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Earthworms in Sustainable Agriculture: A Comprehensive Review

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Abstract

Earthworms are very essential for the health of the soil and the environment. They help to make sure that the soil is in good condition for growing crops. They do this by making tunnels in the soil, which helps to improve its structure. They also help to recycle nutrients in the soil and make it more fertile. Earthworms also have a positive effect on plants, helping them to grow better and protecting them from diseases and problems caused by the environment. They also help to prevent the soil from being damaged and stop harmful gases from being released into the air. It is really important to look after earthworms and make sure they are part of farming practices so that we can have healthy soil and grow food without harming the environment.Understanding the vital role of earthworms in agriculture not only deepens our understanding of soil biodiversity but also provides valuable insights for maximizing agricultural productivity while minimizing environmental harm.

Keywords: Earthworms, Sustainable agriculture, Nutrient cycling, Climate resilience, Holistic farming practices

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1. Introduction

Sustainable agriculture has received significant attention in recent years as a critical approach to addressing the challenges of food security, environmental degradation, and resource depletion. Earthworms have emerged as unsung heroes in this context, improving nutrient cycling, soil fertility, and the general health of ecosystems.

The complex relationship between earthworms and sustainable agriculture has piqued the interest of researchers, agronomists, and environmentalists alike.

Earthworms are soil-dwelling organisms known for their remarkable ability to convert organic matter into nutrient-rich humus through a process known as vermicomposting. Because of this unique ability, they can help improve soil structure, water retention, and nutrient availability, ultimately contributing to sustainable crop production. Understanding the multifaceted role of earthworms is becoming increasingly important as the world grapples with the need to transition to more environmentally friendly and resilient agricultural practices.

This review paper aims to provide a comprehensive overview of current knowledge on the incorporation of earthworms into sustainable agricultural systems. It delves into the role of earthworms in soil fertility, crop productivity, vermicomposting techniques, and its benefits in agriculture. Earthworm's compatibility with organic farming principles, such as reduced chemical input and increased reliance on natural soil processes. The paper also addresses climate resilience, carbon sequestration, sustainability assessment, and earthworms' role in the breakdown of plastic.

By combining existing knowledge and pointing out research gaps, this review hopes to be a useful tool for scientists, decision-makers, and practitioners who want to use earthworms to promote resilient and sustainable agricultural systems.

2. Earthworm Diversity

Earthworms are incredibly diverse worldwide and are frequently disregarded despite being vital components of terrestrial ecosystems. Despite their relatively straightforward look, these segmented invertebrates exhibit a variety of traits and adaptations that allow them to flourish in a variety of settings. Whether they are common garden residents or inhabit other types of habitats, earthworms are vital to the health of the soil, the cycling of nutrients, and the sustainability of entire ecosystems.Examining the variety of these subterranean engineers illuminates the complex network of life under our feet and emphasizes their significance in preserving the global ecological equilibrium.

Numerous species make up earthworm communities, and each one has a distinct function in the activities that occur in the soil. Understanding the function of earthworms in soilecosystems requires first identifying the species that are significant to ecosystem services.There has been research on the diversity of earthworm species, but it has only been done in a few different geographic areas. Less than half of the world's earthworm species have been described, per an earlier survey (Dewi and Senge, 2015).

Earthworms live in the soil. Diverse earthworm species, however, have diverse burrowing habits in addition to differences in eating and dwelling preferences. As a result, various earthworm species exhibit distinct ecological roles.

Earthworms are categorized as follows;

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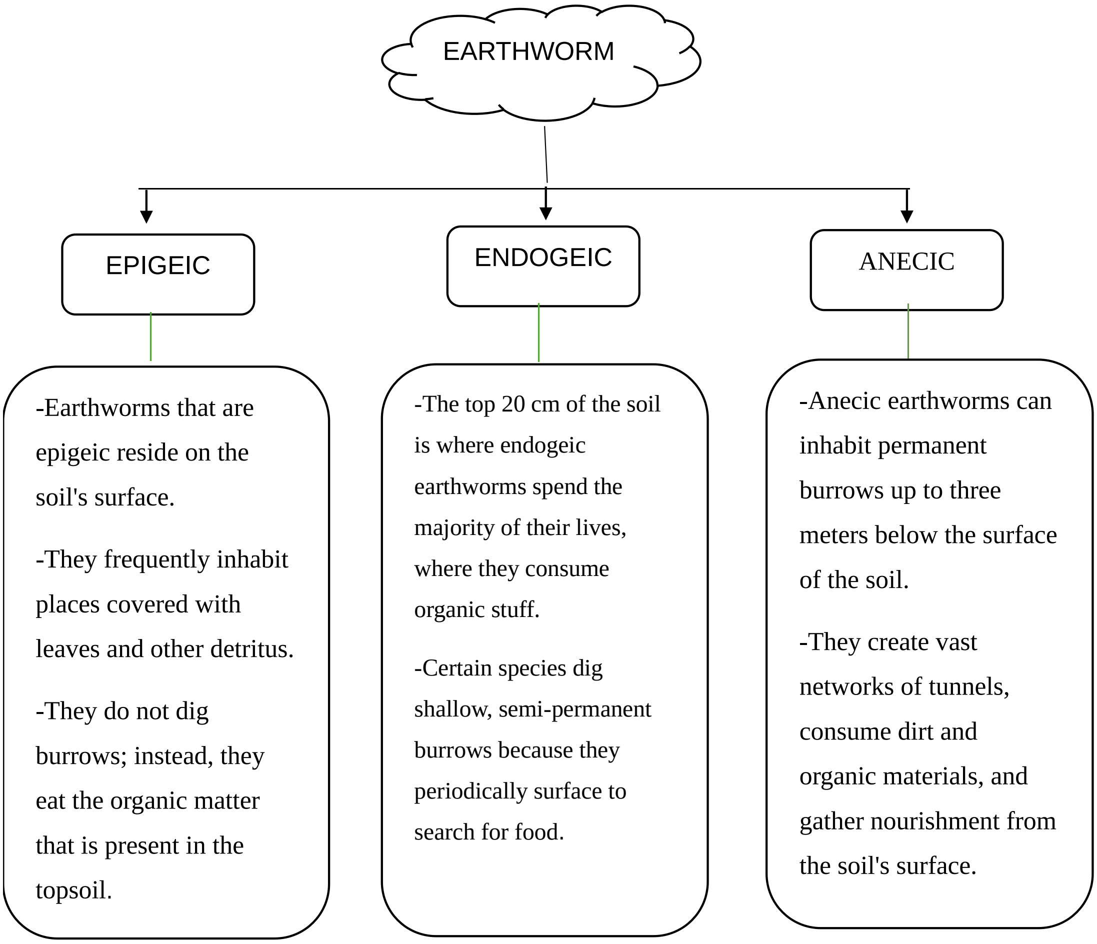

Earthworms come in hundreds of kinds, and new species are always being found. Though estimates differ, the consensus is that there are more than 7,000 species of earthworms recognized around the globe. Out of over 7,000 species, only roughly 150 are found in vast geographic distribution worldwide. Some of the most found species are mentioned in the following table.

Table 1. List of some commonly found Earthworm Species

Sl. No.	Common Name	Scientific Name
1.	Red wiggler	*Eisenia fetida*

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2.	Redhead worm	*Lumbricusrubellus*
3.	Gray worm	*Aporrectodeacaliginosa*
4.	Green worm	*Allolobophorachlorotica*
5.	Asian jumping worm	*Amynthasagrestis*
6.	Kentucky earthworm	*Komarekionaeatoni*
7.	European nightcrawler	*Dendrobaenahortensis*
8.	Canadian nightcrawler	*Lumbricusterrestris*
9.	African nightcrawler	*Eudriluseugeniae*
10.	Louisianaswamp worm	*Lutodrilusmultivesiculatus*
11.	Oregon giant earthworm	*Driloleirusmacelfreshi*
12.	Giant Gippsland earthworm	*Megascolidesaustralis*
13.	Washington giant earthworm	*Driloleirusamericanus*
14.	Composting worm	*Perionyx excavatus*

3. Earthworm and soil fertility

Earthworms play a vital role in preserving the quality and fertility of the soil via a process referred to as bioturbation. Earthworms play a crucial role in the initial and subsequent breakdown of organic matter, as well as in the release and recycling of nutrients contained therein. More surface organic matter can be consumed by earthworms than by all other soil organisms combined(Chauhan, 2014). There are many ways through which earthworms maintain the soil fertility:-

I. Organic matter decomposition- Earthworms dig burrows and fill them with organic matter, such as leftover plant material and dead leaves. Organic materials are broken down into smaller compounds during digestion, and the worm discharges nutrient-rich castings. These castings are a type of vermicompost that contains more accessible nutrients such as nitrogen, phosphate, and potassium, as well as beneficial microbes.

II. Mixing of Soil Layers - Earthworms consume soil particles from various strata and mix them in their digestive tract. This action promotes soil horizon mixing, making important nutrients from deeper layers more accessible to plant roots.

III. Soil Aeration-Earthworms excavate tunnels in the soil that help with soil aeration. Encouraging the growth of aerobic bacteria that break down organic matter and release nutrients into the soil, this improves soil-to-atmosphere oxygen exchange.

IV. Enhanced Soil Structure - The stable aggregates produced by earthworm activity enhance soil structure by facilitating improved root and water penetration. Additionally, the better soil structure lessens soil compaction, which would otherwise obstruct water flow and root development.

V. pH Regulation - Earthworms contribute to soil pH regulation by releasing alkaline mucus that neutralizes the acidity of the soil. This can be particularly helpful in low-pH (acidic) soils, making a greater variety of crops more suitable for them.

VI. Increased Microbial Activity - Earthworms break down organic matter and excrete materials that encourage microbial activity in the soil. This increased microbial activity further aids in the breakdown of organic materials and the cycling of nutrients.

VII. Nutrient cycling - Earthworms play a role in nutrient cycling within the soil ecosystem. They consume nutrients in organic matter and excrete castings that make these nutrients more available to plants. This process aids in the maintenance of a healthy nutrient balance in the soil.

VIII. Water Holding Capacity - Earthworms' enhanced aeration and soil structure can result in a greater capacity to hold water, which lowers the risk of waterlogging and drought stress for plants.

In addition to decomposing organic wastes, bacteria in the gut of earthworms dispose of hazardous chemicals that the worms consume. Earthworm castings contain auxin, a plant growth regulator that encourages deeper and faster root growth. The earthworms' casts have a higher level of nitrogen fixation than the soil because the bacteria that fix nitrogen are found in both their guts and their casts.In addition, casts have higher nitrogenase activity than surrounding soil, which helps to explain why casts have higher nitrogen fixation (Edwards and Bohlen, 1996 and Ranch, 2006).

The concentration of substantial amounts of readily assimilated nutrients (N, P, K, and Ca) in fresh cast depositions has a more notable short-term impact. Earthworm mucus and urine are the main sources of these nutrients. Crop productivity and nitrogen mineralization are also impacted by the species of earthworms and their interactions with one another in the system (Bhadauria& Saxena, 2010).

Despite being a necessary component for plant growth, P is the nutrient that limits plant growth the second most after nitrogen. In the absence of earthworms, the available P content in earthworm casts is greater than in the surrounding soil (Chauhan, RP, 2014). Nuutinen et al. (1998) found a positive correlation between earthworms and soil P content, underscoring the importance of earthworm activities in P cycling. However, Kuczak et al. (2006) clarified in a review that the increase in P in earthworm casts could be caused by the following factors: (a) Higher pH levels (6.8 and 6 for the anterior and posterior portions and 5-5.4 for the soil, respectively) in the earthworms' digestive tracts (Barois and Lavelle, 1986), (b) The earthworm gut secretes a lot of mucus, which can liberate carboxyl groups from carbohydrates. These groups can then block and compete for P sorbing sites, increasing the amount of soluble P. (c) increased microbial activity during the entire digestion process. By providing earthworms with soil and thoroughly mixing it with them, it is possible to alter the concentration and chemical form of P in them. The inorganic phosphorus release rates in the casts were approximately four times higher than those in the surface soil, according to Sharpley and Syers (1976).

The elevated levels of humic acid found in vermicasts serve to sequester and chelate elements such as zinc, magnesium, and iron, thereby rendering them accessible for plant uptake. It is well known that humic acid's various functional groups react violently when exposed to metal ions. Thus, the role that earthworms play in the relationships between microbes and other earthworms provides insight into the exchange of nutrients, particularly trace elements, that occurs between microbes, earthworms, and plants(Akhila & Entoori, 2022).

Earthworms are essential for preserving and improving soil fertility. Their actions support several soil processes that promote healthy ecosystems and plant growth. By excavating and forming pathways, earthworms enhance the structure of the soil, facilitating greater root penetration and water infiltration. Through the breakdown of organic matter caused by their feeding habits, vital nutrients are released, and microbial activity is encouraged. Furthermore, the nutrient-rich earthworm castings that are left over after their digestion are a byproduct that enriches the soil with nutrients.

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4. Vermicomposting: Techniques in Agriculture

Vermi compositing can be done in two ways. The bin method is used for small-scale operations such as home composting or garden composting in vermicompost piles. On a large scale, the

pile method is used for vermicomposting. It necessitated a significant amount of waste. It is

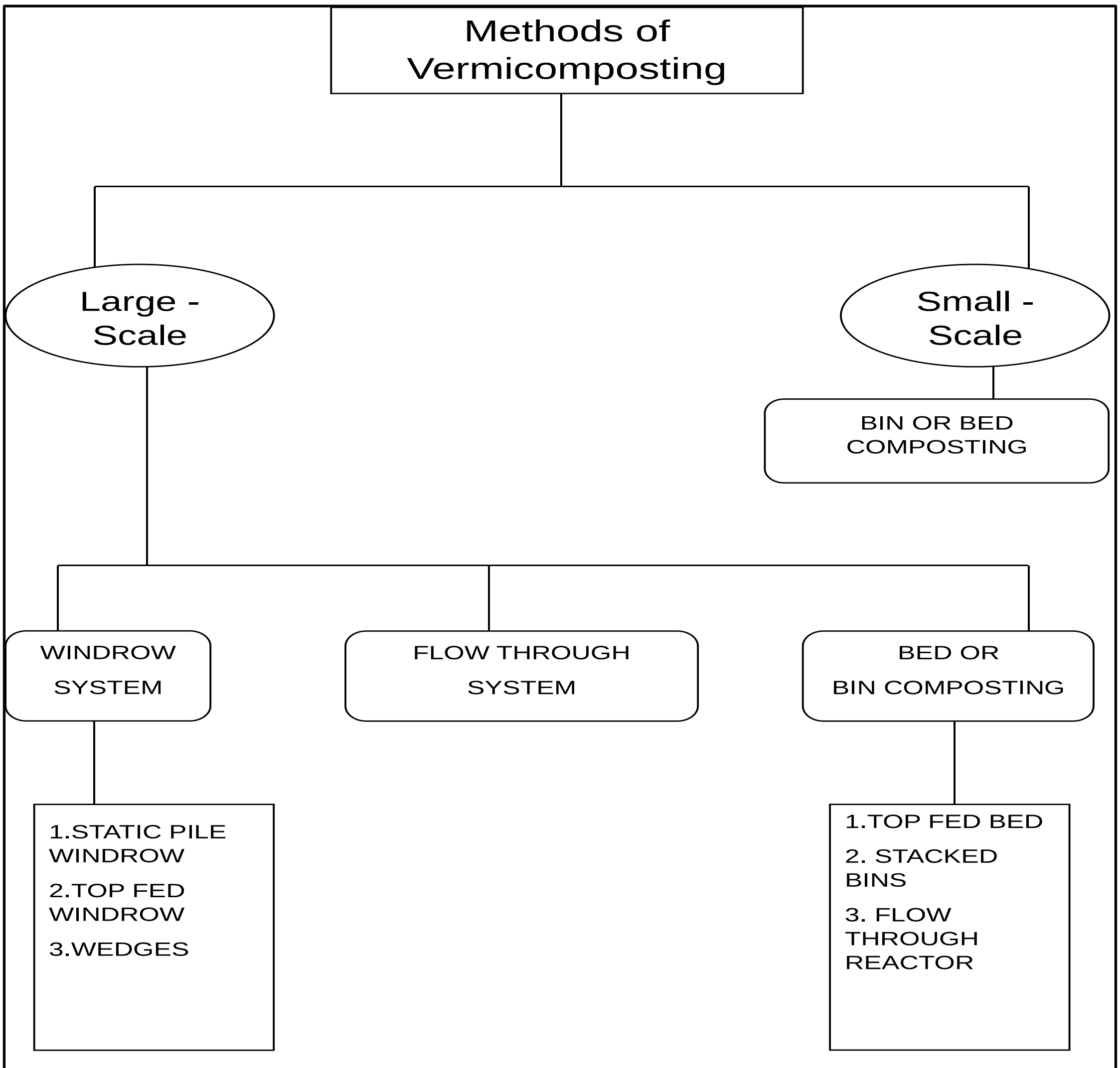

FIG. - CHART SHOWING VARIOUS METHOD OF VERMICOMPOSTING

commonly used for commercial purposes.

4.1. Small-scale production of vermicomposting

Commercially, a large variety of bins are available for small-scale home vermicomposting. You can also use different kinds of containers, like old plastic containers and wooden or metal containers. The way a small bin is stored and how the worms are fed dictates its design. The best way to turn kitchen waste into compost in a small space is to engage in small-scale vermicomposting. Organic matter can be broken down by worms without the need for additional human physical labor. While common earthworms like ***Lumbricusterrestris*** are anecic (deep burrowing) species and cannot be used for vermicomposting, ***Eisenia fetidae*** is an epigeic (surface dweller) species that can.

4.2. Large-scale production of vermicomposting

The fundamental process of earning composing is the same for both small- and large-scale production units. However, in the case of large-scale production, it is critical to maintain the appropriate environment for vermicomposting as well as the quality of the vermicompost. A proper waste and worm issue, pH, moisture, and so on should be maintained. It is practiced. Although beds and bins are the most used warm-grown methods, some prefer windrose, the wedge system, or the continuous flow reactor.

(i) Windrow system: Windrows are three-foot-high linear piles of organic matter on the ground. They are widely used both in the open and under cover. It is composed of materials used as bedding by earthworms. It is intended to keep predators away from the worms and is constructed of concrete. It serves as a sizable bin. It is supplemented with organic material. The windrow's abundance of organic matter keeps the worms from escaping, despite the lack of any physical barriers to stop them from doing so. The front side of the bed is where organic matter is added.It grows large enough and pushes across after mulching and continuous feeding.The back side of the bed is abundant in castings. Worm castings can be removed regularly. This side of the bed is more susceptible to grass and weed growth.

a. Static pile windrows (hatch): Pile combinations of mixed bedding and feed, or bedding layered with feed on top, are known as static pile windrows. After being added, worms are allowed to compost until the process is finished. These piles can take on any shape you can imagine, including squares, rectangles, and elongations. Their maximum height should be one meter. A group of researchers from Nova Scotia conducted experiments with static windrows in 2003–2004. Cattle and poultry manure is utilized as feedstock, and shredded municipally collected fiber (boxboard, cardboard, etc.) is used as bedding.

b. Top-fed windrows (continuous flow) - Similar to batch and static pile windrows are top-fed windrows. The only distinction is that they are handled as a continuous flow process rather than being combined and put in batches. This indicates that the bedding is initially laid out, worms are added, and then thin (less than 10 cm) layers of food are applied. The worms eat at the interface between the food and bedding, leaving their castings close to the bottom of the windrow. The partially eaten bedding is in the center, the fresher food is on top, and the

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finished product is at the bottom. Regular additions of fresh bedding are necessary to replenish the bedding material that the worms have eaten.

c. Wedges (continuous flow) - One variant of the windrow system is the wedge system. Inside a three-sided corral-style structure that is no taller than three feet or one meter, is an initial stock of worms in bedding. The sides of the corral can be constructed from wood, concrete, or even bales of hay or straw. The only restriction on the width of the corrals is that they must come into contact with the interior of the piles for monitoring and remedial measures like adjusting the pH level or moisture content. It would be best to have a corral width of roughly 6 feet, allowing room for foot travel. The worm population, the material being processed, and other factors all affect the length. Regular feeds of fresh material are made through the open side. The completed material is eventually left behind as the worms follow the fresh food. The final product is harvested by taking off the corral's back and using a loader to scoop the material out once it reaches the open end. The direction is then changed and a fourth side is added.

(ii) Flow through system: A breaker bar is pulled over the large mesh screen that forms the base of the bed to harvest an inch of castings from below, and an inch of worm chow is fed across the top of the bed. The flow-through system does away with the necessity of separating red worms from castings prior to packaging, as they are surface dwellers that are continuously looking for new food sources. Flow-through systems are the best option for operations in colder climates because they are perfect for indoor applications.

(iii) Beds or bins

a. Top-fed beds (continuous flow)- It's like having a top-fed windrow. The bed differs in that it has a floor or not and is enclosed by four walls. Rain and wind are kept at bay by larger beds and bins. Straw can be layered on top to act as insulation. Harvesting vermicompost involves utilizing the horizontal migration technique.

For instance, the lowest level of an old barn houses the chicken coop on the Scott farm, which has a concrete floor and walls made of mortared cinder blocks. Although the building has a greenhouse attached, the wintertime temperatures are continuously much below freezing. The bins are filled with pillows made from pink fiberglass insulation bats stuffed inside plastic bags for insulation during the winter.

b. Stacked bins (batch or continuous flow) - Stacked bins are used when there is a shortage of space. The vertical dimension is used in the fight against space-related problems. Bins

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need to be sufficiently light to be lifted. You can feed them for eternity. But that means having to deal with them on a regular basis. The batch method is more economical. The material is put in the bin after being mixed beforehand. After adding the worms, the bin is stacked and left for a predetermined period of time before being emptied. This is the method that professional vermicomposters in North America typically use.

c. Flow-Through Reactors- In the 1980s, Dr. Clive Edwards and associates in England developed the flow-through concept. Since then, a number of businesses have adapted and changed it. The elevated box in which the worms reside is typically rectangular and has a maximum width of three meters. The product is removed through a grid at the bottom after material is added, usually with the help of a hydraulically powered breaker bar. The reason for the term "flow-through" is that the material is constantly forced to the top and the worms are never disturbed in their beds. passes via the reactor and exits at the bottom. E. fetida prefers to feed near the top of the bedding and leaves castings there. The materials are forced to the bottom by a set of breaker bars that are hydraulically driven. (*Handbook on Vermicomposting: Requirements, Methods, Advantages and Applications*, n.d.)

5. Vermicomposting: Benefits in Agriculture

Vermicompost has the following advantageous functions (Adhikary, 2012):

(1) There is a lot of humus in red worm castings. The formation of soil particle clusters is aided by humus, which increases the soil's capacity to hold water and creates air channels. (2) It is believed that humus can protect plants from harmful nematodes, bacteria, fungi, and plant diseases.

(3) A worm casting, also called worm cast or vermicast, is a biologically active mound composed of thousands of bacteria and enzymes along with plant remnants that the worms wereunable to break down.

(4) The nutrients in castings are easily accessed by plants.

(5) The worm's digestive system functions similarly to a tiny composting tube, combining the ingredients and inoculating the waste.

The following factors make vermicompost the best organic manure for improving plant growth and yield (Joshi et al., 2015):

1. Compared to conventional composts, vermicompost has a higher nutritional value.

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2. The higher rate of mineralization and degree of humification can be attributed to earthworm activity.

3. Vermicompost has a high water-holding capacity, drainage, aeration, and porosity.

4. The environment is conducive to plant growth when microbiota, namely actinomycetes, bacteria, and fungi, are present.Plant-available nutrients like nitrates, phosphates, exchangeable calcium, and soluble potassium are found in vermicompost.

5. Vermicompost also contains other substances that influence plant growth, such as plant growth regulators that are made by microorganisms.

6. It was discovered that earthworm-processed organic wastes produced auxins and cytokinins.

7. Earthworms release certain metabolites into the soil, such as vitamin B, vitamin D, and related substances.

8. Besides increased N availability, it is found that the casts have higher availability of P, K, Ca, and Mg.

Vermicompost's primary ingredients are C, H, and O. Additionally, it has micronutrients and nutrients such as N, P, Ca, K, Mg, and S that are similar to inorganic fertilizers applied to the soil in terms of their effect on plant growth and yield. Vermicompost, therefore, contains a high concentration of humic substances, which provide a range of sites for chemical reactions; microbial components that are known to stimulate plant growth and inhibit disease via the activities of bacteria (Bacillus), fungi (Trichoderma), yeasts (Sporobolomyces and Cryptococcus), and chemical antagonists such as phenols and amino acids (Theunissen et al., 2010).

Vermicompost and earthworms are two ways to boost horticultural productivity without using agrochemicals. It will benefit society on many social, economic, and environmental levels by creating safe, "nutritive and health protective" (rich in minerals and antioxidants) foods for people that even protect against certain types of cancer. In addition, it will save human waste and rid the world of dangerous "agrochemicals". By reabsorbing large amounts of atmospheric carbon (absorbed by green plants during photosynthesis), vermicompost is used on farms to increase soil fertility, stop erosion and compaction, lower greenhouse gas emissions, and lessen global warming (Sinha et al., 2013).

6. Earthworms and Organic Farming Practices:

Earthworms are the unsung heroes of organic farming because they are essential to preserving the fertility and health of the soil. The ecological engineers of the subterranean realm are these little, sometimes disregarded organisms. In the context of organic farming, they play a crucial role in establishing a healthy, balanced ecology.

Organic farming is a kind of farming that prioritizes natural processes over artificial chemicals to grow crops. Organic farmers rely on natural processes rather than synthetic pesticides and fertilizers. Earthworms can help in this situation. Their burrowing practices improve the soil's structure and porosity by aerating it. This facilitates roots' deeper penetration and availability of essential nutrients.

In addition, earthworms are excellent decomposers. They turn organic debris, such as dead leaves, into rich, nutrient-dense vermicompost, which is a naturally occurring fertilizer. This black gold helps plants grow strong and colorful by restocking the soil with vital minerals and microbes.

Furthermore, earthworms are essential for controlling moisture levels. Their tunnels serve as pathways, allowing water to seep in and avoiding waterlogging. This is particularly important for organic farming because it reduces the possibility of water-related problems like root rot.

Earthworms are essentially the unsung heroes of organic farming, representing the perfect balance between the natural world and human endeavor. Their existence is evidence of the value of collaborating with nature as opposed to fighting it. Understanding and appreciating the essential function that earthworms play becomes increasingly important as we continue to explore sustainable agriculture approaches.

“In Indian agriculture, use of chemical fertilizers cannot be eliminated; rather it can be reduced or minimized” (Gupta, S et al., 2014).

6.1. Earthworm’s function in preserving sustainable Agriculture:

Because of intensive agriculture, the green revolution has increased production in developing nations. While using effective irrigation systems to harvest three crops in a year has produced outstanding yields and productivity, its long-term negative consequences on the ecosystem and soil conditions have not been taken into account, particularly over the last forty years. The soil's productivity is being severely diminished by the widespread use of chemical fertilizers and inappropriate irrigation techniques. The best and most cheap approach to undo the negative effects of modern agriculture is to use simple, low-cost methods like vermi-biotechnology to create a farming system that is long-lasting and financially successful in sustainable or natural farming. As a result, the sustainability of traditional agricultural systems—such as those that are biological, organic, ecological, regenerative, natural, and biodynamic—is a concern.

An innovative technique known as vermi-biotechnology allows organic waste resource management to be done with minimal capital expenditure and without the need for expensive laboratory or specialized industrial instruments. It is commercially viable, socially conscious, and environmentally benign. In a handful of years, it can feed the hungry, provide 460453 million jobs for young people, eliminate our dependency on chemicals, convert waste into fertilizer, repurpose underutilized land, and make our country wealthy and environmentally friendly.

It is basically composed of earthworms (Eisenia fetida, Eudriluseugeniae, and Perionyxexcavatus), as all organic waste eventually breaks down in its natural habitat. It might occur practically anywhere, outside, or inside. Composting is the process of converting various organic wastes such as paper, cotton clothing (if not being recycled for useful products, can be recycled with this technology), animal dung (cattle, sheep, horse, goat, and poultry droppings), forestry waste (wood-sawing, peels, sawdust, and pulp), and agricultural waste (after harvesting and threshing the produce). Earthworms do all the natural processing, and the result is stable organic matter. It improves the pH, biological activity, production, quality, and capacity of the soil to hold water.

Using Perionyx excavatus, earthworms were used in India for the first time to try breaking down solid trash. Eudriluseugeniae was later given to the University of Agricultural Sciences in Bangalore to investigate the viability of their establishment in this subcontinent, which has a climate akin to their natural habitat.Since 1982, Eudriluseugeniae has been sold as a trash composting plant. When it comes to feeding and reproduction rate, this species performs better than Perionyx excavatus. It was long thought that the response would be temporary because many species tend to perform particularly well in novel situations until they get accustomed to them. Large-scale observations of this change in their efficacy have not before been made.

Earthworms are essential to organic farming since they drastically cut down on the demand for artificial fertilizers. Their actions in the soil, which promote healthy microbial communities, better soil structure, and nutrient cycling, are mostly to blame for this.

6.2. Earthworm and Crop Productivity

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A vital part of ecosystems that support good soil are earthworms. They are essential for enhancing the drainage, fertility, and structure of the soil—all factors that are critical for crop yield. Earthworms are crucial for sustainable agriculture because they play a role in the cycling of nutrients and the breakdown of organic materials. Earthworms improve soil fertility by adding nutrients to the soil through their castings. The organic matter, nitrogen, phosphorus, and potassium that earthworm castings are rich in are necessary for plant development. Because earthworms increase the accessibility of other nutrients to plant roots, they also contribute to increased soil availability.

Although earthworms are essential soil ecosystem engineers who facilitate plant development in a variety of ways, their impact on the world's agricultural output has not been measured. We can evaluate the impact of earthworms on the production of significant crops globally by looking at maps of earthworm abundance, soil properties, and crop yields along with earthworm-yield responses from the literature. More than 140 million metric tons of grains (maize, rice, wheat, and barley) and 2.3% of the world's legumes are produced by earthworms each year, according to the research. Earthworms are especially important in the global south; in Sub-Saharan Africa, they contribute 10% of grain production, and in Latin America and the Caribbean, they account for 8% (Fonte *et al.*, 2023).

Earthworms improve the structure of the soil by creating channels and tunnels in it. These channels and burrows improve drainage and aerate the soil, making it more suitable for plant growth. Furthermore, earthworms contribute to the breakdown of large soil particles into smaller ones, improving the overall structure of the soil. Crop productivity is influenced by the soil's structure. It provides unrestricted air and water passage through the soil, which is necessary for root development and nutrient uptake. Another advantage of having a healthy soil structure is less soil erosion.

It is possible that earthworms and plants co-evolved because earthworms are the most prevalent subsurface biomass in most terrestrial ecosystems and have existed in soils for several hundred million years. Over a century ago, it was determined that earthworms aided in the development of plants. When earthworms aided in plant development, biomass production increased by more than 20%. The output of biomass varied when earthworms were present, and many environmental conditions were shown to be the cause of this fluctuation. Soil type, particularly its texture and carbon content, is a significant influence, accounting for 43% of the variation in plant yield response. When earthworms are present, sandy soils with a pH of mildly acidic exhibit the highest increase in biomass output.

Earthworms cause changes in the physicochemical properties of soil, such as: (i) changing the porosity and aggregation of the soil, which impacts the availability of oxygen and water for plants; and (ii) increasing the mineralization of SOM (Soil Organic Matter), which improves the availability of nutrients for plants. Interactions with other species are involved in the other three mechanisms: symbiont stimulation, biocontrol of parasites and pests, and the synthesis of plant growth regulators through the stimulation of microbial activity. Because of the various processes involved and the unpredictable nature of field environments, it is difficult to establish these effects in agroecosystems; this implies that more research on earthworm-plant interactions in real environments is necessary (Bertrand *et al*., 2014).

7. Techniques for Managing Earthworms to Increase Crop Productivity:

Farmers may increase crop production and support earthworm populations in several ways. These consist of:

- ✓ Minimizing tillage: Tillage can destroy and harm earthworm burrows. Earthworm populations can be raised by decreasing tillage or converting to no-till farming.
- ✓ Adding organic matter: Since earthworms consume organic matter, increasing the amount of compost or manure in the soil will aid in the population of earthworms.
- ✓ Steer clear of pesticides: Since pesticides can damage earthworms, it's best to stay away from them whenever you can. If pesticides are necessary, it's critical to select those that won't hurt earthworms as much.
- ✓ Mulching: To control temperature and preserve moisture, cover the soil's surface with organic mulches. Additionally, mulches decompose over time to give earthworms a consistent source of organic matter.
- ✓ Crop Rotation: To vary the plant leftovers and root exudates in the soil, rotate your crops. Numerous earthworm species are supported by the diverse organic elements that are contributed by various crops.
- ✓ Control pH: In general, earthworms like neutral to slightly acidic soil. Maintaining a pH balance in the soil will help to foster earthworm activity.

- ✓ Green Manure Crops: As part of your crop rotation, include green manure crops. In addition to adding organic matter, these cover crops assist in enhancing the structure of the soil, which encourages earthworm activity.
- ✓ Composting: Set up systems for composting on your property. Compost that has broken down well is a great source of food for earthworms and improves soil fertility in general.
- ✓ Water management: Keep the right amount of moisture in the soil. Moisture is necessary for earthworm activity. However, as it might lower the amount of oxygen in the soil, severe waterlogging should be avoided.
- ✓ Preserve the natural ecosystems surrounding the farm, including riparian zones and hedgerows. These places may act as havens for earthworms and facilitate their migration into fields used for agriculture.

8. Earthworm and bioremediation

Earthworms facilitate aerobic soil conditions that encourage the decomposition of pollutants and help keep the soil continuously mixed. Earthworm-mediated soil bioremediation offers promise for sustainable agriculture. In addition to supporting the microbiological and metabolic activity of the soil on the substrate, earthworms also help to partially stabilize their excretions, which lowers environmental concerns. Furthermore, earthworms are said to be essential to the bioaccumulation of polyaromatic hydrocarbons (PAHs). Earthworms can accelerate the bioremediation of polluted soils by stimulating the growth of microorganisms and plants. Earthworms are widely regarded as bioindicators of soil fertility because they have been demonstrated to enhance the soil quality of damaged land. Given how important earthworms are to soil processes, any action that fosters an environment that is favourable to them will eventually increase soil fertility and protect biodiversity (Datta *et al*., 2016).

In bioremediation, or the use of living organisms to clean up or alleviate environmental contamination, earthworms are important. They provide a variety of contributions to the process:

- ✓ Improved Soil Aeration: As earthworms burrow, they form channels in the soil. This increases the activity of aerobic soil bacteria, which degrade contaminants more efficiently than anaerobic settings.
- ✓ The decomposition of organic matter occurs as a result of earthworms eating and digesting organic matter found in the soil. One technique that helps break down

various organic contaminants like hydrocarbons and some pesticides is vermicomposting.

- ✓ Enhancement of Microbial Activity: Earthworms encourage the development and activity of helpful microorganisms in the soil. These microorganisms help break down organic pollutants and change some toxins into less dangerous forms.
- ✓ By converting organic waste into nutrient-rich castings, earthworms contribute significantly to the cycle of nutrients. This improves the soil's fertility and encourages the development of plants that can help with phytoremediation, which uses plants to absorb or neutralize toxins.
- ✓ Metal Remediation: The tissues of certain earthworm species are capable of accumulating heavy metals. Metals from polluted soils may be extracted using this process, called bioaccumulation. However, since using earthworms for metal cleanup varies depending on the species, care must be taken and not all species are appropriate for this usage.
- ✓ Enhanced Soil Structure: Earthworms increase the porosity and ease of water flow in the soil by improving the soil's structure. This facilitates the diluting and leaching of pollutants that are soluble in water.
- ✓ Reduced Bioavailability: By changing the chemical forms of certain contaminants in the soil, earthworms might lessen their bioavailability. This may lead to a reduction in the toxicity and mobility of pollutants.
- ✓ Pesticide Degradation: It has been discovered that some earthworm species aid in the breakdown of specific pesticides. Enzymatic processes within their digestive systems can degrade pesticides into less toxic forms.

9. Soil erosion prevention and earthworm

The soil biota plays a significant role in determining the physical properties of soil and its structure. In particular, an abundance of studies shows that earthworms' digging and feeding activities have an impact on soil aggregation, aggregate stability and tensile strength, soil roughness, water infiltration, and particle size distribution. Soil erodibility and erosion are significantly influenced by all those characteristics. However, there isn't much quantitative research on earthworms' impact on soil erosion. While some research highlights earthworms' control over structural stability, which reduces soil erosion, other studies claim that earthworms increase soil losses (Blanchart et al., 2004).

Earthworms and other soil macroinvertebrates, like termites and ants, have earned the moniker "ecosystem engineers" due to their crucial role in the establishment and upkeep of soil structure through the formation of continuous macropores, stable macroaggregates, and organo-mineral complexes. Earthworm activity can be positively correlated with reduced soil disturbance and/or crop residue retention. Consequently, earthworm activity can be a major factor in determining the structural characteristics of soil under different crop management techniques

(A. Castellanos-Navarreteetal.,2012).

In terms of soil fertility loss and water quality deterioration, soil erosion is a major global issue. Soil erosion is commonly attributed to changes in land use, which result in the removal of buffering plants. Rapid population development has resulted in the expansion of farming areas into more marginal locations, such as mountains, and the shortening or complete abandonment of fallow times (Pascal jouquetetal, 2008).

Given their swift response to changes in land use, earthworms are typically seen as intriguing markers to track various agricultural techniques as well as various landscape architectures and transformations. When natural, or undisturbed, ecosystems are replaced by agroecosystems, it discovered that earthworm biodiversity is altered. There were mostly endogeic species in this watershed, and there was a low density of earthworms (Pascaljouquet et al, 2008).

Bulk density, texture, organic matter, water potential, cations, aggregate size and stability, and shear strength are the main factors affecting soil erosion (including splash and surface sealing and crusting). Based on their ability to burrow and feed, earthworms affect most of these factors, as evidenced by numerous studies on their activity regarding soil erosion in tropical environments.
Earthworms can first modify the roughness of the soil by depositing casts at the soil's surface.

Furthermore, there is a direct correlation between soil erodibility and aggregate stability, which depends on the distribution of particle sizes as well as the amount and quality of organic matter. It is well known that earthworms affect these dimensions. Even though earthworm cast stability has been extensively researched, field behavior and soil erosion have not always been directly linked to the findings. The last factor that earthworms affect is soil porosity, which has an immediate impact on water infiltration, hydraulic conductivity, and soil storage ability(Blanchart et al., 2004).

10. Carbon Sequestration and Earthworms

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The urgent need to address climate change has led to an increased focus on sustainable agricultural practices that not only reduce greenhouse gas emissions but also enhance carbon storage in soils. In this context, earthworms, often overlooked as mere soil inhabitants, play a critical role. Their activities in the soil environment have profound implications for both carbon sequestration and the broader aspects of climate resilience (Smith, Jones, Houghton, & Saunders, 2022).

10.1. Mechanisms of Carbon Sequestration

Decomposition of Organic Matter: Earthworms consume organic residues and soil organic matter, breaking them down into simpler compounds. This process increases the availability of these compounds for microbial action, leading to the formation of humic substances, a stable form of soil carbon.

Formation of Soil Aggregates: The physical activity of earthworms, including burrowing and casting, leads to the formation of stable soil aggregates. These aggregates encapsulate organic matter, protecting it from rapid decomposition and thus, contribute to long-term carbon storage in soils (Lee & Foster, 2021).

Enhancement of Root Growth and Plant Residue Return: Earthworms improve soil structure and nutrient availability, fostering better plant growth. Increased plant biomass and the subsequent return of plant residues to the soil further contribute to soil organic carbon.

11. Impact on Greenhouse Gas Dynamics

Reduction in Methane Emissions: Earthworms aerate the soil, creating an environment less conducive to methane-producing microbes, thus potentially reducing methane emissions, a potent greenhouse gas.

Influence on Nitrous Oxide Emissions: Earthworms play a complex role in nitrous oxide emissions that varies depending on the species and the environment. While some studies suggest that earthworm activity can increase nitrous oxide emissions due to enhanced nitrification and denitrification processes, others report a reduction or no significant effect (Chen & Gupta, 2019).

12. Earthworms and Climate Resilience

12.1. Soil Water Management: Earthworm channels improve soil infiltration and water-holding capacity, which is vital for crop resilience during drought conditions.

12.2. Soil Biodiversity and Health: Earthworms support a diverse range of soil microorganisms and contribute to the suppression of soil-borne diseases, enhancing overall soil health (Rodriguez & Brown, 2020).

12.3. Reduction in Soil Erosion: Earthworms can lessen soil erosion, which is a major concern in light of extreme weather events associated with climate change, by enhancing the structure of the soil.

13. Challenges and Considerations in Earthworm Management

Species-Specific Roles: Different earthworm species exhibit diverse effects on soil processes and carbon dynamics. Understanding these differences is crucial for effective earthworm management in agricultural systems.

Agricultural Practices: Earthworm populations are greatly impacted by agricultural practices like crop rotation, tillage, and the use of pesticides. To maximize their benefits, earthworm-friendly farming methods like organic farming and reduced tillage must be promoted.

14. Role of Earthworms in Plastic Degradation

The ability of earthworms to absorb microplastics—smaller pieces of plastic and their role in the breakdown of plastic have received more attention recently. The worm alters microplastics' physical size and stimulates microbial activity to raise the likelihood of decomposition. However, no study has demonstrated that earthworms can chemically break down microplastics.to an element, such as H_2O or CO_2. This review thoroughly examines prior research to investigate the possible role of earthworms in the decomposition of plastic in soil. Vermicelli can significantly alter the physical characteristics of plastics. However, nothing has been found regarding earthworms' ability to understand the chemical structure of polymers or their chemical breakdown, nor about microplastics. In addition, earthworms have a selective diet, rejecting plastic and avoiding areas with a high concentration of plastics. The ability of earthworms to adapt to the microplastics in soil found in the environment could therefore lead to issues.

Based on this analysis, it is expected that the complexity and toxicity of the plastic material, along with external factors like soil composition, microbial population, moisture temperature, and feeding strategy, will be the main causes of the challenges faced when employing earthworms to break down plastic.

Earthworms are important because they accelerate the biodegradation processes that lead to the breakdown of plastics. Their burrowing practices improve soil aeration and microbial activity, which in turn improves the conditions for the breakdown of plastic. The sluggish rate of deterioration and possible environmental hazards connected to plastic additives are obstacles, though. To fully comprehend the extent of earthworm engagement and to create strategies for more effective plastic breakdown in diverse ecosystems, more research is needed.

14.1. Role of Earthworms in Physical and Chemical Degradation of Plastics

Opinions have varied about the possibility of earthworms decomposing plastics or microplastics. Any alteration in a polymer's chemical or physical characteristics brought on by external elements like heat, light, or moisture is known as polymer degradation. Biological action as well (PospíŠil&Nešpůrek, 1997). Few studies, nevertheless, have documented physical alterations. Attributable to earthworm activity, both in microplastics and ingestion of microplastics (Rillig et al., 2017; Lwanga et al., 2017; Alauzetet al.,2002) Eisenia Andrei and Eisenia Foetida, two earthworms, have consumed five different kinds of plastic. This led to a decrease in bulk, and ethylene-vinyl acetate, nylon, polypropylene, polyethene, Among the polymer powders examined was and linear low-density polyethene (Kim, 2016). Even so, if the study found a decrease in polymer mass, it was probably unrelated to earthworm digestion. Instead, it may have shown that the earthworms had been consuming and accumulating microplastics.

Earthworms are only partially responsible for the chemical and physical deterioration of plastics.

They have little effect on plastics, even though they might help the soil break down organic matter, like plant material. Earthworms lack the digestive enzymes required to break down the complex molecules that makeup plastics, which are synthetic polymers. Environmental elements like UV radiation, temperature changes, and microbial activity are the main causes of plastic degradation. By processes like biodegradation, microorganisms—including bacteria and fungi—have a greater influence on the breakdown of plastics.

In conclusion, there was a correlation between the earthworms' mass and basal metabolism. Thus, the interaction of the microplastics with their diet, which would reduce the amount of organic matter in the food, may be linked to the mass reduction of the earthworms' weight. causing a decrease in the amount of nutrients consumed. Additionally, the earthworms' decreased weight could additionally be a result of the earthworms' contact with the microplastics stomachs, producing more mucus to shield them from possible harm from microplastics. The defense mechanisms of earthworms are connected to this decrease. They typically produce more mucus in their intestines after consuming inorganic debris to shield their digestive system from foreign substances. Intestinal mucus speeds up the decomposition of organic materials. Additionally, humification may enhance microbial growth, activity, and species diversity density in a vermicomposting system (Huang & Xing, 2018).

However, Lwanga et al. (2016) discovered that low-density polyethene microplastics shrank in size as they entered Lubricous Terrestre's digestive tract. The lack of a decrease in plastic mass during the feeding phase indicates that the low-density polyethene microplastics were only impacted in their physical properties by the earthworms' incapacity to break them down. This proves that degradation does not occur, but the digestive systems of earthworms are capable of breaking down microplastics into smaller pieces. Furthermore, Alauzet et al. (2002) discovered that the earthworm Eisenia Andrei could eat two lactic acid-based stereo-copolymers as well as corresponding oligomer-impregnated paper or coated tree leaves. There was a negative correlation found between the molecular mass of the oligomers and the breakdown of polylactic acid, despite the fact that the earthworms could consume specific oligomers. The PLA with a high molar mass was too large for the worms to consume. polymers directly, regardless of the stereo-copolymer composition. As a result, they could only consume them following the PLA's treatment (Khaldoon and others, 2022).

15. Economic and Socio-Ecological Aspects of Earthworm-Based Agriculture:

Earthworms are distributed nearly everywhere in the world, except for areas with sandy, humus-deficient soil. Due to their sparse and deficient soil, they are also not found in mountainous areas. Additionally, they dislike extremely acidic or clayey soils. They often inhabit the upper levels of gardens, lawns, and somewhat damp soil. They dig tunnels down to a depth of 12 to 18 feet to protect themselves from predators and unfavorable weather. Earthworms need their skin to stay moist to breathe, and they achieve this by both secreting mucus on their skin and having a natural need to stay wet.

Earthworms are nocturnal animals that spend the day in their burrows and emerge at night in response to feelings of love and hunger. They consume organic matter such as dead leaves, which they may even incorporate back into their burros. Despite lacking any unique sensory organs, they react to a variety of stimuli. In addition to staying out of direct sunlight, they will retreat inside their burrow in reaction to noxious chemical vapors and the mechanical vibrations produced by heavy footfall. They seem to be irritated by mechanical vibrations like pounding, and occasionally this causes them to suddenly rise to the surface as though in pain.

When compared to their temperate counterparts from Europe and other Western nations, the ecological research conducted on tropical earthworms from India is not as thorough. In

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Orissa's tropical grasslands and soils, Thambi and Dash (1973) documented seasonal variations in the populations of enchytraeus, achaeta, marionia, and enchytraeidae worms as well as their biomass. Dash et al. (1974) compared the secondary production of oligochaetes from three families—the enchytraeidae, magascolecidae, and ocnerodrilidae—with the primary production of plant material in the same tropical grassland in Orissa.

Varma and Chauhan (1979) reported on a few earthworms' preferred pH.Microfungi linked to the breakdown of lampitomauritii and octochaetonasurensis tissue in pasture soil were described by Dash et al. in 1979. However, Dash and Patra (1979) have reported on the creation of worm casts and the nitrogen that Lampitomauritii contributes to the soil. By examining the morphology of cocoons, hatching, and other related aspects at the pasture location, Senapati et al. (1979) documented the seasonal dynamics and emergence pattern of DrawidaCalebi. Furthermore, Senapati et al. (1980) noted that the breakdown activity of the worm Octochaetonasurensis caused changes in the chemical characteristics of sterilized agricultural soil. Dash et al. (1980) looked into how a population of Lampitomauritii worms affected four different functional units.

Earthworms are unassuming, everyday organisms that are very important to human commerce. Despite their modest size, they serve us well both directly and indirectly. Without them, our planet would be a very different place.

They are used as bait for fishing all around the world. They are forced from their burrows using a variety of techniques to create sizable collections. Using an electric current, mercuric chloride, or other toxic chemical solutions, to jar soil are a few methods. Another is driving a stick into the soil and beating it. They make up the best fish food found in aquariums. Enchytraeusalbidus, a tiny white earthworm, is commonly found growing in soil and is fed to small lab animals and aquarium fish. Uncivilized cultures utilize numerous parts of the birds—particularly robins and chickens—as food. Frogs, moles, lizards, tiny snakes, centipedes, and other predatory invertebrates devour large quantities of them. Earthworms have also been utilized as sustenance for humans. The Moari people of New Zealand consider them to be a delicacy. Earthworm pies have been created in Japan, and there have been accounts of eating fried earthworms from South Africa (Ljungstrom and Reinecke, 1969). There have been reports of raw earthworm consumption by aboriginal people in New Guinea and other parts of Africa.

Generally, earthworms are good for agriculture. They are great friends to farmers and gardeners since they are always tilling and fertilizing the soil, even though they occasionally may harm young, fragile plants. In many respects, the soil becomes more fertile due to their habit of digging and consuming earth beneath the surface. Their burrows facilitate the roots' downward growth, enhance drainage, and allow air and moisture to penetrate the permeable soil. One type of effective soil "cultivation" is the thorough grinding of soil in the gizzard. Additionally improving the soil are the worms' various secretions and excretory wastes, which contribute nitrogenous materials that serve as vital plant food. Their effect on the turning over of soil is considerable. An acre of ground may contain 50,000 earthworms and the quantity of earth brought up from below and deposited on the surface as wormcasting has been estimated to be as 18 tons per acre per year, by Darwin. In 20 years, a layer of 3 inches thick would be transferred from the subsoil to the surface. Darwin wrote, “The plow is one of the most ancient and valuable of man’s inventions but long before he existed the land was regularly ploughed and continues to be thus plowed by the earthworms” (Romana Afreen, 2018)

16. Conclusion

The thorough analysis of "Earthworms in Sustainable Agriculture" concludes by highlighting the important and diverse role that earthworms play in boosting agricultural sustainability. Because of their complex relationships with soil, organic matter, and plant roots, earthworms are important for soil fertility, structure, and nutrient cycling. This review has highlighted the positive effects of earthworm activity on soil health, including enhanced aeration, water infiltration, and nutrient availability.

Additionally, research on the symbiotic connections between earthworms and advantageous microorganisms has illuminated the complex network of interconnections that support plant resilience and growth. Adding earthworms to agricultural systems can also help control pests by controlling the populations of unwanted organisms.

The impact of environmental factors, agricultural practices, and the requirement for cautious management strategies are some of the challenges and factors that have been identified as being important to the successful integration of earthworms into sustainable agricultural practices. The review also highlights the need for more investigation to completely grasp the precise mechanisms behind earthworms' beneficial effects on various crops and in various agroecosystems.

To sum up, the incorporation of earthworms into sustainable agriculture exhibits significant potential in tackling significant issues in contemporary farming, enhancing soil fertility, and ultimately building a more robust and eco-friendly agricultural system. To fully utilize earthworms in sustainable agriculture and guarantee a more stable and sustainable future for world food production, we must carry out more research and develop useful applications.

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