedes have untapped potential for biotechnological applications, as their secretions may contain bioactive metabolites with therapeutic properties. Future research focusing on the identification and characterization of these metabolites could uncover new avenues in medicine and agriculture, including natural pesticides and antimicrobial agents. Understanding millipede dynamics and their bioactive potential is critical for advancing biodiversity conservation, sustainable practices, and innovative therapeutic solutions.

Keywords: Millipedes biodiversity, marathwada & surrounding ecosystems, soil health, nutrient cycling, research Significance & future scope

Introduction

As members of the class Diplopoda, millipedes are a significant group in the arthropod phylum and are widely distributed around the world (Alagesan, 2016).^[4] Millipedes are distinguished by their multi-segmented bodies, cylindrical morphology, and distinctive dual pairs of legs on the majority of segments. They also display a range of forms and adaptations that allow them to flourish in a variety of environments (Yaqoob, 2023).^[63] Because of their ecological versatility, millipedes are categorized into a wide range of orders, families, and species worldwide. According to taxonomy, millipedes are categorized into roughly 16 orders, such as Julida, Polydesmida, Spirobolida, and Spirostreptida (Golovatch & Kime, 2009; Koch, 2015).^[25] Each order has distinct physical and behavioral characteristics that are tailored to its particular ecological niche. With physiological adaptations that enable them to retain moisture and thrive in a variety of terrestrial habitats, millipedes are distinguished morphologically by their hard exoskeleton, segmented bodies, and antennae. Their ecological relevance has been enhanced by these modifications, especially in their detritivores, which are essential for decomposing organic debris and returning nutrients to the soil.

Because they improve soil fertility and structure, millipedes are essential to many ecosystems. Their consumption of decomposing leaves, wood, and other organic waste speeds up the breakdown process and improves the soil's nutrient availability because they are major decomposers (Bagyaraj

et al., 2016).^[7] Millipedes also contribute to soil aeration through their movement and burrowing in the soil, which improves water penetration and root development and eventually supports plant development (Dangerfield & Telford, 1991). Millipedes play a crucial role in preserving soil ecosystems and ecological balance because of their involvement in nitrogen cycling. Additionally, millipedes are an important component of local food webs because they provide food for a variety of predators (Mawcha, 2023; Shear, 2015).^[40, 41, 54]

A wide variety of millipede species can be found in the Marathwada region of Maharashtra, India, which boasts a distinctive topography that supports a diversity of flora and wildlife (Abdar, 2022).^[1] Geographically speaking, Marathwada has a semi-arid environment with moderate rainfall and a mostly tropical climate, with winter temperatures often hovering around 17°C and summer temperatures exceeding 40°C (Bej, 2018).^[9] The terrain of the area ranges from agricultural grounds to grasslands and forests, each of which offers a unique environment for millipede populations. The forests of Marathwada, which are mostly made up of tropical dry deciduous and scrub forests, provide the perfect environment for millipedes since they have leaf litter and moist soil, both of which are essential for their survival. The region's ecological richness is further enhanced by Marathwada's grasslands and agricultural zones, which are home to distinct assemblages of millipede species that have adapted to the microhabitats present there (Deshmane, 2020).^[18]

The biodiversity and populations of millipedes in Marathwada are still little understood, despite their ecological importance. Due to the paucity of thorough research on millipedes in this area, a large portion of their ecological significance and possible advantages are still unknown (Golovatch, 2009).^[25] It is crucial to comprehend the diversity and habitat preferences of millipedes in Marathwada, given their significance in preserving soil health and biodiversity. Studying the millipede populations in Marathwada can help with conservation efforts, reveal patterns of biodiversity in the area, and possibly even boost agriculture because of their ability to improve soil.

This review aims to give a thorough understanding of the ecological significance, variety, and habitats of millipedes in the Marathwada region. This review attempts to emphasize the importance of millipedes in Marathwada's ecosystems by looking at their taxonomic variety, preferred habitats, and contributions to ecosystem services. The economic and agricultural responsibilities of millipedes will also be covered in this article, along with the advantages and possible drawbacks they may have for human endeavors (Cock *et al.*, 2012).^[13] This assessment will highlight the need for focused conservation efforts to safeguard these ecologically significant invertebrates by thoroughly examining the conservation status and hazards facing Marathwada's millipede species. In order to improve our knowledge of millipede populations in Marathwada, especially in light of habitat loss and environmental changes, this paper will also make recommendations for future study directions.

This review aims to close current information gaps by concentrating on the ecological roles and diversity of millipedes in Marathwada, providing a baseline knowledge that can direct future studies and conservation initiatives. Developing sustainable solutions to protect soil ecosystems and sustain biodiversity in the Marathwada region requires an understanding of these dynamics.

Diversity of millipedes in marathwada

The variety of habitats and climatic conditions present in the Marathwada region of Maharashtra, India, are reflected in the millipede diversity there. Marathwada's millipedes, which belong to several taxonomic families and genera, exhibit a broad range of adaptations that allow them to flourish in a variety of ecological zones, such as forests, grasslands, and agricultural areas. Marathwada is home to the Xystodesmidae, Paradoxosomatidae, Spirobolidae, Trigonulidae, Julidae, Spirostreptidae, and Polydesmidae millipede families, which are the most prevalent in the region. The genera in each family have unique physical and ecological traits that enable them to thrive in the region's semi-arid to tropical climate (Ahsan *et al.*, 2022 and Abdar, 2022).^[3]

Millipedes, which belong to the Julidae family, are typically cylindrical and have segmented bodies that aid in the decomposition of organic materials and soil burrowing. This family's species, such as *Julus terrestris* is suited to environments with lots of wetness; they are frequently found in damp, shaded forest floors with a lot of leaf litter (Shridhar and Ashwini, 2016). The dry deciduous woods of Marathwada exhibit a high degree of endemism within this family, highlighting the region's ecological distinctiveness. The millipedes in the Spirostreptidae family have a more robust, wider body structure, making them suitable for both

open grassland and forest environments. This family's species, including *Spirobolus orientalis*, have characteristics that enable them to live in both moist and somewhat dry conditions. The majority of *Spirostreptus sp.* observations have been made in grasslands, where it is essential to the breakdown of coarse organic matter and the processes that lead to soil formation (Armstrong & Hamer, 2015).^[6] In addition to their ecological functions, members of the Spirostreptidae family are known for their interactions with the local flora and fauna, forging intricate bonds with other decomposer species that contribute to the biodiversity of Marathwada's ecosystems.

The species in the Polydesmidae family, another well-known family, are frequently flat-bodied and have lateral extensions on each segment, which offer further defense against predators and environmental stressors. One species in this family, *Polydesmus sp.* is very common in the agricultural lands of Marathwada, where it has adapted to places affected by human activity. *Polydesmus sp.* exhibits exceptional resistance to soil disturbance and moderate levels of pesticide exposure, in contrast to other millipede families that favor undisturbed habitats. This adaptation not only demonstrates the Polydesmidae family's ecological versatility but also its potential for regulating agricultural ecosystems through soil aeration and organic matter decomposition (Anh *et al.*, 2024).^[5]

The fact that Marathwada is home to both endemic and adaptable species emphasizes the significance of more taxonomic and ecological research since knowledge of these species can offer important insights into the resilience and health of regional ecosystems.

Habitats of millipedes

A variety of habitats that offer diverse microenvironments necessary for millipede survival can be found in the Marathwada region. These habitats, which include agricultural regions, grasslands, and wooded areas, each have their own biotic and abiotic characteristics that affect the distribution and behavior of millipedes. Since these habitat preferences influence the organization of millipede communities and their ecological responsibilities in the area, it is imperative to comprehend them.

Forested habitats: The forests of Marathwada, which are primarily tropical dry deciduous and scrub forests, provide an ecosystem that is abundant in organic detritus, leaf litter, and moist soil. Particularly those belonging to the Julidae and Spirostreptidae families, such as *Julus terrestris* and *Spirobolus orientalis*, which flourish in moist, shaded settings, these habitats are perfect for millipedes. These detritivores are supported by the abundance of organic materials and dense vegetation, which provide them with plenty of food sources in the form of wood and decaying leaves. Because millipedes need moist conditions to avoid desiccation, the forest soil in Marathwada is frequently loamy or somewhat clayey and can hold moisture (Cloudsley-Thompson, 1951; Adkine, 2016).^[12, 2] A complex network of nutrient cycling and organic matter decomposition is also facilitated by the interactions that millipedes have with other decomposers such as termites, fungi, and earthworms in forest settings (Osman, 2013 and Culliney, 2013).^[15]

Grasslands: Although they still provide pockets of organic material that millipedes eat, Marathwada's grassland portions are more exposed and typically drier than its forested areas. Millipedes like *Spirostreptus sp.* exhibit exceptional adaptations in these grasslands, finding cover behind boulders, decomposing logs, or soil fissures to endure in comparatively dry circumstances. Species of grassland millipedes have developed strategies to reduce water loss, frequently increasing their activity at night when humidity is higher. Because grasslands' soils are usually sandy or clay-based, they drain quickly, making it difficult to hold onto moisture (Crawford *et al.*, 1987).^[14] However, in these environments, millipedes play a vital role in the decomposition of organic matter and soil aeration, which helps to preserve the health of grassland soil (Druce, 2000 and Homung, 2024).^[21]

Agricultural lands: The abundance of agricultural fields in Marathwada is indicative of the area's reliance on farming. These areas support more hardy millipede species, such *Polydesmus species* from the Polydesmidae family, despite

being influenced by human activity and frequently exposed to soil disturbance and chemical inputs. This plant has shown resistance in habitats changed by cultivation by adapting to low pesticide doses and frequent soil disturbances (Nuria *et al.*, 2011 and Huot *et al.*, 2018).^[46, 29] Though irrigation and seasonal rainfall assist in maintaining adequate humidity levels for millipedes, the soil in agricultural regions is typically less wet than that in forests. In these regions, millipedes are essential to the decomposition of organic materials, particularly after harvest when crop residues are plentiful. Millipedes improve nutrient availability by breaking down this debris, promoting crop yield and soil fertility (Kishore *et al.*, 2024). Each of these habitats presents unique challenges and resources for millipedes, influencing their distribution, behaviour, and ecological functions. The ability of certain species to adapt to various soil compositions, moisture levels, and human disturbances highlights the ecological flexibility of millipedes in Marathwada, as well as their importance in sustaining soil health across different land types (Kunte, 2000).^[37]

Table 1: Habitat types and millipede species in marathwada and surrounding regions

Habitat Type	Key Characteristics	Typical Species	Abiotic Factors	Biotic Interactions
Forests	Dense vegetation, moist soil, leaf litter	<i>Julus terrestris</i> , <i>Spirobolus orientalis</i>	Loamy soil, high moisture, shade	Fungi, termites, earthworms
Grasslands	Open, drier conditions, organic debris	<i>Spirostreptus sp.</i>	Sandy or clayey soil, moderate moisture	Interactions with small decomposers
Agricultural Lands	Soil disturbance, crop residues, irrigation	<i>Polydesmus sp.</i>	Loamy to sandy soil, irrigation, variable moisture	Crops, resilient to low pesticide exposure

An overview of the main millipede habitats in Marathwada is given in this table, together with information on the environmental conditions that sustain the species and the interactions that take place within each habitat. The resilience and significance of millipedes in each type of habitat are demonstrated by their capacity to adapt to a wide range of soil types and moisture levels (Abdar, 2022).

Ecological importance of millipedes

Because of their functions in the decomposition of organic matter, the cycling of nutrients, and the improvement of soil structure, millipedes are essential to the Marathwada environment. As detritivores, millipedes break down organic materials into simpler forms by consuming decaying leaves, wood, and other things. In addition to quickening the rate of decomposition, this process makes more vital elements like phosphorus and nitrogen available in the soil, which promotes soil fertility and plant growth (Rannavre & Donde, 2023). In Marathwada, where soil health is essential for local agriculture, millipedes support the productivity of both natural and agricultural ecosystems by aiding in the cycling of nutrients.

Decomposition of organic materials is one of the millipedes' main ecological roles. Millipedes aid in the fragmentation of bigger organic particles by their eating of decomposing plant matter, which bacteria subsequently break down further. Because it allows nutrients that would otherwise be trapped in organic matter to be released, this two-step breakdown process is crucial for establishing a nutritious soil ecosystem (Nweze *et al.*, 2024). For instance, species such as *Spirostreptus sp.* and *Julus terrestris* are important contributors to nitrogen cycling in the grassland and woodland regions due to their effectiveness in breaking down plant litter (Bogyo *et al.*, 2015).

In addition to decomposition, millipedes are essential for soil structure and aeration. Millipedes loosen the soil when they burrow into it in pursuit of food or shelter, making holes that allow water and air to enter (Bowen & Hembree 2014). In areas like Marathwada, where agricultural activities can cause soil compaction, this aeration process is very crucial. Millipedes indirectly encourage root growth and improve water retention by enhancing soil structure, which is particularly advantageous for crop production in semi-arid regions (Culliney, 2013).^[15] The consequences of intensive farming techniques are offset by species like *Polydesmus sp.*, which have demonstrated resilience in agricultural soils through their burrowing activities, which increases soil tilth and fertility (Bedolla-Rivera *et al.*, 2023).^[8]

As prey for a variety of birds, small animals, and invertebrates, millipedes are also vital parts of regional food webs. By giving predators a consistent food source, their presence promotes biodiversity and affects the population dynamics of several species throughout the ecosystems of Marathwada. Millipedes participate in intricate trophic relationships in wooded environments, frequently facing off against termites and fungi, among other decomposers (Holle, 2022).^[27] In addition to increasing the effectiveness of nitrogen cycling, this rivalry keeps the decomposer community balanced and keeps any one species from taking over the ecosystem (Javed *et al.*, 2023).^[34] Furthermore, millipedes engage in mutualistic interactions with other living things, including symbiosis with soil bacteria that aid in the digestion of complex plant compounds in their digestive tracts. In addition to increasing the rate at which organic waste decomposes, this mutualistic interaction may help beneficial microbial communities

proliferate throughout the soil. Millipedes are crucial for preserving ecological balance because they indirectly affect soil health and productivity by promoting microbial variety (Mawcha *et al.*, 2023 and Singh *et al.*, 2024).^[40, 41, 55] Ultimately, millipedes' ecological significance in Marathwada goes beyond their function as decomposers;

they are essential for preserving soil structure, promoting biodiversity, and facilitating the cycling of nutrients among various habitats. Because of their many roles, they are essential to the stability of ecosystems and their populations must be protected in order to maintain the long-term health of the soil and ecosystem (Roy *et al.*, 2017).^[52]

Table 2: Ecological Functions of Millipede in Marathwada and Surrounding regions

Organism	Ecological Function	Role Description
<i>Julus terrestris</i>	Organic matter decomposition	Breaks down plant litter in forests, aiding nutrient cycling
<i>Spirostreptus sp.</i>	Soil aeration and structure	Enhances soil structure through burrowing, promoting water retention
<i>Polydesmus sp.</i>	Soil aeration in agriculture	Contributes to soil health in agricultural lands, countering compaction
<i>Spirobolus orientalis</i>	Food web integration	Serves as prey for birds and small mammals, supporting local biodiversity

The ecological responsibilities that the major millipede species in Marathwada play are clearly summarized in Table 2, with each species making a distinct contribution to the health of the soil and ecosystem. We can better understand how millipedes affect the resilience and sustainability of Marathwada's ecosystems by looking at these roles.

Human and economic importance

Millipedes contribute significantly to human economies in several ways, especially in agriculture, where crop output depends heavily on the fertility and quality of the soil (Gaikwad, 2021).^[23] The functions of millipedes as soil conditioners and decomposers are particularly significant in areas like Marathwada, where agriculture is the main source of income. Millipedes benefit agricultural soils by assisting in the decomposition of organic matter, preserving soil health and production. Furthermore, although millipedes are typically advantageous, some species can be problematic in particular situations, such as when their populations get very dense and can cause crop damage.

The improvement of soil quality is one of the main ways millipedes help agriculture. By consuming decaying plant matter, millipedes degrade complex organic molecules into simpler forms that improve the soil. Important minerals like phosphorus and nitrogen are released into the soil during this decomposition process, allowing plants to absorb them. Millipedes contribute to the sustainability of agricultural fields' output by enriching the soil in this way, particularly in semi-arid areas like Marathwada where soil fertility is frequently low (Alagesan *et al.*, 2016 and Rao & Patra, 2009).^[4, 50] For example, in agriculture fields, where organic residues left over after harvest serve as these millipedes' main food source, millipedes like *Polydesmus sp.* play a crucial role in the nutrient cycle. By encouraging sustainable agricultural methods and supporting healthy crop growth, nutrient recycling lessens the demand for synthetic fertilizers (Kumar *et al.*, 2020).^[36]

Because of their digging habits, millipedes are also essential for soil aeration. They improve water retention and encourage root growth by forming channels in the soil that let air and water reach deeper soil layers. Because it avoids waterlogging and promotes healthy soil structure, this is especially advantageous in areas with clay-heavy or compacted soils. Because millipedes' movement counteracts

compaction and promotes natural soil regeneration, their burrowing can help maintain soil aeration in regions that see extensive agriculture. Therefore, millipede activity may indirectly benefit farmers in Marathwada since their burrowing helps to preserve the physical condition of the soil (Bhavya & Bhavana, 2024).^[10]

Millipedes, however, can cause problems in agricultural environments in specific situations. Certain species may feed on delicate plant tissues or early seedlings when the environment supports high millipede populations, which could result in mild crop damage (Farfan, 2010).^[22] Farmers may grow concerned about this behavior during planting seasons, even though it is often uncommon and only happens when there are few other food sources available. For example, if there are many fragile plant parts next to agricultural fields, *Julus terrestris* and other species may occasionally graze on them, which could affect the growth of early-stage crops (Wolters, 2000).^[62] Even though these occurrences are rare, they highlight the necessity of balanced population control, particularly in areas with extensive cultivation.

In addition to agriculture, millipedes may find use in environmental rehabilitation and soil restoration. There is increasing interest in using millipedes for soil rehabilitation initiatives on degraded lands because of their ability to improve soil quality. It might be feasible to hasten the repair of soil organic matter by introducing millipede populations to deficient soils, which would increase total land productivity (Menta, 2020).^[44] Additionally, studies are looking at the use of millipedes in biotechnology and medicine, where some of the molecules they manufacture have antifungal or antibacterial properties as well as other bioactive potentials (Dossey, 2010; Ilic *et al.*, 2018; Ilic *et al.*, 2019a; Ilic *et al.*, 2019b and Romão *et al.*, 20204).^[20, 30, 31, 32, 51]

In conclusion, millipedes are useful partners in agriculture because of their contributions to soil structure and nutrient cycling, but population fluctuations may occasionally cause problems. The advantages of millipede activity in Marathwada can be maximized by comprehending these dynamics and putting into practice efficient management techniques, which will promote soil health and sustainable farming methods.

Table 3: Contributions and Challenges of Millipedes in Agriculture and Economy

Aspect	Contribution/ Challenge	Description	References
Soil Quality Enhancement	Positive	Break down organic matter, enriching soil with nutrients	Alagesan, 2016 ^[4]
Soil Aeration	Positive	Burrowing activities improve soil structure and root penetration	Mawcha, 2023 ^[41]

Crop Impact	Challenge	Occasional feeding on young seedlings in high population scenarios	David and Handa, 2010 ^[17]
Soil Restoration	Positive	Potential use in degraded land rehabilitation	Tudose and Rîșnoveanu, 2023 ^[59]

The economic benefits of millipedes in agriculture are shown in Table 3, which also highlights the slight difficulties that may arise in some situations as well as the benefits they provide in terms of soil quality. This well-rounded viewpoint acknowledges the necessity of sporadic management interventions while highlighting the potential of millipedes to promote sustainable agriculture.

Conservation status and threats

The growing demands on the region's biodiversity are reflected in the conservation status of millipedes in Marathwada. Because of their sensitivity to temperature, moisture, and soil quality, millipede populations are extremely vulnerable to changes in their habitat, just like many other creatures that live in soil. Despite receiving less research attention than larger species, millipedes are essential to the health of ecosystems. However, because so little is known about the ecological significance of millipedes, conservation efforts to save them are still quite low. Because of this, Marathwada millipedes are threatened by a variety of factors, such as pollution, climate change, habitat loss, and intense farming methods that disturb their habitats and weaken population resilience.

Habitat loss: One of the biggest dangers to millipede species in Marathwada is the quick alteration of natural habitats brought on by urbanization and deforestation. There is less habitat available for millipedes like *Julus sp.* and *Spirostreptus sp.* due to the growing fragmentation of forested areas, which offer the moist, shaded conditions essential for their existence (Paul *et al.*, 2022).^[47] Because they are less able to locate appropriate microhabitats, millipede populations are disrupted by habitat fragmentation, which lowers biodiversity in the impacted areas (Toth *et al.*, 2019). Millipede habitat loss is exacerbated by the fact that grassland areas, which are also threatened by agricultural expansion, provide fewer refuges.

Climate change: Global climate change is predicted to exacerbate the semi-arid environment of Marathwada, which is already characterized by erratic rainfall and hot summers. Millipedes, which are extremely dependent on consistent moisture levels, are vulnerable to extended dry periods and rising temperatures. The ability of millipedes to carry out vital ecological services may be diminished by climate change, which may also decrease the availability of suitable habitat and interfere with their moisture-dependent behaviors (Mengru *et al.*, 2018).^[43] Particularly, extended droughts have the potential to dry out soil habitats, rendering them inhospitable for species that are sensitive to moisture, such as *Spiroboles orientalis* and *Julus terrestris*.

Pollution: Millipedes are seriously threatened by soil and water contamination, which is frequently caused by industrial processes and the overuse of agricultural chemicals. Commonly applied pesticides and herbicides in Marathwada's agricultural areas have the potential to build up in the soil and have a direct or indirect impact on millipede populations. According to studies, millipedes'

physiology and behavior are disturbed by exposure to specific chemicals, which causes population decreases (Sánchez-Bayo, 2021).^[53] Pollutants can also change the microbial populations in the soil, which can affect the food supplies for millipedes and put their survival at even greater risk.

Agricultural practices: Millipede habitats are adversely affected by intensive agricultural methods such as deep plowing, frequent tilling, and monoculture crops (Stašiov *et al.*, 2014).^[57] The organic layer that millipedes rely on for food and shelter is removed when soil disturbance occurs, upsetting the soil's natural structure. In agricultural fields, monoculture systems reduce biodiversity, simplify habitats, and make it difficult for millipedes to locate sufficient food sources. Even while members of millipedes like *Polydesmus sp.* have evolved to certain agricultural settings, unsustainable farming practices can still cause them to lose soil organic matter and utilize excessive amounts of pesticides (Tudose & Risnoveanu, 2024).^[59, 60]

Targeted conservation initiatives for millipedes in Marathwada have received little attention despite these dangers. Millipedes and other soil-dwelling creatures must be included in larger biodiversity conservation plans due to their ecological roles. While encouraging sustainable farming methods may lessen risks in farms, efforts to create protected areas that incorporate forest and grassland habitats can offer safe havens for millipede populations (Knapp *et al.*, 2022).^[35] Support for millipede conservation may also be increased by raising public knowledge and implementing educational initiatives on the species' ecological importance. To maintain soil health, nutrient cycling, and the general stability of local ecosystems, Marathwada's millipede species must be protected.

Future research directions

Despite the importance of millipedes to the ecosystems of Marathwada, little is known about their distribution, biodiversity, and functional roles. Filling this knowledge gap is crucial to comprehending how these species support ecosystem sustainability and resilience, particularly in the face of shifting environmental conditions. Future studies could concentrate on a number of particular topics, such as the effects of climate change, genetic analyses to uncover evolutionary linkages, and the investigation of uncharted ecosystems in Marathwada. In addition to advancing scientific understanding, these investigations would supply vital information for sustainable ecosystem management and conservation planning.

Impact of climate change on millipede populations:

Knowing how temperature and moisture variations impact millipede populations is essential as Marathwada's climate patterns become increasingly erratic. Examining the effects of seasonal variations and extreme weather events on millipede behavior, reproduction, and survival could be the main area of research. Field research and ecological modeling could be used to investigate issues like "How do drought conditions affect millipede diversity and

abundance?" and "What is the impact of rising temperatures on moisture-dependent species?" (Luan *et al.*, 2024).^[38] In order to protect vulnerable species, the results of such studies could guide climate adaptation efforts like habitat restoration or artificial moisture retention techniques.

Genetic studies and species identification: Although the full extent of the diversity of millipedes in Marathwada is still unknown, it includes both common and possibly endemic species. Genetic research can assist identify distinct genetic lineages that might be in danger as well as shed light on the evolutionary ties between millipede species (Qu *et al.*, 2020).^[48] In areas where physical changes alone might not be enough to differentiate closely related species, molecular approaches like DNA barcoding can improve species identification. For conservation planning and biodiversity recording, questions such as "What genetic markers distinguish endemic species in Marathwada?" and "Are there cryptic species within well-known millipede populations?" might be helpful (Moir *et al.*, 2009 and Choudhari, 2014).^[45]

Unexplored and microhabitat studies: Although millipede populations are known to be supported by major habitat types such as woods, grasslands, and agricultural fields, little is known about the function of certain microhabitats including riverbanks, rock crevices, and caves. In-depth investigations of these microhabitats may identify new species of millipedes and record unique behaviors. The complete biological range of millipedes in Marathwada may be better understood by addressing research issues like "What special adaptations allow millipedes to survive in microhabitats with fluctuating conditions?" and "How does microhabitat variation influence community structure?" (Marek *et al.*, 2021 and Gilgado *et al.*, 2022).^[39, 24]

Interactions with soil microorganisms and decomposition processes: As decomposers, millipedes

have a close relationship with bacteria and fungi in the soil. Future studies could examine the symbiotic connections between millipedes and soil microorganisms, examining how these partnerships affect nutrient availability and decomposition rates. By emphasizing the function of millipedes in improving soil health, an understanding of these dynamics could guide sustainable agriculture methods. Both ecology and agronomy would benefit greatly from studies that address issues such as "How do millipedes influence microbial communities within the soil?" and "What impact does millipede activity have on nutrient cycling in agricultural soils?" (Victor *et al.*, 2017).^[61]

Ecotoxicology and pollution impact studies: Research on the effects of pollutants and pesticides on millipede populations is crucial because these substances are common in Marathwada's agricultural zones (Rajmohan *et al.*, 2020 and Dhuldhaj *et al.*, 2022).^[49, 19] The sub-lethal effects of frequently used pesticides on millipede physiology, behavior, and reproductive success could be evaluated through ecotoxicological research. Inquiries such as "How does pollution change the decomposition functions of millipede species?" and "What levels of pesticide exposure are toxic to millipedes?" would assist steer agricultural practices toward more sustainable methods that reduce harm to non-target species.

In order to inform conservation and management measures in Marathwada, these research directions are crucial. By concentrating on these topics, scientists can gain a thorough grasp of millipede resilience, biodiversity, and ecosystem health contributions, which will ultimately help with the sustainable management of Marathwada's natural resources. Proposed study topics that could improve conservation initiatives and expand our knowledge of millipedes in Marathwada are listed in Table 4. Scientists and conservationists may create focused plans to preserve millipede biodiversity and advance sustainable land management techniques by filling in these research gaps.

Table 4: Proposed Research Directions for Millipede Conservation in Marathwada

Research Area	Research Questions	Potential Significance	References
Climate Change Impact	How do drought and temperature fluctuations affect millipedes?	Inform climate adaptation strategies	David and Culins, 2015
Genetic Diversity and Species ID	What genetic markers distinguish endemic species?	Aid species identification, conservation planning	David & Gillon, 2009, Means <i>et al.</i> , 2021 ^[42]
Unexplored Microhabitats	What adaptations support millipedes in unique microhabitats?	Reveal full ecological range, potential new species	Zha <i>et al.</i> , 2023 ^[64]
Soil Microbe Interactions	How do millipedes affect soil microbial communities?	Enhance soil health understanding, sustainable agriculture	Gonzlez & Bel., 2012 ^[26]
Pollution and Ecotoxicology	What are the effects of pesticides on millipede populations?	Guide sustainable agricultural practices	Sánchez-Bayo, 2021 ^[53]

Conclusion

In the Marathwada region, millipedes are essential to the health of the soil and the operation of the ecosystem. Many facets of their biodiversity, distribution, and protection are still poorly known, despite their ecological significance. To guarantee the preservation of the millipede species of Marathwada and the ecosystems they sustain, this review emphasizes the necessity of thorough taxonomic surveys, ecological investigations, and conservation initiatives. The detailed exploration of millipedes in the Marathwada region highlights their critical ecological, economic, and conservation significance. As essential decomposers,

millipedes play a pivotal role in nutrient cycling and soil health, enhancing fertility by breaking down organic matter and improving soil structure through burrowing. Their diverse adaptations, spanning forests, grasslands, and agricultural lands, showcase their ability to thrive in Marathwada's semi-arid to tropical climate. Millipede families like Julidae, Spirostreptidae, and Polydesmidae exhibit specialized roles, from decomposition to aeration, underlining their importance in maintaining ecological balance across varied habitats. Despite their ecological contributions, millipedes face significant threats due to habitat loss, climate change, pollution, and unsustainable

agricultural practices. These challenges underscore the urgency for conservation measures, including habitat protection and promoting sustainable farming methods. Furthermore, the untapped potential of millipedes in environmental restoration and biotechnology highlights the need for advanced research, particularly in their interactions with soil microbes, genetic diversity, and resilience to pollutants. Addressing these knowledge gaps through targeted studies will not only deepen our understanding of their ecological roles but also aid in developing strategies for sustainable ecosystem management in Marathwada. Beyond the ecological aspects, millipedes can be a promising source of novel bioactive secondary metabolites in their secretions and can reveal a new era of bioactive molecules with therapeutic significance. Ultimately, the protection of millipede biodiversity is integral to the long term health of the region's soil and ecosystems, ensuring resilience in the face of environmental changes.

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