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Research Article

An Overview of the Role of Vermicompost in Reducing Green House Gas Emissions, Improving Soil Health, and Increasing Crop Yields

Oluwaseyi Matthew Abioye*, Matthew Folorunsho Amodu, David Olorungbon Raphael, David Ayodeji Olasehinde and Mathias Maduakolam Aniobi
Department of Agricultural and Biosystems Engineering Landmark University, Omu Aran, Kwara State, Nigeria

Kamorudeen Olaniyi Yusuf
Department of Agricultural and Biosystems Engineering University of Ilorin, Kwara State, Nigeria

Adebayo Isaac Olosho
Department of Industrial Chemistry, University of Ilorin, Ilorin, Kwara State, Nigeria

* Corresponding author. E-mail: abioye.oluwaseyi@lmu.edu.ng DOI: 10.14416/j.asep.2024.09.011
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Abstract

Vermicomposting provides a green alternative to composting, which can reduce greenhouse gas emissions and improve soil health. As a result of existing waste management practices, greenhouse gases are released into the environment. Still, vermicomposting offers a sustainable solution by recycling organic waste into a soil amendment that improves soil health and increases crop yields. This study provides an in-depth overview of the benefits of vermicomposting, a practice that recycles organic waste materials into a nutrient-rich soil amendment called vermicompost, which can reduce greenhouse gas emissions, improve soil fertility, and boost crop yields by enhancing soil structure and microbial activity, thereby presenting vermicomposting as a sustainable way to recycle organic waste, while mitigating climate change, protecting soils, and boosting agriculture. This overview examines how vermicomposting organic waste lowers greenhouse gas emissions from landfills, improves crop yields through improved soil structure and fertility, and enriches soils by increasing microbial biodiversity and nutrient availability. Vermicomposting provides degradation and detoxification of organic waste with some nutrient-rich castings. The potential of these castings to improve soil health sparked interest among agricultural researchers. Crops fertilized with vermicompost thrived, producing higher yields and the nutrient density of the plants increased significantly. Emerging research reveals that vermicompost can fight against climate change. As an organic fertilizer, it enhances the ability of plants and soil to sequester carbon, decreasing greenhouse gases and also reducing emissions of methane and nitrous oxide compared to conventional fertilizers. With broader implementation, vermicomposting offers a meaningful path to combat climate change through regenerative agriculture.

Keywords: Carbon sequestration, Environmental quality, Nutrient retention, Organic waste recycling, Soil management, Sustainable agriculture

1 Introduction

Conventional agriculture has caused significant harm to society over the past few decades by overusing land and water resources, causing biodiversity loss, and erosion, and using pesticides in an uncontrolled manner. In contrast, organic agriculture aims to make the best possible use of natural resources, promoting sustainability [1]. Today, huge amounts of waste are produced all over the world. Developing countries generate approximately 998 million tons of agricultural waste each year due to poor management practices, which has negative effects on both people and animals as well as substantial environmental effects, resulting in an increase in greenhouse gas emissions exacerbating the climate change challenge [2], [3]. Agricultural wastes contribute significantly to this waste accumulation, as agricultural activities are intensified to meet the demand for growing agricultural products and to meet the food requirements for a rapidly increasing population such as in Africa [4]. Agricultural wastes are residual materials generated as a byproduct of agricultural activities [5]. These materials are typically considered agricultural waste after the main crop harvest, but they can be converted into a valuable resource through the vermicomposting process [6]. Agricultural waste sources which have been of concern to the public and threatened the viability of agricultural systems, include crop residues such as leaves, hulls, stems, straw, hulls and weeds. Another important category is animal wastes, which include urine, feces, washing water, milk residues and feed waste. Spilled feed, feathers, droppings, and bedding are all examples of poultry waste. Waste from slaughterhouses includes substances such as blood, hair, skin, meat and bones [7]–[9]. The extraction of syngas from biomass-based feedstock has emerged as a prominent way of producing renewable energy [10], [11]. The most popularly used feedstock is lignocellulosic biomass from agro-industrial and wood residues. By utilizing this feedstock waste, accumulations can be drastically reduced and also minimize the potential effect on environmental sustainability [12]. Table 1 shows agro wastes and their sources. In India, agrowastes has been estimated to be a major source of its solid waste generation contributing between 350 to 990 million tonnes annually. Similarly, in China up to 130 million tonnes are generated from paddy straw alone [13].

While improper disposal of agricultural waste may pose significant environmental risks and increase greenhouse gas (GHG) accumulations when properly handled and managed can lead to a significant decrease in greenhouse emissions and even boost soil carbon absorption [22], [23]. Greenhouse gas emissions can be decreased by implementing various biological resource management strategies, such as the mixing of organic and inorganic soil amendments [24], [25]. Effective land management practices, supported by appropriate land use policies, can help preserve the existing carbon stocks and ensure the resilience of carbon sequestration in agricultural soils. In areas where unclear property rights and lack of single-party ownership may hinder management changes, contract terms and liability for discounting carbon-preserving practices could be useful for adopting and mitigating GHG practices.

Table 1: Waste generation in agriculture and agro-processing.

Sources of Wastes	Types of Wastes	Ref.
Cereal crops	Straw	[14]
Wood	Wood ash	[14]
Grasses	Dry grass	[14]
Plants	Fresh plant residues	[14]
Rice plants	Rice straws	[15]
Leaves	Leaf litter	[15]
Trees	Tree pruning	[15]
Crops	Crop residue	[15]
Animals	Animals waste	[15]
Medicinal herbs	Medicinal herbal residues	[15]
Brewing industry waste	Brewer spent grains	[15]
Sewage	Sewage sludge	[15]
Dairy farms	Dairy farm wastes	[16]
Dairy farms	Dairy farm waste	[16]
Aquatic fern	*Azolla pinata*	[17]
Sugar industry waste	Pressmud	[18]
Agro-industrial lignocellulosic waste	Non-food fermentable sugars	[19]
Mint distilleries	Distillation waste of *Mentha arvensis*	[20]
Weeds	Rice field weeds	[21]
Coconut husks	Coir pith	[21]
Cows	Cow dungs	[21]
Biodegradable waste	Biodigester slurry	[21]

Additionally, improved cultivation methods and forestry management can help reduce emissions and increase contributions to the mitigation effort from agricultural soils [26]. The Green Revolution increased worldwide food production, but it also increased farmers' dependency on synthetic chemical fertilizers as well as herbicides and insecticides. There has been a severe degradation of soil and pollution of the environment due to overreliance on mineral fertilizers in cereal production. By utilizing integrated nutrient management practices such as vermicompost, it is possible to mitigate these issues. Soil quality is improved, organic carbon is sequestered, and excessive CO_2 emissions are reduced with vermicompost [27]–[30]. Continuous utilization of inorganic fertilizer can bring about a detrimental effect on the environment and soil. Soil quality in particular is important in climate change mitigation as it serves as both a source and sink of greenhouse gases. Raw animal manure, processed bio-digesters from waste materials, and biochar from various organic sources are examples of soil amendment that have been identified as having a crucial role to play in lowering

GHG emissions and enhancing soil fertility [31], [32]. Agricultural activities contribute significantly to the greenhouse effect. This is due to the elevated greenhouse gas (GHG) emissions, which are produced during these processes and management. The fermentation of enteric bacteria and the farming of rice, for example, can release methane (CH_4). Whereas, nitrous oxide (N_2O) is released from synthetic fertilizers, and carbon dioxide (CO_2) is produced through various other processes. According to Malyan *et al.* [33], N_2O and CH_4 have 298 and 28 times higher global warming potentials (GWP) than CO_2 on a 100-year time scale, respectively [34]. According to estimates from 2018, agricultural activities were responsible for producing 9.3 gigatons (Gt) of CO_2 equivalents (CO_2 eq) in greenhouse gases. Crops and livestock were responsible for emitting 5.3 Gt CO_2 equivalent into the atmosphere. Within this, agricultural soils contributed 39.2% and enteric fermentation contributed 39.2% as well [35]. Microbial processes in agricultural soils lead to the production of CO_2, CH_4, and N_2O. The CO_2 flux, ecosystem respiration, and net ecosystem exchange (NEE) are controlled by agricultural soil respiration (root and microbial respiration), which is different from plant photosynthesis. Methanogens are responsible for the production of CH_4 under anoxic conditions, Methanotrophs are capable of consuming methane in both oxygenated and oxygen-depleted environments.

N_2O is mainly produced by denitrification in anaerobic environments and by denitrification in aerobic environments (hydroxylamine oxidation and nitrifier denitrification) as demonstrated in studies conducted by [36]–[38]. Studies have shown that soil salinity and sodicity have significant impacts on processes that contribute to greenhouse gas (GHG) emissions, the process involves the decomposition of organic matter, nitrification, denitrification, methanogenesis, and oxidation of CH_4. When soil salinity and sodicity levels increase, GHG emissions tend to decrease. Multiple studies have reported a decrease in N_2O, CH_4, and CO_2 emissions with increased salinity and sodicity. However, some studies also report an increase in N_2O, CH_4, and CO_2 emissions with increased salinity and sodicity. Ali *et al.*, [39] noted that after conversion into fermentation residues and application to the soil as fertilizer, the ability of the raw manure to emit CH_4 and N_2O is significantly checked. Biofermentation, a processed, nutrient-rich organic waste, not only serves as a fertilizer for the soil but also aids in decreasing greenhouse gas emissions [40]. Biodigestate is a promising method of recycling waste from a variety of sectors including agriculture and wastewater treatment. It is an environmentally friendly alternative to inorganic fertilizers for nutrient management in agriculture [41]–[44].

Organic fertilizers made from locally produced materials like agricultural waste, vermicompost, and animal and green manure are becoming more and more popular as a viable alternative to synthetic chemical fertilizers that aid in carbon sequestration, soil aggregation, soil moisture, and the reduction of greenhouse gas emissions. This is due to the positive effects of organic fertilizers on agricultural production, nutrient availability, and water retention [45]–[49]. Vermicomposting combines the process that producing compost from biodegradable garbage and earthworms found in damp soil. Earthworms consume garbage, digest it, and excrete vermicompost as a byproduct. It is an organic fertilizer containing organic substances including humus, nitrogen (N), phosphorus (P), potassium (K), trace elements and beneficial soil microorganisms such as bacteria, fungi, actinomycetes, diazotrophs, contains hormonal stimulants like auxins and gibberellins as well as microbes that fix nitrogen and dissolve phosphate and cytokines. Therefore, plant waste and inedible parts that are normally discarded during harvesting, marketing and processing can be excellent materials for composting. Vermicompost has several advantages, including fluidity, ease of use, convenience in handling and storage, and the absence of odors generated by residues mixed with bedding in cattle stalls. It also improves the ecological and soil physicochemical properties, stimulates nitrogen fixation and P dissolution, and introduces some enzymes from the worm gut into crop residues as they pass through [50]–[53]. Proteases, amylases, lipases, chitinases, and cellulase are important enzymes that help break down crop leftovers by integrating bacteria and speeding up the decomposition process. Composting, on the other hand, has several positive effects: it promotes the papillary roots of legumes, establishes symbiotic relationships with mycorrhiza and plant roots, reduces phytotoxic effects, which ultimately result in a rise in crop yields, increases organic matter, encourages stress tolerance in plants, increases earthworm activity and population in the soil, gets rid of weed seeds and illnesses, improves organic matter, and serves as seedling beds to develop seedlings, improves the immune system of plants, acquires a bright green color, imparts luster, and ensures the manufacture of high-quality items [54]. The interaction of worm culture and worm composting is called worm technology. Vermicomposting is of great value in commercial aquaculture as it provides a convenient and reliable supply of worms for ornamental fish farming in aquariums. This makes it possible to integrate vermiculture into a sustainable lifestyle. The use of worm culture and worm composting in aquaculture practices is both environmentally friendly and ethical [55]. Vermicomposting offers a solution to the large amounts of organic agricultural waste currently incinerated by farmers. It enables the recycling and reuse of this waste, thus contributing to more efficient, economical, and environmentally friendly agricultural development. Earthworms and microorganisms work symbiotically to produce vermicompost, which enhances soil quality, increases microbial diversity, and is cost-effective and environmentally friendly [56]–[61].

There has been much research on the potential of integrating vermicompost into crop production systems as a way of boosting grain crop productivity without negatively impacting the environment. To effectively combat environmental degradation, one of the most effective approaches is to turn abundant and unused biodegradable organic waste into vermicompost. This process can make a significant contribution to improving the environment and sustainable development.

Insufficient soil oxygenation can lead to the formation of various gases such as CH_4, H_2S, N_2O, C_2H_2, and H_2. The presence of methane implies that organic matter is decomposing while nitrous oxide is formed as a result of denitrification caused by the absence of oxygen in the soil. Greenhouse gas emissions from vermicomposting have only recently been documented [62]–[64]. Yang *et al.*, [65] conducted research showing the positive effect of earthworms on vermicompost production and as a result, gas emissions have been reduced. In soil-grown on areca nuts, vermicompost improved soil test calcium and magnesium and raised soil pH, organic carbon, and phosphorus [66]. By raising the amount of total organic matter, phosphorus, nitrogen, calcium, and soil glomalin, vermicompost increases soil fertility [67]. Vermicompost improves crop production and aeration by enhancing soil fertility physically, chemically, and biologically. However, it should be sprayed in modest amounts [68].

Compared to no fertilization, vermicompost increases fruit output in greenhouse tomato crops by enhancing soil quality and microbial functions [69]. According to Padmavathiamma and Kumar [70], vermicomposting efficiently lowers organic waste and enhances the quality of agricultural soil, increasing the yield and quality of bananas, cassava, and cowpeas. Overall, vermicompost has lower greenhouse gas emissions (8.1 kg CO_2 equivalent/t dm) than thermophilic compost. The incorporation of earthworms during composting has been found to reduce gas emissions from animal waste [71], [72]. Waste management methods have become a significant concern due to their contribution to rising greenhouse gas (GHG) emissions. Addressing this issue urgently is required to ensure optimum circumstances with lower emissions that ensure a high-quality environment [73]. Previous research on climate change indicates that it may cause agricultural productivity to decline and prices to rise. However, these unfavorable effects could be lessened with the support of the right policies, plans, strategies, and initiatives. A few policy suggestions have been made to lessen the adverse effects of climate change. To motivate farmers to embrace agricultural practices that will mitigate the negative effects of climate change, it is imperative to comprehend their perspectives on the issue and develop appropriate intervention instruments. Policymakers should take into account the viewpoints of farmers who implement the measures made to mitigate the effects of climate change in addition to study findings [74]. The main objectives of the review are to provide a detailed analysis of the current research and evidence on vermicompost. The focus is on understanding its potential benefits in terms of soil health improvement, reduction of greenhouse gas emissions, and increase in crop yields. The ultimate goal is to evaluate the viability of vermicompost as a sustainable agricultural practice. Vermicompost would be thoroughly reviewed, laying a strong basis of knowledge for future research, which will boost agricultural productivity, perform optimally regarding soil health, and significantly reduce greenhouse gas emissions.

2 The Function of Vermicompost in Sustaining Agricultural Productivity during Climate Change

Agricultural activities contribute to the emission of 15 billion tons of CO_2, which accounts for 30% of the total global emissions [75]. The agroecosystem plays a crucial role as a source of CO_2. Soil respiration is the metabolic process of animals, roots, fungi, and bacteria in the soil, which is responsible for the emission of CO_2 from the soil. The three stages of the process are the respiration of soil animals, soil microbes, and plant roots. Additionally, carbon-containing substances can also be chemically oxidized [76], [77]. In the photosynthesis process, CO_2 in the atmosphere is converted into organic matter. Root exudates, dead roots, or fallen leaves are all ways in which organic matter releases carbon into the soil. Soil carbon sinks when it is transformed into organic matter by soil microorganisms. In total, the agroecosystem contributes 15–30% of CH_4 emissions [78]. The fermentation of organic acids by microorganisms in poorly aerated soil leads to the production of CH_4. There are two ways that CH_4 can be produced in an agroecosystem: 1) either by methanogens using formic acid and CO_2 or organic acids and their breakdown products, CO_2 and H_2 to produce CH_4 in the presence of methanogens; 2) by methanogens produce CH_4 by demethylating methyl compounds. In dryland soil with good aeration, methane-oxidizing bacteria are the dominant microorganisms, absorbing and using around 82% of the CH_4 before it is released into the atmosphere and gets into the soil ecosystem [33], [79]. The processes of microbial nitrification and denitrification predominantly generate N_2O, a gas that is expelled from farmland soil. Nitrification is a two-stage process, which includes autotrophic nitrification and heterotrophic nitrification. In autotrophic nitrification, ammonia-oxidizing archaea (AOA) and bacteria (AOB) first convert NH_3 to NH_2OH and then reduce it to NO_2^-. In the second stage, nitrite-oxidizing bacteria oxidize NO_2^- to NO_3. Heterotrophic nitrification occurs when nitrifying bacteria and fungi transform organic ammonia nitrogen into NO_2^- and NO_3^- in an aerobic environment [80]. On the other hand, in the process of denitrification, different enzymes, and an aerobic environment are required for microorganisms to convert NO_3^- and NO_2^- to NO, N_2O, and N_2 [81].

2.1 *Factors influencing the ecosystem output of greenhouse gasses*

2.1.1 Burning fossil fuels

The main cause of emissions of greenhouse gases is the combustion of fossil fuels for transportation, heat, and power. Due to the reliance on coal, natural gas, and oil in numerous sectors, it makes up a sizeable amount of overall emissions and raises atmospheric carbon dioxide (CO_2) levels [82], [83].

2.1.2 Methods of agriculture

Particularly for methane (CH_4) and nitrous oxide (N_2O) emissions, agricultural activities are a major source of greenhouse gas emissions. The management of agricultural soils, the use of synthetic fertilizers, and the digesting processes of cattle are important sources. Particularly significant emissions include those of nitrous oxide from fertilizer application and methane from rice paddies and cattle [84], [85].

2.1.3 Land use and the loss of forests

Changes in land use and deforestation liberate carbon dioxide that has been stored in soil and trees, which increases greenhouse gas emissions. The carbon contained in biomass is released when forests are removed for development, agriculture, or other land uses, which exacerbates climate change [86], [87].

2.1.4 Handling of waste

Methane and carbon dioxide are released during waste management procedures like landfilling and trash decomposition. Methane, a strong greenhouse gas released during the decomposition of organic waste in landfills, greatly increases overall emissions [88].

2.2 *GHG impact on the environment*

Emissions of greenhouse gases fuel climate change, which causes extreme weather, increasing sea levels, disturbances to ecosystems, and changes in the distribution of species. Elevated concentrations of greenhouse gases are directly associated with an increase in the frequency of extreme weather events, such as heatwaves and storms [89], [90]. GHGs are responsible for the greenhouse effect. Global warming gases keep the Earth's climate habitable for humans and millions of other species. There are major health consequences from the air pollution caused by greenhouse gas emissions, including allergies, respiratory illnesses, and higher death rates. In addition, the effects of climate change pose a threat to water supplies, food security, and human welfare in general [91], [92]. There is an imbalance in GHG production that threatens to change dramatically, which is immensely detrimental to the survival of life on the planet [93]. There are several environmental impacts associated with greenhouse gas emissions:

2.2.1 Global warming

Human activities have had a significant impact on climate change over the past two centuries. This has been observed through various studies conducted by researchers, [94]–[96]. The chemical composition of the atmosphere has been altered due to these human actions. Greenhouse gases (GHGs) and the Earth's magnetic field are the two main reasons for global climate change [97]. There is an imbalance between the amount of radiation coming in and going out as GHG emissions rise and less radiation is reflected. The climate of Earth changes as a result of this. Increases in greenhouse gas emissions cause more radiation to be trapped on the Earth's surface, which raises air temperatures and causes climate change and global warming [98]. To combat the impacts of global warming, scientists have examined many strategies for lowering greenhouse gas emissions and carried out several studies. The Earth's surface temperature has increased by 0.5–1 °C in the last century, and even this small increase has had a major impact on weather patterns and cloud cover. In its third assessment, the Intergovernmental Panel on Climate Change [34] projected that the average global temperature will rise from 1.4 °C to 5.8 °C by the end of 2100, leading to increasingly dire scenarios [99].

2.2.2 Acidification of ocean

The ocean absorbs around half of the man-made CO_2 emissions, which is crucial in slowing down global warming. However, this absorption has led to a decrease in the pH of the ocean, making it more acidic. The pH of the ocean was 8.2 around 300 million years ago, but it is now approximately 8.1, indicating a decline. This slight decrease in pH has resulted in a 30% increase in the ocean's acidity during the last two centuries, which has had significant impacts on marine life. The upper layer of the ocean is currently absorbing 2 billion tons of CO_2 per year, which is causing severe changes in the life cycles of numerous marine creatures [100].

2.2.3 Melting of glaciers and ice sheets

Ice can serve as an indicator of climate change. Glaciers and ice sheets reflect the sun's radiation into space. However, when the ice melts, less radiation is reflected, and more is absorbed, leading to an increase in temperature. Global warming, which results from climate change, poses the greatest risk to ice masses like ice sheets and mountain glaciers. As these masses melt, it can cause glaciers and permafrost to become unstable. Accelerated melting, increasing glacier flow, supra-glacial lake expansion, and permafrost deterioration are indicators of instability. Some glaciers are predicted to retreat even in the absence of future temperature increases, while the number of glaciers melting is anticipated to rise [101], [102].

2.2.4 Rise in sea level

The continual emission of greenhouse gases has resulted in a significant increase in sea levels. Scientists predict that between 1990 and 2100, the average sea level will rise anywhere from 0.09 to 0.88 meters [103]. The expansion of seawater brought on by increasing temperatures and the melting of Antarctic and Greenland glaciers, which increases the amount of water in the ocean, are the two main causes of this. According to studies, the biggest contributors to rising sea levels will likely be thermal expansion and glacier melting in mountains and ice caps [102]. About 80% of the heat trapped by greenhouse gases is absorbed by the ocean, raising water temperatures and generating an expansion of the water column [103]. Sea levels are thought to rise mostly due to thermal expansion over time. Because of thermal expansion, sea levels have risen by 0.14 inches per year since 1990. With the rising temperatures, snow and ice melt [104], [105].

2.3 *Solutions to greenhouse gas emission*

2.3.1 Advancements in technology

The electrification of energy demands, the switch to renewable energy sources, and developments in carbon capture, utilization, and storage (CCUS) are examples of potential technological solutions. Emissions can be greatly decreased by the development and application of wind, solar, and bioenergy resources [106], [107].

2.3.2 Improvements in energy efficiency

Reducing emissions requires increasing energy efficiency in industries, transportation, and buildings. Strategies such as building retrofits for improved insulation, employing efficient production methods, and endorsing electric vehicles can result in significant reductions in energy consumption and greenhouse gas emissions [108], [109].

2.3.3 Developments in regulation and policy

Reducing emissions requires the implementation of efficient climate policies, such as carbon prices, technology subsidies, and performance criteria. According to Van Vuuren *et al*., [110] and Bhattacharyya *et al*. [109], these restrictions facilitate the market-based approach to decreasing greenhouse gases and boosting the use of clean technologies.

2.3.4 International accords and collaboration

Global efforts to reduce climate change are crucially coordinated by international agreements such as the Paris Agreement. To promote global cooperation in addressing systemic concerns associated with greenhouse gas emissions, countries are urged to establish and follow national emissions targets [111], [112].

3 Vermicomposting and Earthworms

Earthworms are the primary soil macrofauna, contributing to the biogeochemical cycles of the soil and affecting its organic, inorganic, and physical properties with the aid of sediments. The mineralization of carbon and nitrogen in certain substrates, which is greatly influenced by earthworms, is the subject of the nocturnal robot's general workouts. Due to their involvement in the biochemical breakdown of the problematic substrate, microorganisms divide and form deposits, or structural breaks, with the aid of worms. Earthworms are common soil organisms that can be found in a variety of terrestrial habitats. According to Bartlett *et al*. [113], they are essential to the stability and fertility of the soil ecosystem. For humans engaged in agriculture, earthworms have enormous ecological significance. They make a substantial contribution to the creation of organic fertilizers that support soil structure preservation, aeration, and increased fertility as well as the recycling of organic waste. Earthworms are used primarily for associative purposes, creating fertile agricultural land, breaking down natural sediments, and working with high airflow and waste. Soil bacteria are enhanced by earthworms due to intestinal conditions that promote the growth of bacteria and hinder fungal growth [58]. Burrowing by earthworms is good at preserving anaerobic conditions, which lowers greenhouse gas emissions [73]. Vermicompost and worm tissue, which are readily accessible from waste materials, are utilized as animal feed and offer a biological balance that can assist in increasing soil fertility and lessen heavy metal poisoning. According to a recent study by Garnier *et al*., [114], carbon in soil is mineralized more efficiently by earthworms. The study's statistical model demonstrated a significant 24% increase in carbon mineralization and a density of 1.95 grams per kilogram of soil is observed in the presence of earthworms. In India, the initial step in using earthworms to break down solid waste was the elimination of *Perionyx* excavations [115]. Table 2 shows the benefits of earthworms in agroecosystems.

Table 2: Earthworms effect on soil and yield

No.	Earthworm Benefits	Ref.
1	By altering the composition of the soil to favor bacterial energy channels and fostering stronger biotic relationships, earthworms improve the multifunctionality of ecosystems and provide a variety of ecosystem services in sustainable agriculture.	[116]
2	Through their activities, earthworms help in both ecological and socioeconomic ways by improving the structure and function of the soil.	[117]
3	Enhancing soil stability, microbial activity, and nutrient cycling in cropping areas can increase earthworm numbers and possibly increase agricultural sustainability.	[118]
4	By incorporating organic material into the soil, increasing aeration, and releasing pollutants for microorganisms to eat, earthworms can hasten the elimination of organic toxins from the soil.	[119]
5	Earthworms release stored nitrogen in the form of residue and soil organic matter, their presence in agroecosystems boosts crop yield by 25% and biomass by 23%, respectively.	[120]
6	By quickly absorbing detritus and generating organic matter, earthworms improve soil nutrient cycling and aid in the stabilization and buildup of soil organic matter in agricultural systems.	[121]
7	Through accelerating deterioration, improving soil quality, and stimulating degrading microorganisms, earthworms can enhance the bioremediation of organic contaminants.	[122]
8	Through comminution, burrowing, and casting, earthworms contribute favorably to the diversity of soil microflora and fauna, but they may also harm larger fauna populations by increasing competition for food and altering food availability.	[123]
9	By dispersing organic materials, enhancing soil penetration, and affecting nutrient availability, earthworms increase soil fertility.	[124]

3.1 *Types of earthworms in vermicompost production*

The earthworm species that are utilized to produce vermicompost are referred to as nocturnal caterpillars in the animal kingdom and are members of the genus Annelida. These worms have visible segments and are elongated and cylindrical. Worldwide, there are about 3,000 kinds of nocturnal caterpillars, and each species has evolved to survive in a particular climate. In the nation, more than 300 species of chamber pots have been documented. Reproduction usually involves two bisexuals, nocturnal animals. The clitoris becomes a hard shell that serves as a protective cover throughout the deposition phase. There can be one to five eggs in each shell, but very few of them make it through to hatching. It takes 50–60 days for young worms to form their shell. Worms can live anywhere from one to ten years on average in favorable environmental circumstances. In vermicomposting, earthworms that consume surfaces are especially crucial. Among the many different species of earthworms, the epigaeal worms especially *Eudrilus eugeniae* and *Eisenia foetida* remain distinctive [125]. These vibrant worms are related, and they are widely used in vermicomposting systems to recycle organic waste. Physiological, genetic, and ecological research also frequently uses them. Because of their vast distribution, short lifespans, rapid rates of reproduction, resistance to temperature and humidity variations, and ease of management, these species are popular [61]. By primarily feeding on litter and topsoil, these worms actively contribute to the decomposition of crop residue at the site as well as the decomposition of organic components. These worms have thin bodies and an extensive color spectrum, ranging from red to the darkest shades of brown, with an adjustable temperature range of 0–40 °C and an optimal temperature range of 20–30 °C. Figure 1 shows the commonest species of earthworm used in vermicomposting.


Eudrius euginae *Eisenia fetida* *Perionyx excavates*

Figure 1: Different species of earthworms used in vermicompost production.

3.2 *Enzymatic and microbial processes in vermicomposting*

Vermicomposting, an eco-friendly composting technology that decomposes food waste using several species of worms, is considered a sustainable and eco-friendly approach to handling organic waste [126]. Vermicompost is regarded as a valuable organic provider of essential plant nutrients that are toxin-free. As earthworms digest waste, the physical decomposition in their stomachs reduces the particle size to less than 2 microns. The grinding and conditioning of the materials enhances the surface area of the soil, which promotes microbial growth and enhances its physical, chemical, and biological qualities. Worms consume organic matter, increasing its surface area and facilitating microbial breakdown. This environmentally friendly and bio-oxidative approach converts garbage into a useful bio-product [127]. Vermicomposting converts food waste into nutrient-rich compost by the beneficial microbes and turns it into valuable products that enhance soil fertility [128]. Worms commonly used for vermicomposting include white grubs, red grubs, and earthworms, which eat leftover food and produce vermicompost pellets, also called cocoons. Earthworms are important in expanding the surface area available to microorganisms, boosting enzymatic activity, and changing the physical properties of organic waste [129]. When the substance goes through the worms' intestines, particular enzymes such as proteases, lipase, amylase, cellulose, and chitinase are released, which aid in the breakdown of the bacteria. Microorganisms contribute significantly to the metabolic breakdown of complicated substrates, which is facilitated by worm activity and the breakdown of organic materials. These enzymes are mainly useful for breaking down a complex biomolecule into simple compounds [130]. The basic soil macrofauna, nocturnal vines, play a significant part in the soil biogeochemical cycle. These enzymes affect the biological, chemical, and physical properties of soil. The nocturnal larval population has a significant impact on carbon and nitrogen mineralization in various substrates. Ingested material is consumed by the worms for growth and development only in the range of 5 to 10% and the remainder is considered as a patch. Waste products such as urea and ammonia are excreted in the worm's gut, giving a readily available supply of nutrients that can provide nutrition to microorganisms, adding to their structural stability. The production of vermicompost processes is highlighted as presented in (Figure 2).

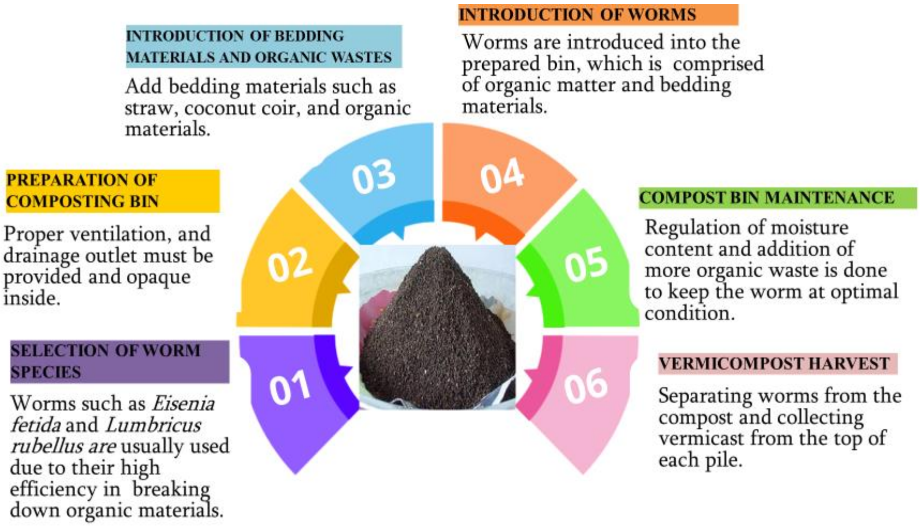

Figure 2: Vermicompost production process.

Table 3: Comparative analysis of vermicompost physicochemical properties.

Agrowaste Raw Materials	pH	OM (%)	N (%)	P (ppm)	K (ppm)	Zn (ppm)	Other Nutrients	Ref.
Spent grain from brewers	7.08	6.64	3.28				C: N = 11	[15]
Animal feces and rice straw	7.62	31.92	1.69	12,600	13,100		C: N = 11.46	[27]
Cow dung		58.48	1.68	4100	13,000		S = 50,000 ppm C: N = 11.09	[95]
Cow dung	6.8	98.04	3.1	12,000	8900		Organic N= 2.0% C:N = 9.2	[133]
Dung from cows	7.82	48.92	2.26	9100	10,400		C:N = 15, C:N = 11.3	[16]
Dung from cows	7.43	49.00	2.53	15,400	13,700	369	Cu = 164.8 ppm Fe = 416.6 ppm Mn = 248.7 ppm, C:N = 17.14	[17]
Rice straw and cow dung	7.6	87.6	2.16	12,700	10,100	342	Cu = 152 ppm Fe = 372.1 ppm Mn = 212 ppm, C:N 11.3	[17]
Rice straw	7.98	2.01	0.07	6.34	127	0.97	EC = 2.98 msm^{-1} Fe = 4.21 ppm	[134]
Paper waste	8.01	2.1	0.24	23.2	1425	1.02	EC = 6.12 msm^{-1} Fe = 1.84 ppm	[134]
Cow dung	8.00	2.1	0.3	11.56	346	1.06	EC = 5.95 msm^{-1} Fe = 3.09 ppm	[134]
Cow dung	7.4	40.00	1.4	18,000	22,000	110	EC = 1.12 (ds m^{-1}) Mg = 12,000 ppm Na = 8000 ppm Mn = 450 ppm Cu = 20 ppm	[135]
Dung from cows			1.71	11,800	9800	100	Fe = 940 ppm Mn = 240 ppm Cu = 120 ppm	[136]

C: N- Carbon to Nitrogen, CU-Copper, EC-Electrical Conductivity, Fe-Iron, Na- Sodium, N-Nitrogen, P-Phosphorus, K-Potassium, Mn-Manganese OM-Organic Matter, S-Sulphur, Zn-Zinc, dsm^{-1}-millimhos per meter, ppm-parts per million, msm^{-1}- milliSiemens per meter

3.2.1 Composition of vermicompost

The composition of vermicompost is nutrient-rich, containing elements such as N, P, K, Ca, Mg, Fe, Mn, Zn, and Cu (Table 3), which contribute to its high microbial activity. Compost can supply these nutrients to plants by boosting the activity of beneficial microbes, enzymes, and chemicals that stimulate plant growth, such as hormones making them readily available and easily absorbed [131]. Vermicompost also exhibits biocontrol properties, as it contains antagonistic organisms that inhibit pathogenic plants [132]. Vermicompost’s nutrient content is dependent on the input materials used. The significance of taking input materials into account when choosing vermicompost for nutrient recycling and organic waste management is emphasized by Jeyabal and Kuppuswamy [21].

3.3 *The vermicomposting approach in mitigating greenhouse gases*

Agriculture depends on soil, which also serves as the world's biggest carbon sink. It can minimize the rising atmospheric CO_2 concentrations [137]. About 30% of all anthropogenic emissions of greenhouse gases come from agriculture [138]. Most of the greenhouse gas emissions from agriculture are a result of the use of synthetic fertilizers and emissions of methane and nitrous oxide, while carbon dioxide emissions account for 20% of global emissions, and two-thirds of nitrous oxide arise from interactions with the soil [139], [140]. The most significant yet controllable source of atmospheric carbon absorption in the world is soil. In the past, tillage and land conversion have been major sources of greenhouse gases (GHGs) in the atmosphere. About a third of greenhouse gas emissions, according to the FAO, are caused by changes in land use and agriculture. By reducing emissions from farming and other sources and storing carbon in soil and plant biomass, more effective agricultural practices can, nonetheless, reduce greenhouse gas emissions. As they affirm the storage and conversion of organic carbon in the soil, organic farming has the advantage of storing atmospheric carbon, which would otherwise cause pollution and climate change, in the soil. Their diversity and wealth might be considered a resource for achievement and environmental sustainability [138], [141]. Vermicompost is a product of the biological treatment of trash by earthworm activity, which can reduce pollution, combat climate change, and ensure food safety. Earthworms promote soil carbon sequestration, which can assist in lowering greenhouse gas emissions. Vermicompost is a naturally occurring stable organic substance that can be used to store or sequester carbon. A vermicomposting system's carbon flux can be used to promote soil fertility and productivity while also enhancing the physical, chemical, and microbiological characteristics of the soil [142]. Similarly, biochar is used as a soil conditioner to improve soil fertility and carbon sequestration [143]. According to Lal, [108] carbon sequestration in terrestrial ecosystems can store between 50 and 75% of the carbon that has previously been lost. Additionally, Lal, [144] proposed that the restoration of 2,000 million hectares of damaged land might improve the average soil and vegetation carbon content by 1.5 tons/ha, offsetting the annual increase in atmospheric CO_2 concentration. The effects of desertification and land degradation have an impact on the global carbon cycle. Changes in land use result in a decrease in plant cover, which in turn affects soil quality and organic C levels. Plant productivity, soil deterioration, and SC are tightly connected processes. Degradation of the soil causes a drop in soil organic carbon and a rise in atmospheric CO_2 emissions. A loss in water holding capacity and consequent reduction in crop output result from the degradation of soil structure and quality. New strategies and regulations have been created on a global scale to promote agricultural and forestry techniques that boost soil and biomass carbon sequestration (CS). The scientific community and farmers are developing a wide range of agricultural practices that can improve agricultural systems and make them more resilient to climate change [145], [146]. The significance of these actions lies in the fact that they all enhance soil organic matter, which in turn benefits ecosystems' environmental, agricultural, and biodiversity aspects by helping to sequester carbon from biomass and soil in general. Food production and food security are improved by higher soil fertility and soil productivity which prevent soil deterioration and promote soil carbon sequestration.

3.3.1 Vermicompost in soil carbon sequestration

Fixing and storing atmospheric carbon dioxide to slow down global warming is known as carbon sequestration. Carbon sequestration in soil relies on soil organic matter (SOM), which is created through the decomposition of waste [147]. There is a series of processes that take place when comparing earthworm and earthworm systems that are genuinely connected to carbon cycling and carbon sequestration. Earthworms may modestly increase mineralized carbon and stabilized carbon while decreasing mineralized carbon. According to a study by Pottoff *et al*., [148] and Bernard *et al*., [149], earthworms cause organic matter mineralization, which has the effect of accelerating carbon mineralization in straw. According to certain reports, adding 5 t ha^{-1} treatment of vermicompost modestly boosts soil organic C stock and carbon sequestration [132]. The atmospheric carbon dioxide content may be significantly reduced as a result of this little increase in soil organic carbon. Earthworms enrich the physical, chemical, and biological properties of the soil in addition to introducing more worms to it, which promotes plant root growth in the soil and extra carbon uptake from the soil [132]. A sustainable agricultural system is ensured by increasing soil organic carbon, which also effectively absorbs atmospheric CO_2 [150]. To decrease CO_2 emissions and increase soil C sequestration, minor tillage, soil biodiversity enhancement, waste/worm compost management, microaggregation, and mulching can all play significant roles [151]. According to Zhang *et al*., [152], net carbon sequestration is mostly influenced by the size of the activated carbon pool and how it is used to create stabilized and mineralized carbon. According to Drinkwater *et al*. [153], Pimentel [154], and Reganold *et al*., [155], the net reduction in greenhouse gas emissions is precisely proportional to the amount of carbon sequestration from soil organic matter. Depending on the quantities of soil organic carbon, earthworms can have varying effects on the carbon cycle and have little impact on CO_2 emissions. However, because there are substantial amounts of C present, which have been activated and stabilized by earthworms, they increase net C sequestration [152]. Recently, there has been discussion about how earthworms can encourage carbon storage and therefore reduce greenhouse gas emissions. Researchers from Europe, the US, and Colombia discovered that earthworm activity causes soil nitrogen oxide levels to rise by about 42% and carbon dioxide emissions to rise by about 33% [156]. Organic carbon is abundant in vermicompost; the soil becomes richer in organic matter when organic carbon is added [157]. Soils with higher organic matter contents have a propensity to store more carbon [158]. By employing vermicompost to assist in storing carbon in the soil, a reduction in the amount of carbon dioxide in the atmosphere can be achieved.

3.3.2 Vermicompost in enhancing soil structure and reducing soil erosion

The most crucial factor affecting soil fertility among its different characteristics is its structure. According to Vickers, [159], an optimum soil structure leads to an increase in water-holding capacity and lowers water and soil loss. By creating humus, modifying minerals, and combining organic matter to create soil aggregates, earthworms enhance soil structure. Although *E. foetida* has been found to make minerals including kaolinite, biotite, smectite, and anorthite more weatherable [160], it is still unclear how earthworms affect mineral erosion. If earthworms and the microorganisms in their gut are to blame for increased mineral loss, more investigation is required. Studies show that earthworms stabilize aliphatic carbon in kaolinite and improve aggregate stability, which controls soil structure. Earthworm burrowing modifies the mechanical and hydraulic characteristics of the soil by forming macropores that allow water to infiltrate [161]. Enhancing the soil structural stability and porosity, earthworm's activities can lead to soil erosion reduction most especially in the tropics and temperate soils [162]. Depending on the species and how they interact with the soil, earthworms can have a positive or negative effect on soil erosion and compaction. The preservation of soil structure in tropical areas is aided by long-term interactions with the *Eudrilidae* species of compaction worms and *Reginaldia omodeoi* (compaction worms) [163]. Vermicompost improves soil structure and porosity, which in turn improves soil aeration and water retention. This encourages the growth of soil microorganisms, which are crucial for breaking down organic material and storing carbon in the soil. Healthy, well-structured soils are less likely to erode. A profitable agricultural area may be lost due to erosion, and carbon dioxide may be released into the atmosphere. By preventing erosion, vermicompost indirectly helps to keep carbon in the soil.

3.3.3 Vermicompost as a plant growth promoter

The use of vermicompost has greatly impacted the physical, chemical, and biological properties of soil [98]. Soils amended with vermicompost have improved levels of aeration, porosity, and structure

[164], as well as increased levels of pH, conductivity, organic matter, and nutrients. This results in enhanced crop growth and yield when using vermicompost [68]. Vermicompost growth-promoting qualities improve plant output and supply essential plant nutrients [165], [166]. By adjusting root systems, increasing root exudates, promoting plant-microbial interactions, and changing nutrient transport of nutrient uptake, humic substances (HS) can affect nutrient uptake. Humic chemicals are produced when organic molecules are humified. Mature vermicompost is primarily composed of humified materials produced by earthworms, which speeds up the humification process [167]. HS improved the resilience of soil aggregates while reducing soil erosion and nitrogen leaching. They can combine with cations and inorganic phosphorus to form complexes that reduce leaching and boost plant availability. They have a strong affinity for the soil's inorganic and organic ions. These complexes are important because the lower availability of these metal cations is associated with nutrient restriction [168], [169]. They are created as a result of the functional groups in the HS structure that contain O, N, and S. At 5% and 0% concentrations, vermicompost as well as humic and fulvic acids from VC were used to promote the growth of *Cannabis sativa* L. by 1% [170], or 0.05 mg/mL. The increase in plant growth brought on by the application of vermicompost is primarily due to the ongoing availability of macro and micronutrients, as well as the biological effects linked to enzyme activity and plant hormones [171]. Earthworms and bacteria work together to produce phytohormones like auxins, gibberellins, and cytokinins during the vermicomposting process [50]. Vermicompost can boost the abundance of oxygen, regulate soil temperature, improve porosity, infiltration, and nutrient levels, as well as improve crop productivity and quality [172]. Vermicompost encourages the diversity of advantageous microorganisms and increases soil biodiversity by fostering beneficial microorganisms, consequently promoting plant growth through the synthesis of hormones and enzymes and inhibiting the growth of nematodes and plant diseases. Vermicompost-covering wormholes make a great nesting habitat for bacteria in the soil that fix nitrogen. Vermicompost is used as a substitute in place of conventional fertilizer to boost plant growth. Important nutrients are provided by vermicompost, which also increases soil fertility. Better-growing plants take in more atmospheric carbon dioxide during photosynthesis and store it in their biomass and roots. Table 4 shows the different benefits of vermicompost in boosting agricultural productivity.

Table 4: Harnessing vermicompost utilization in crop yields.

Type of Crops	Country	Agricultural benefits	Ref.
Benth. Pogostemon cablin (patchouli)	India	Enriched soil properties and boosted essential oil production.	[173]
Strawberries (*Fragaria ananassa*)	India	Improvements in marketable yield and quality of fruits.	[174]
Sorghum (*Sorghum bicolor* L.)	Mexico	Development of fruits.	[141]
Maize (*Zea mays*)	Mexico	Improvements in growth.	[175]
Cowpea, cassava, and banana	Canada and India	Optimizing organic soil amendments boosts crop yields and enhances desirable biometric traits for agricultural productivity.	[176]
Tomatoes (*Lycopersicum esculentum*)	Mexico	Organic soil amendments foster vigorous plant development and increase carbohydrate synthesis for enhanced crop performance.	[177]
Tomatoes (*Lycopersicum esculentum*)	Germany	Soil fertility.	[178]
Greenhouse peppers (*Capsicum annuum* L.)	USA	Enhanced soils with organic inputs that stimulate improved flowering and fruit production.	[179]
Peppers (*Capsicum annuum*)	USA	Soil fertility.	[180]
Strawberry (*Fragaria ananassa*)	USA	Soil fertility.	[180]
Sorghum (*Sorghum bicolor* L.)	USA	Higher development of plants.	[181]
Tomatoes (*Lycopersicon esculentum*)	USA	Augmentation of growth.	[182]
Watercress (*Lepidium sativum*)	Italy and Spain	High productivity.	[183]
Paddy (*Oryza sativa*)	India	Higher nutrient availability.	[184]

3.3.4 Vermicompost in methane and nitrous oxide reduction

Methane and nitrous oxide emissions were reduced by vermicomposting by 22–26% and 25–36%, respectively. The carbon dioxide emissions increased by 3–14% with higher earthworm densities, but the methane emissions decreased by 10–35%. Earthworm density had a negligible impact on N_2O emissions. At low and high relative humidity, vermicomposting reduced nitrous oxide emissions by 23% and 40%, respectively. Vermicomposting additionally reduced methane emissions by 32% and 16% at various humidity levels [71]. Earthworms reduced N_2O emissions by > 80% and CH_4 emissions by > 40% during the vermicomposting of pig manure, according to Wang *et al*. [62], and Luth *et al*. [185]. A mesophilic technique of composting at 30 °C can be of great replacement to reduce nitrogen losses and greenhouse gas emissions. According to other studies by Hobson *et al*. [186], earthworms emit N_2O because the bacteria in their guts are denitrifying. Additionally, earlier research overlooked elements that might influence nitrogen loss, carbon content, and greenhouse gas emissions from worm composting. These elements included worm density, mineral nitrogen concentration, carbon quality, and moisture content. Denitrification processes in earthworms' guts are influenced by quantities of accessible C and mineral nitrogen [187]. Vermicomposting is successful in lowering greenhouse gas emissions across a range of factors, including C: N ratio, char quality, moisture, and earthworm density, according to a study by Nigussie *et al*. [71]. The drop in CH_2 and N_2O emissions following worm compote, which is also linked to a decrease in CH_4 emissions at greater earthworm densities, is explained by the earthworms' constant rotation of the substrates and the improved air circulation that results from this. Vermicompost can lessen the conditions that encourage anaerobic processes of methane production in the soil by improving soil aeration and microbial activity. Nitrous oxide emissions may be impacted by the rise in microbial activity brought on by vermicompost [188]. Strong greenhouse gas nitrous oxide is frequently released from agricultural soils. The amount of nitrogenous molecules that are converted to nitrous oxide can be lowered by balanced soil microbial activity [189].

3.3.5 Vermicompost in reducing greenhouse gas emissions through agro wastes

Vermicomposting can reduce greenhouse gas emissions using several strategies and guidelines. These include the inclusion of red mud and fly ash [190], the utilization of inorganic materials [191], the use of sawdust as a coal enrichment material, and the use of an aeration system. Agricultural waste products like wood chips [192], maize stalks [193], dried mushrooms, and gin [194] are among the local agricultural waste products that can be used as fillers. The contribution of biochar to decreasing greenhouse gas emissions has been thoroughly studied [156], [195]. According to Yasmin *et al*. [196], the carbon/nitrogen (C/N) ratio, pH, temperature, and aeration all affect the greenhouse gas emissions from composting and vermicomposting. Adding cow manure and sewage sludge reduces greenhouse gas emissions significantly, according to research [197]. Duck droppings and sugarcane straw were combined, and Wang *et al*., [62] reported a reduction in the amount of N_2O. However, as manure might increase greenhouse gas emissions, it should not be used for vermicomposting [196]. Emissions of greenhouse gases are influenced by the quantity of carbon left in the waste after treatment. Vermicomposting can successfully lower methane emissions from sewage sludge when granulated wheat straw is used as a supplement [198]. According to some investigations, vermicomposting reduces CH_4 emissions when compared to controlled environments, which is ascribed to the earthworms' maintenance of an aerobic environment. During the vermicomposting process, shorter aeration times and appropriate maintenance procedures assist in cutting down on CH_4 emissions. When vermicomposting, humidity is crucial in controlling greenhouse gas emissions, it enhanced N_2O emissions from enhanced nitrification and denitrification processes, as well as increased CH_4 emissions from the growth of methanogenic bacteria in earthworms, which can all result from excessive moisture in worm composting bins. Worm mortality is another effect of excessive moisture. Vermicomposting, in contrast to conventional composting, reduces methane emissions [199], [200]. High humidity levels have been demonstrated to reduce CH_4 emissions by 32% and N_2O emissions by 40%, whereas low humidity levels have been shown to reduce CH_4 emissions by 16% and N_2O emissions by 23% [71]. The area with the highest N_2O content in earthworms was shown to be their anaerobic gut core [201], [202]. The possibility that N_2O will be further reduced to N_2 before leaving the digestive system may rise with a bigger earthworm radius [112]. Additionally, Peter *et. al*., [203] found competitive redox mechanisms and gut transit time as key elements influencing N_2O and N_2 emissions from earthworms *in vivo*. Increased carbon storage and physical protection of soil organic matter in submerged aggregates result from the acceleration of decomposition of organic matter by the earthworm gut through mineralization, fragmentation, and subsequent microbial activity [204]. When vermicomposting, the ideal humidity, temperature, and ventilation levels can be maintained to reduce greenhouse gas emissions. Maintaining oxygen regulation conditions during the composting process can help reduce greenhouse gas emissions, according to certain studies [205], [206]. Vermicompost has an important advantage over traditional thermophilic composting in that it can be used straight away [207].

3.4 *The impact of earthworms and their gut microorganisms on mineral loss*

Earthworms are essential to soil ecosystems because they aid in the decomposition of organic matter, nutrient cycling, and soil structure. Recent research, however, has cast doubt on their possible contribution to soil mineral loss. Earthworm activity has been demonstrated in several studies to hasten the mineralization of organic materials, which may result in a greater release of minerals [208]. Microbial activity thrives in the perfect environment found in earthworm guts, enabling them to break down complex organic molecules more quickly than they could in bulk soil [209]. Earthworm burrows can alter the soil's preferred flow patterns, which may accelerate the leaching of minerals. According to Mer *et al*. [210], earthworm burrows have the potential to enhance water infiltration rates by a factor of ten, hence increasing the leaching of minerals. It has been demonstrated that the makeup and activity of microbial communities are changed when soil passes through earthworm guts. According to some scientists, these changes may favor microbes that are more adept at mineral breakdown [211]. Studies have shown that earthworms can improve soil mineral retention, in contrast to the loss of minerals. For instance, earthworm casts may be able to exchange ions more readily than the nearby soil, which could improve the soil's capability to hold onto minerals [212]. According to Ferlian *et al*. [213], earthworms are recognized to be essential to the cycle of nutrients, with the ability to counteract any losses of minerals by transferring nutrients from lower soil layers to the top. The soil's upper layers' mineral balance may be preserved by this vertical soil mixing. Through their casting activity, some earthworm species can control the pH of the soil, which may affect the availability and solubility of minerals. This pH control may, in certain circumstances, actually lessen the loss of minerals [212], [214], [215]. Comprehending these mechanisms is essential for formulating enduring methods of managing soil and preserving soil fertility in both agricultural and natural environments.

3.5 *Feeding ratio effect on greenhouse gas emissions*

Greenhouse gas emissions by vermicompost are heavily influenced by feed ratios about the proportion of new substrate to the biomass of worms. Greater nitrogen mineralization is encouraged by low nutritional factors than by high nutritional factors [216]. A high feeding rate, however, may hurt earthworm biomass and reproduction by slowing the rate at which fresh material is converted into vermicompost [185]. High feed levels can also change the compost heap's temperature and airflow, which can have an impact on greenhouse gas emissions [187]. Maintaining adequate feed levels can reduce greenhouse gas emissions by 23 to 8% when compared to composting without worming. There are numerous reasons why vermicomposting reduces greenhouse gas emissions. The substrate is continuously moved and rotated by earthworms, which enhances aeration [217], [218]. According to Luth *et al.* [185], the stability of the substrate following passage through the earthworm's stomach results in a decrease in greenhouse gas emissions. According to research, adding earthworms to the substrate during the vermicomposting process can increase its stability and hence lower greenhouse gas emissions. Due to increased microbial activity and nutrient cycling made possible by earthworms, vermicomposting has been shown to produce substantially less emissions of methane (CH_4) and nitrous oxide (N_2O) than conventional composting techniques [219]. On the other hand, it has also been shown that, under certain unfavorable circumstances, the introduction of earthworms may result in higher greenhouse gas emissions. According to research, earthworm activity can, on average, raise emissions of nitrous oxide by 42% and carbon dioxide (CO_2) by 33% [220]. This problem is made worse by higher temperatures in compost heaps, which cause earthworm death as well as an increase in N_2O emissions as a result of accelerated nitrification and denitrification processes [219]. Vermicomposting yields 2.28 kg CO_2-eq per ton of dry matter (DM) as opposed to 5.76 kg CO_2-eq per ton of DM in traditional composting, according to recent research that detected decreased emissions of CO_2 and N_2O during the process [219]. During the composting process, the carbon to nitrogen (C/N) ratio is another important factor that affects greenhouse gas emissions. However, higher temperatures in the compost heap can result in worm death and higher greenhouse gas emissions when the ratio of nutrients per unit of worm biomass surpasses ideal limits.

3.6 *Effects of vermicompost on soil quality and crop productivity*

Food security is threatened by soil degradation as a result of overutilization of chemicals, which lowers yields of crops and may lead to land desertion [221]. Chemical fertilizer has been extensively used due to deficiencies of essential macronutrients, such as nitrogen, phosphorus, or potassium necessary for crop growth and development, the fertilizer has been reported to be costly, and unaffordable and also causes environmental degradation, as result leading to constraints in nutrient adoption rate for plants. A possible solution to this problem is the adoption of organic fertilizer to supplement insufficient nutrient resources [222]. Organic farming offers significant benefits that help curb environmental degradation. This not only increases the economic viability and productivity of the land by preventing pollution and enabling nutrient-rich crops but also helps control and control pests and diseases by enabling higher market prices [223], [224]. Vermicompost is considered an excellent organic plant substrate. It is largely free of organic matter and chemicals, making it environmentally friendly. It is rich in nutrients and releases them gradually so that the plants can absorb them quickly. As healthy plants are more resistant to pests and diseases, the requirement for pesticides is reduced. Vermicompost is an ecological alternative to mineral fertilizers as it contains significant amounts of micronutrients necessary for plant growth and production [225]. The use of organic farming methods, such as vermicomposting, is becoming a popular trend in sustainable agriculture. Vermicompost provides a long-lasting supply of essential nutrients that are easily absorbed by crops [226]. In addition, vermicompost contains nitrogen-fixing and phosphorus-solubilizing bacteria [227] as well as natural substances like gibberellins, auxins, cytokinins, vitamins, humic acids, and defensive enzymes [228], [229], which promote the growth, development, and productivity of crops [230], [231], [232]. The application of vermicompost has proven to be an effective method for enhancing soil fertility, increasing nutrient availability, and conserving soil water [233]. Vermicompost releases nutrients slowly, allowing for better uptake by plants and improving soil moisture retention, resulting in improved plant quality and yield. In addition, using vermicompost for crop production helps solve waste disposal problems and ensures a constant supply of organic matter. According to Abdelaziz *et al.* [234], combining organic and inorganic fertilizer sources can improve financial performance and foster soil health. The effects of mature, healthy compost, including vermicompost, on a variety of crops, including beans, black peas, okra, tomatoes, squash, eggplant, watermelon, maize, and pepper, have been thoroughly studied. Higher yields have been obtained by using vermicompost [235]. The cost-effective control of soil fertility in the cultivation of sugarcane depends heavily on integrated nutrient management strategies. Vermicomposting can enhance nutrient intake, root development, and plant growth. According to Oworu *et al.* [236], humic compounds, the primary component of soil organic matter, boost shoot biomass by having a hormonal effect on root elongation and overall plant development. Vermicompost is added to the soil to increase the soil's nutrient availability and plant uptake. Direct or indirect consequences may result from this. Direct effects include the nutrients contained in composted manure. Indirect effects include improved microbial activity, preservation of soil structure, increased organic matter content and improved water quality. Microbial activity can mobilize nutrients and improve soil composition, promoting plant root development and overall soil health [237]. Numerous measures can be used to evaluate the growth quality of plants treated with various composts. According to Ibrahim *et al.* [238], these include quantifying plant height, the quantity of leaves and branches, and dry plant weight. These measurements provide insight into the overall development and biomass accumulation of plants and their response to compost fertilizer. By comparing these parameters between plants treated with different types of compost, it is possible to assess the compost's effectiveness in promoting plant growth and to determine the optimal compost for specific plant species or cultivation purposes. Figure 3 illustrates the significance of vermicompost in enhancing physicochemical properties of soil thereby promoting plant growth.

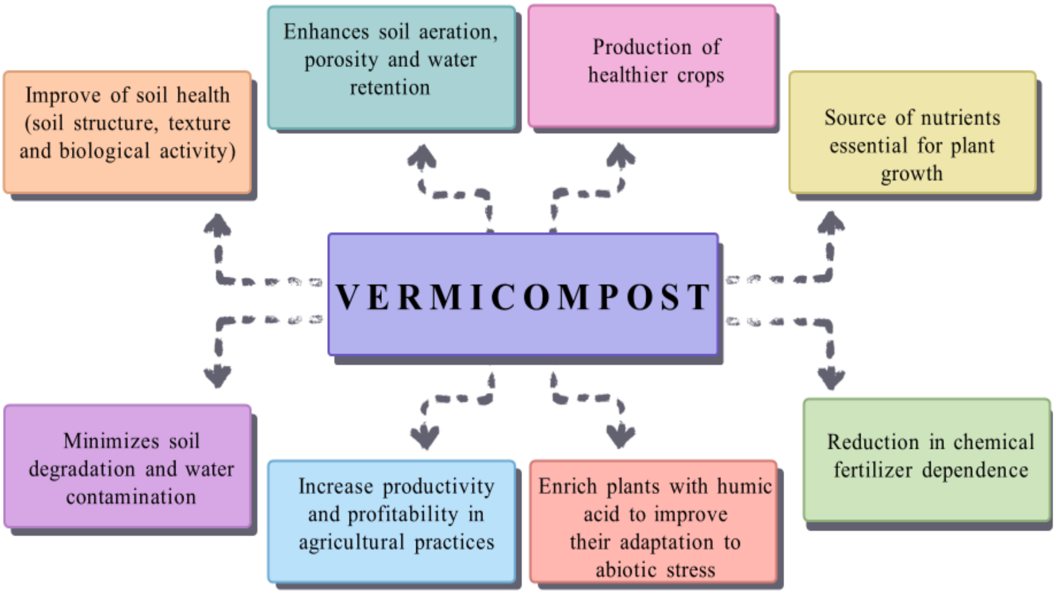

Figure 3: Vermicompost role in promoting crop growth and improvement on soil physicochemical properties.

3.6.1 Vermicompost effects on crop yield and growth

Studies on the development of significant vegetable crops, including eggplants (*Solanum melongena*) and tomatoes (*Lycopersicon esculentum*), have yielded encouraging results. The overall productivity of the potatoes was much higher than that of the control group, even when vermicompost was applied at a rate of roughly 6 tons per hectare. Furthermore, vermicomposting resulted in higher pea yield, increased green pod growth, the weight of green beans per plant, and an overall increase in green pod yield compared to using inorganic fertilizers [239]. Upon review of the data, it was found that the use of "Vermicompost *Parthenium*" at a dose of 5 tons per hectare resulted in an improvement in the yield of aubergines (*Solanum melongena*). Farmers across the country are increasingly using vermicompost as an organic additive to chemical fertilizers because it increases yields, possibly due to its ability to increase nutrient uptake [240]. Worms and vermicompost have been shown to promote excellent growth of horticultural crops and result in improved flower and fruit development [239]. According to Tringovska and Dintcheva [241], the usage of vermicompost can significantly affect plant growth, blooming, fruiting, and yield metrics. After vermicompost stimulation, tomato plants exhibited enhanced growth, resulting in a rise in shoot biomass. Although the physical and biological characteristics of the substrate may have contributed to this variation, the observed growth variations can be attributed to the different amounts of nutrients available in the potting soil [242]. Data analysis revealed that with the use of "Vermicompost *Parthenium*"; at the dose of 5 tons per hectare, the growth of aubergines (*Solanum melongena*) was accelerated [240]. The use of vermicompost favors an increase in plant growth parameters [242].

For example, when 10 tons per hectare (t ha^{-1}) of vermicompost were applied to maize, the grain yields were 4277.8 kg ha^{-1}, a considerable increase over grain yields fed with conventional fertilizers. Vermicompost was found to boost maize production by 100%, demonstrating its effectiveness as a powerful soil amendment [241]. The amount of vermicompost applied has a direct bearing on crop yield as well. To optimize advantages, research indicates that an application rate of between 20% and 60% of the total soil volume is ideal. Research has indicated that crop yields can rise by about 26% within this ratio [239]. Beyond this ideal range, oversaturation may result in declining rewards, and large amounts (over 60%) may impede growth because of possible nutritional imbalances and compaction of the soil. Variations exist in how different crops react to the quantity of vermicompost applied. During the 30 days' spray before planting, tomatoes treated with 100% of the required nitrogen derived from vermicompost produced yields as high as 12338 kg ha^{-1}. On the other hand, research has shown that using conventional chemical fertilizers by themselves produced lower yields, emphasizing the improved performance of crops grown with vermicompost [240]. According to Patra and Sinha [243], applying 2.5 tons of vermicompost per hectare produced plants that were 48.1 cm tall, had 41.00 pods per plant, and had 6.3 The highest number of branches per plant was produced by applying 10 tons of manure per hectare, which produced plants that were 42.00 cm tall, had 33.3 pods per plant, had 4.7 branches per plant, and had an increase in pod yield of 1,960 kg/ha and weed yield of 2,122 kg/ha. According to Bekel *et al.* [244], utilizing 2.5 tons of vermicompost per hectare led to a height growth of 26.8 cm, 6.4 branches per plant, and a total of 36.28 nodules per plant. Total mature pods per plant: 8, seed yield/ha: 2.11 t, and shells and seeds make up 100% of the total weight. The application of vermicompost at a distance of 35.10 cm (treatment 2) also resulted in a notable rise in all of the previously mentioned parameters. This could be due to the presence of microorganisms in vermicomposts that increase nitrogen fixation and phosphate dissolution in the rhizosphere, thus enhancing both plant growth and nutrient uptake [245]. Table 5 shows the effect of the biochemical and nutritional characteristics of vermicompost on different types of plants.

Table 5: Impact of vermicompost biochemical and nutritional composition on plant growth parameters.

Sources	Test Plants	Biochemical and Nutritional Characteristics	Results	Ref.
Trichoderma longibrachiatum fungus and *Amynthas gracilis*	*Pistachio* seedlings	pH: 7.4, EC: 2.2 dS/m, C/N: 25.8, TN: 1.32%, TP: 0.4%, TK: 0.4%, Fe: 1100 ppm, Zn: 50 ppm	Drought stress increased plant growth by 232%. Likewise, nutrient uptake increased significantly by 30%. A 52% increase in P uptake and a 35% increase in Zn uptake was observed.	[246]
Wheat Straw	*Triticum aestivum* L.	pH: 7.55, EC: 2.26 dS/m, N: 0.85%, P: 0.45%, K: 0.83%, Ca: 2.91%, S: 0.23%	Plants treated with VC at a rate of 8 t ha^{-1} showed significant improvements in their physiological state. The activities of SOD (Superoxide Dismutase), POD (Peroxidase), and CAT (Catalase) increased by 14.28%, 27.28%, and 50%, respectively. The transpiration rate and photosynthesis rate increased by 49.25% and 27.65%, respectively.	[247]
Leaves of *C. erectus* + FYM	*Vigna radiata* L.	pH: 6.69, N: 1.86%, P: 0.15%, K: 0.41%, Zn: 39.4 ppm, Ca: 4085.80 ppm, Fe: 1572 ppm	Mung beans showed an increase in biological yield of 34% and an increase in economic yield of up to 59%.	[248]
Cattle manure	*Lycopersicum esculentum*	pH: 6.90, EC: 2.0 dS/m, OM: 50.3%, N: 1.20%, P: 0.50%, K: 0.80%	Under the given conditions, there was a decrease in Na^+ contents observed in the leaves, and the tomato yield and quality were both increased.	[249]
Vegetable bark and leaf litter	*Solanum lycopersicum* L.	OM: 74%, pH: 8.74, EC: 2.15 mS/cm, Salinity: 1.5 g/L, Porosity: 62.5%	improved growth and better resistance to salinity stress.	[250]
Vegetable bark and leaf litter	*Solanum lycopersicum*	EC: 2.15 mS/cm, pH: 8.74, OM: 74%, TOC: 43.02%, Porosity: 62.5%	Plants cultivated on a VC substrate exhibited enhanced growth characteristics and showed better resistance and tolerance to salinity stress conditions.	[250]
	Zea mays	pH: 7.98, EC: 2.98 mS/cm, N: 0.07%, AP: 6.34 mg/kg, AK: 127 mg/kg, Zn: 0.97 mg/kg	A decrease in Na^+, H_2O_2, and malondialdehyde concentrations led to an increase in salinity.	[251]
Digested earthworm sewage sludge	*Hordeum vulgare* L.	pH: 6.34, EC: 8.92 mS/cm, TN: 24.4 g/kg, TP: 15.9 g/kg, Alkaline N: 2467 mg/kg, AP: 869 mg/kg, Zn: 805 mg/kg	The bulk density, pH, and electrical conductivity (EC) of saline soil decreased when VC was applied. As more VC was applied, the crops cultivated in this soil produced grains at a rate of 512%.	[252]

Table 5 *(Continued)*

Sources	Test Plants	Biochemical and Nutritional Characteristics	Results	Ref.
Leachate	*Sedum album*	pH: 8.32, total organic matter: 7.5%, total P: 1.2%, K: 1.5%, and N: 2.2%, and total humic + fulvic acid: 6%	Plants undesirable responses to salt stress decreased as a result of the treatment's execution. As a result, the *Sedum album* species growth characteristics and quality attributes were improved.	[253]
Coffee skins + green wastes + biochar	*Coffee*	pH: 5.60, N: 2.76%, K: 3.84%	Physiological and morphological parameters of the coffee plant were observed to increase under the given conditions.	[254]
Grass biomass and cow dung	*Dracocephalum moldavica* L.	pH: 8.03, N: 20 mg/L, P: 1997 mg/L, K: 8300 mg/L, Mg: 3600 mg/L, Ca: 7850 mg/L	Increased the biomass of the plant by 148% in VC modified with peat and 68% in VC amended soil.	[255]
Crop residues (rice and maize straw) + cow manure	*Triticum aestivum* L.	OM content: 42%, pH: 7.4, EC: 3.8 dS/m, total N: 2.1%, total P: 7.8%, total K: 0.5%, BC had pH: 7.90, EC: 2.05 dS/m, total N: 1.9%, total P: 2.2%, total K: 2.9%	The plant's levels of proline, oxidative stress, and leaf sodium (Na^+) concentration all decreased due to the treatment. Grain yield and nutrient uptake both showed increases, and there was a decrease in the pH, EC, and ESP (exchangeable sodium percentage) of the soil.	[256]
	Borago officinalis	OC: 20.7%, EC: 5 dS/m, P: 0.7 mg/kg, K: 0.9 mg/kg, Na: 473 mg/kg	Increase in antioxidant enzymes, photosynthetic pigments activities and reduction in the salinity.	[257]
Cow dung	*Ocimum basilicum* L.	C: 53.4%, pH: 8.7, N: 3.05%, S: 0.72%, humic acid: 4.82%, fulvic acid: 7.17%	Sensitive plant varieties' vegetative characteristics and tolerance to salinity were enhanced by the biostimulant treatment.	[258]
Cow dung	*Ananas comosus* L.	Total N: 1.54%, Total P: 0.64%, Total K: 6.31%, total Mg: 0.58%, total Ca: 1.39%, total Zn: 0.01%, total S: 0.34%	Fruits produced contained higher levels of total soluble solids, titratable acidity, ascorbic acid (vitamin C), and total chlorophyll content.	[259]
		pH: 7.1, EC: 6.5 dS/m, OM: 65.5%, TN: 2.2%, TP: 7.3 mg/kg, TK: 12.8 mg/kg, Ca: 25.1 mg/kg, Zn: 216 mg/kg	Soil's exchangeable sodium (Na) concentration, bulk density, and electrical conductivity (EC) all decreased as a result of the application. Both the soil's overall porosity and aggregate stability increased.	[260]
Animal fleshing and waste from tanning	*Lycopersicom esculentum*	pH: 6.56, EC: 1.08 dS/m, TKN: 20 g/kg, Total P: 39 g/kg, Total K: 4.4 g/kg	Plant height (10%), stem girth (8.9%), and leaf number (14%), all increased with the use of VC.	[228]
	Lactuca sativa var.	pH: 8.1, EC: 6.5 dS/m, OM: 65.5%, N: 2.2%, P: 1.7%, K: 1.5%	Under drought stress, the application of VC boosted the activity of the enzymes catalase (CAT) and superoxide dismutase (SOD) in the plants. There was a decrease in the MDA (malondialdehyde) content, a sign of oxidative stress. Chlorophyll a, b, and carotenoids were shown to be present in higher concentrations in lettuce plants.	[261]
Straw, leaf litter, and cow dung	*Capsicum annuum* L.	-	Chilli pepper growth and development were greatly enhanced by the treatment of 50% VC treatment. The entire quality of the soil also improved as a result of the treatment.	[262]
Green wastes	*Pelargonium zonale* L. and *Calendula officinalis* L.	pH: 7.43, EC: 1.77 dsm^{-1}, CEC:117.44 c mol kg^{-1}, N: 21.47 g/kg, P: 4.82 g/kg, K: 7.87 g/kg, Ca: 179.15 g/kg, Mg: 12.58 g/kg, Zn: 189.12 mg/kg, EC: 1.8 dS/m	Plant species showed greater growth and flowering when cultivated on VC-containing media compared to other media.	[263]
Green wastes	*Cicer arietinum* L.	pH: 7.1, EC: 1.5 dS/m, C/N: 17.5, N: 3.0%, P: 0.9%, K: 1.2%, Ca: 4.5%, Mg: 0.50%	Photosynthetic pigments, transpiration, Fv/Fm, Ca, and K in root and leaf tissues, as well as the proline and soluble protein levels in root tissues, were all enhanced by 30% VC.	[264]

Table 5 *(Continued)*

Sources	Test Plants	Biochemical and Nutritional Characteristics	Results	Ref.
Green wastes	*Cicer arietinum* L.	pH: 7.1, EC: 1.5 dS/m, C/N: 15.5, N: 0.9–3%, P: 0.9–2.5%, K: 0.6–2.5%, Ca: 4.85–8%	At the flowering stage, VC additions of 10% and 20% considerably increased the chlorophyll levels and Fv/Fm under MS and Fv/Fm, Ci, and PN under SS.	[265]
Green wastes	*Sorghum bicolor* L.	pH: 7.2, EC: 2.69 mS/cm, N: 0.98%, P: 121 ppm, K: 46 ppm.	Application improved the soil's overall nutritional condition. In turn, this improved the plant's growth and development by reducing the harmful effects of salt stress on them.	[266]
Cow dung, food industry sludge	*Cicer arietinum* L.	pH: 6.6, C/N ratio:11.9, TKN: 26 g/kg, TAP: 9.75 g/kg, TK: 7.6 g/kg	Plant overall chlorophyll contents increased as a result of the application. It was also observed that the crop yield had increased.	[267]
	Zea mays	pH: 7.17, EC: 1.05 dS/m, TN: 4.13 g/kg, TP: 1.24 g/kg, TK: 1.70 g/kg, C:N = 15.04	The exchangeable sodium (Na^+) concentration of the soil decreased as a result of the application. Also, the total amount of soil microbial activity was enhanced. In turn, the maize crop's growth and development were improved.	[268]

AP- Available Phosphorus, AK- Available Potassium, Ca- Calcium, CEC- Cation Exchange Capacity C: N- Carbon to Nitrogen, CU-Copper, EC-Electrical Conductivity, Fe-Iron, Na- Sodium, N-Nitrogen, P-Phosphorus, K-Potassium, Mg-Magnesium, Mn-Manganese OM-Organic Matter, S-Sulphur, TAP-Total Available Phosphorus, TN-Total Nitrogen, TKN-Total Kjeldahl Nitrogen, TK-Total Potassium, Zn-Zinc, ppm-parts per million

3.6.2 Vermicompost impact on crop nutrient content

Compared to chemical fertilizers, the use of vermicast in peas resulted in increased protein and carbohydrate content [128]. Seethalakshmi [239] reported that data research showed that using Vermicompost *Parthenium* at a rate of 5 tons per hectare improved the food quality of eggplants (*Solanum melongena*). Increasing the content of micro and macro elements, chlorophyll and proteins, carbohydrates, pH and total soluble solids in the juice was achieved through the use of vermicompost, thereby improving nutritional quality. According to Joshi *et al*. [242], vermicompost and bacterial treatments that encourage plant development can be employed as sustainable agricultural methods that are better for the environment than synthetic fertilizers.

3.6.3 Vermicompost's role in plant protection

The considerable decrease in disease incidence in plants treated with worms and vermicompost was one of the most important findings [128]. By stifling, discouraging, and stimulating biological resistance in plants, vermicompost also protects against pests and diseases [269]. The combined action of the non-aerated extract and solid vermicompost has shown promise in alleviating serious diseases common to most horticultural crops and caused by *Pythium aphanidermatum*, as demonstrated in laboratory studies at Cornell University. Despite knowing that Pythium disease does not typically affect garlic, the impact of compost on leaf growth and weight gain was significant [270]. Improved plant health and vitality attributed to root zone microbiology allow plants to resist damage from harmful microorganisms that can cause disease in crops. Recent research shows that worm-fed plants have increased resistance to harmful microorganisms compared to traditional inorganic fertilizers, resulting in poorer yield growth [270]. Many researchers found that organic fertilizers such as vermicompost are consistent with sustainable agriculture goals. Inevitably, high-quality crops can be influenced by vermicompost crops. Increasing the usage of vermicompost significantly improved some plant attributes, including seed germination, leaf count, length, fresh weight, and chlorophyll content (a, b, and total). Additional advantages encompassed general expansion and blossoming, generation of fruits and seeds, yield of byproducts, and yield of fresh and medicinal plants [271]–[275]. Additionally, according to Vengadaramana and Jashothan [276], applying organic fertilizers enhances the quality of the soil. Figure 4 shows the importance of Vermicompost in soil fertility, leading to improved crop yields.

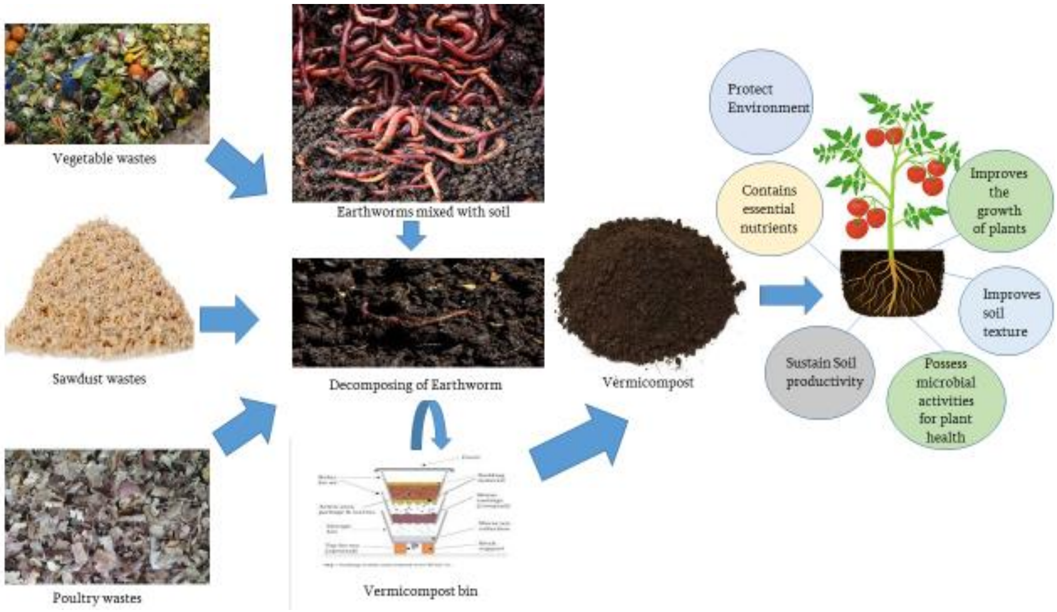

Figure 4: The process of vermicomposting and its impact on soil fertility, leading to improved crop yields.

3.7 *Vermicompost effects on soil characteristics and developments in sustainable soil management*

Nearly every aspect of agricultural productivity is significantly hampered by low soil fertility [277]. Due to insufficient and improper application of fertilizers, the soil nutrient balance in Africa, notably in Ethiopia, is persistently negative, which causes soil nutrient depletion and a loss in agricultural output [278]. Continuous agriculture without enough soil improvers exacerbates this issue [279], [280]. Vermicompost fertilizers have the potential to increase yields, but their application is now constrained by their scarcity, high cost, and nutrient imbalances [281]. Humic acids are abundant in vermicompost, which fosters a suitable environment for microbial populations and chemical reactions [282]. Additionally, vermicompost-fertilized soils showed increased levels of nitrogen (N), phosphorus (P), potassium (K), copper (Cu), magnesium (Mg), and iron (Fe), which benefited plants' metabolic processes [283]. According to Theunissen *et al*. [284], plants treated with vermicompost displayed higher root growth and root development, which may account for better absorption and assimilation of macro- and micronutrients. However, the benefits of vermicompost rely on how much fertilizer is used because too much fertilizer might stifle plant growth by depleting soil aeration and increasing salt concentration [171], [285]. In dry and semi-arid areas, where organic matter is sparse, organic matter plays a critical role in enhancing soil physical characteristics and preserving soil production. According to Nnaji [286], the physical characteristics of the soil have a big impact on crop productivity and soil fertility. It has been demonstrated that adding organic wastes, such as manure, compost, municipal biosolids, and others to soil can improve its physical and chemical characteristics [287]. Vermicompost application appears to hasten germination and encourage the early emergence of seedlings by improving soil porosity, water retention capacity, and aeration, all of which are factors that contribute to the growth of plants [180].

Applying vermicompost has several advantages for soil health and plant growth. Faster seed germination and stronger seedling emergence are encouraged by the improvement of soil structure, which also increases porosity and water retention capacity [162]. Vermicompost's high nutritional content, especially when it comes in forms that plants can use, promotes strong plant growth and higher yields [180]. Vermicompost also increases soil microbial activity, which benefits soil health overall and inhibits some pests and plant diseases [288]. Vermicompost is a desirable alternative for sustainable horticultural and agricultural activities because of these benefits. Nonetheless, there may be disadvantages to using vermicompost regularly and in large quantities. Overapplication may cause nutritional imbalances, especially an accumulation of phosphorus, which could alter the chemistry of the soil [61]. Additionally, depending on the feedstock used for vermicomposting, there is a chance of heavy metal accumulation and increased soil salinity [289], [290]. Moreover, high rates of vermicompost application may lead to increased microbial activity and nitrogen cycling, which could raise greenhouse gas emissions, particularly nitrous oxide [71]. Because of these possible hazards, it's crucial to use vermicompost with appropriate management techniques, such as routine soil testing, rotating or mixing with other organic additions, and keeping an eye on pH and salinity levels.

Vermicomposting can optimize its positive effects on soil and the ecosystem while limiting its negative effects by implementing these methods. Vermicompost makes it easier for microorganisms to enter the rhizosphere of plants by increasing the availability of nitrogen (N) and phosphorus (P) through biological nitrogen fixation and P dissolution through intensive mixing of the ingested particles with the vermicompost [291]. Vermicomposting increases the amount of phosphorus accessible in the soil, which supports the findings [292]. According to studies by Yousefi and Sadeghi [293], adding vermicompost to the soil significantly increases wheat production. Because of its rich content, vermicompost can be used in nutrient-deficient soils, particularly to replenish NPK, and to enhance plant growth, yield, and yield components, such as in cereals. Vermicompost is also regarded as a source of nutrients and hormones that encourage growth [294]. This could improve plants' uptake of nutrients and increase the advantages of vermicompost for crops. While organic fertilizers can boost yields and lower the hazards associated with chemical fertilizers during the later growth stages of an integrated nutrient management approach, inorganic fertilizers can supply plants with easily available nutrients during the early growth stages [295]. Earthworms in the soil let water penetrate more effectively and rebuild compacted soils. Foraging, burrowing, and flinging by earthworms all help to change soil and organic matter in physical, chemical, and biological ways. As was already noted, vermicompost frequently contains more nutrients than normal compost.

Vermicompost can improve the physical, chemical, and biological fertility of the soil. Vermicompost has been found by Lim *et al.*, [68] to improve soil fertility as a result of its physical, chemical, and biological characteristics. Vermicompost makes the soil more porous, airy, huge, and able to store more water. Vermicompost has been demonstrated to increase yields and plant growth when used to improve soil chemistry, including pH, electrical conductivity, organic matter, and nutritional status [296]. In addition to being chemically and physiologically rich, vermicompost also stimulates the generation of humic acid and plant growth hormones, boosts the activity of microbial communities, lowers the risk of root infections and soil-borne illnesses, and enhances plant development and yield [275]. Integrated soil fertility management strategies increase crop growth and productivity [297]. To achieve optimal yields, improve the physical and chemical properties of the soil, and provide economically viable nutrient solutions to crops that are practically feasible and safe for the environment, integrated nutrient management is a key component. It encompasses the intelligent use of organic and inorganic resources, incorporating biological resources [298]. Vermicompost has the power to successfully combat plant illnesses that are transmitted through the soil, such as root rot. This method preserves a healthy, functioning soil structure while enabling agricultural land to flourish in rural locations. Vermicomposting also improves the soil's aeration and nutritional content, which makes it simpler for good bacteria to live and flourish in the environment. However, it should be kept in mind that depending on the size of the farm, vermicomposting may demand considerable investments. The potential lethality of the worms, on both a big and small scale, is one of the major difficulties. Worm composting and its effects on soil fertility for best results. The condition described above can occur in worms when they do not eat enough, when they receive food that is too dry or moist, or when they are kept in a garbage can that is too hot [128]. To preserve soil fertility and lessen soil pollution, vermicomposting creates beneficial organic fertilizers [299], [300]. Figure 5 shows the role of vermicompost in soil and crop growth and the best result of using vermicompost on crop yield and quality of crop produce.

Figure 5: Overall impact of vermicompost on crop yield.

4 *Vermicompost Remediation of Soils for Environmental Quality*

4.1 *Heavy metals removal*

Organic amendments such as VC have been reported to have effectively decreased cadmium and arsenic accumulation in soil and plants. Recent research by Liu *et al*., [301] has shown that the addition of VC can decrease the amount of cadmium extractable by CaCl in soil. This is because VC absorbs cadmium and raises the soil's pH level. However, the success of using organic amendments to reduce the accumulation of cadmium and arsenic is dependent on several factors, including plant type, amount and type of organic materials used, and changes in the rhizosphere's physical, chemical, and biological characteristics. The use of organic amendments has also been effective in decreasing the bioavailability of arsenic in soil by binding it to organic compounds and reducing its uptake by plants, as demonstrated in studies by Sengupta *et al*., [302]. This immobilization process is achieved through humic acid complexation and cation bridge binding mechanisms. The concentration of arsenic compound in rice grains has also been predicted using machine learning techniques like random forest (RF), which are based on the physicochemical characteristics of the soil, including its pH, organic carbon content, and phosphorus concentration [302]. Numerous studies have demonstrated the effectiveness of using natural amendments to reduce the buildup of cadmium in plants, including VC, biochar, and humic compounds [303]. Likewise, research has shown that humic substances derived from VC (volatile compounds) have a high affinity to retain Cd^{2+} ions. The relationship that exists between these substances, plant roots, coupled with acid exudation and rhizosphere acidification, can influence the production of weak Cd^{2+} bonds. It should be noted that the uptake of Cd^{2+} by plants on different substrates can influence the levels of toxicity on plant growth compared to biochar and humic, VC and its derivatives reported to have less of an inhibitory effect on root and shoot growth.

4.2 *Mitigating salt stress with vermicompost*

A recent study by Shen *et al*., [252] found that the growth of barley plants in muddy environments can be significantly improved by adding vermicompost (VC). This is because VC contains a high amount of organic matter and colloids, which help to enhance soil structure and cause a reduction in bulk density. As a result, capillary tension is reduced, preventing the rise in water and salt leading to a decrease in soil desalinization. The acidity of VC also aids in reducing electrical conductivity after application. According to Ibrahim *et al*. [304], research has shown that the use of both VC and water treatment residuals (WTR) can increase wheat yield and improve saline-sodic soils. The combined use of VC and WTR work to improve water retention, soil structure, and nutrient uptake, thereby causing an increase in crop productivity. In addition, Mahmoud and Ibrahim [305] reported that the use of both VC and WTR effectively reduces salinity and sodicity of soil in turn improving soil physical properties and nutrient availability. These practices indirectly benefit cereal crops by reducing soil salinity and improving soil conditions, although they do not directly address pest management. Another study conducted by Alamer *et al*., [251] assessed the effectiveness of using VC and sorghum water extract (SWE) to reduce salt stress in maize seedlings, the use of VC and SWE showed a significant way of mitigating the harmful effects caused by salt stress on the growth of the crop, photosynthetic efficiency, and nutrient uptake in such affected soils. Figure 6 shows the role of Vermicompost in remediation.

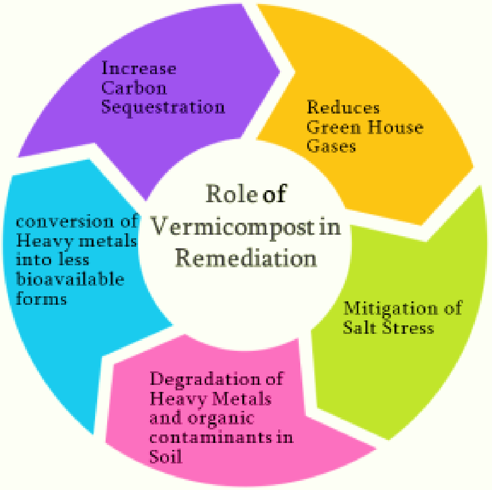

Figure 6: The role of vermicomposting in remediation.

4.3 *Methods of vermicompost remediation of soils*

4.3.1 *Cover cropping and crop rotation with vermicompost application*

Soil rehabilitation can be expedited by combining vermicompost and cover crops. Incorporating vermicompost into crop rotation systems, enhancing microbial activity, nutrient availability, and cover crops can all improve the remediation effects of the soil by preventing erosion and adding organic matter. Vermicompost can enhance soil structure and nutrient cycling more successfully than monoculture systems since different crops have different nutrient requirements and root systems. The health and structure of the soil can be quickly improved by this combination [180], [306].

4.3.2 *Phytoremediation with vermicompost support*

Vermicomposting can help phytoremediation efforts by increasing the effectiveness of plants in eliminating pollutants from the soil. Plant growth and pollutant uptake can be enhanced by the better soil conditions that vermicompost provides [307].

4.3.3 *Biochar-vermicompost blends*

Vermicompost and biochar together have a synergistic impact that can be beneficial for remediating soil. More so than each amendment alone, this combination can enhance soil water retention, nutrient availability, and carbon sequestration [308].

4.3.4 *Vermicompost for saline soil reclamation*

Salinity-tolerant plants combined with vermicompost can aid in the reclamation of saline soils. Vermicompost's organic matter and helpful microbes can enhance soil structure and facilitate the drainage of excess salts [268]. These techniques show how versatile vermicompost is when it comes to soil remediation tactics. Vermicompost can be included in a variety of ecological and agricultural techniques to enhance soil health and build farming systems that are both economically and sustainably viable.

5 Challenges of Vermicompost

The scientific evidence presented in this paper highlights the significant potential of vermicomposting as a sustainable agricultural practice that can improve soil health, reduce greenhouse gas emissions, and increase crop yields. However, the widespread adoption of vermicomposting faces various challenges such as a lack of awareness among farmers, high initial costs, labor-intensive requirements, and insufficient policy support. To overcome these barriers, targeted strategies are necessary to promote vermicomposting and unlock its benefits. Agricultural policymakers need to provide subsidies, incentives, and training programs to farmers to encourage the adoption of vermicomposting. Academic and extension services must educate farmers on best practices for producing and applying vermicompost tailored to specific crops and contexts. Standardized protocols should be developed to ensure consistent quality. More field trials and pilot studies are required to demonstrate the feasibility of vermicomposting for large-scale farms. Research should analyze the costs, labor needs, and impacts across various agro-ecological regions. The vermicomposting industry should leverage new technologies like automation to make the process more scalable and affordable. Partnerships between farmers, scientists, industry, and policymakers can drive a coordinated transition toward sustainable agriculture based on vermicomposting.

6 Conclusions

According to the comprehensive literature review conducted, Vermicompost has shown a lot of promise in terms of reducing greenhouse gas (GHG) emissions and improving environmental quality. Because of its numerous mechanisms of action, vermicompost offers workable ways to mitigate the effects of climate change and promote sustainable agriculture. By lowering CO_2 emissions during the waste treatment process, the production of vermicompost from widely available agricultural waste directly contributes to lowering greenhouse gas emissions. Improving soil fertility and structure is one of the main processes because it encourages the growth of plants with a higher potential for carbon sequestration. This aids in lowering greenhouse gas emissions since soil holds carbon for a long time. Vermicompost enhances the soil's ability to retain moisture, lessens the need for irrigation and the energy-intensive pumping of water that goes along with it, and so lowers greenhouse gas emissions. By fostering an aerobic environment that prevents methanogenic bacteria from growing, vermicompost can reduce methane emissions. In addition, the use of vermicompost optimizes the nitrogen cycle and minimizes the production of nitrous oxide. In addition to reducing greenhouse gas emissions, vermicompost offers other environmental benefits such as improved soil fertility, reduced dependence on synthetic fertilizers, increased soil water storage capacity and support for sustainable agricultural practices. The entire potential of vermicompost to lower greenhouse gas emissions and enhance environmental quality needs to be explored. Although vermicomposting has a lot of promise for waste management and sustainable agriculture, it is not always well accepted or supported. It is imperative to stress the economic importance of regular users tackling this. Vermicompost offers farmers a more affordable option for fertilizer than chemical fertilizers. Studies show that vermicompost can save fertilizer costs while preserving or increasing crop yields. In addition to supplying vital nutrients, this organic amendment improves soil structure, water retention, and microbial activity, all of which contribute to the long-term health of the soil. Furthermore, crops that are cultivated with vermicompost frequently show greater resistance to pests and illnesses, which may lessen the need for pesticides and meet consumer demand for organic goods. Promoting the usage of vermicompost can help community leaders address several regional issues. It provides a practical way to manage organic waste, potentially reducing the waste stream from landfills in the neighborhood. The establishment of vermicomposting facilities can boost the local economy and provide jobs while reducing the carbon footprint caused by emissions from landfills and chemical fertilizers. Additionally, vermicompost is essential for promoting urban agricultural programs that provide access to fresh produce and food security in metropolitan settings. Vermicompost-using community gardens have demonstrated yield increases above traditional techniques. By emphasizing these concrete advantages, we can show how vermicompost supports social, environmental, and economic objectives, making it a desirable and workable option for a range of stakeholders in daily life.

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Author Contributions

O.M.: conceived the draft, analyzed the reference coding, and reviewed the entire manuscript. D.A.: searched through the bibliography, selected relevant references, coded the information, and wrote the initial draft of the manuscript; K.O.: synthesized the manuscript and revised the final version; D.O.: prepared the work plan; M.F.: defined the bibliographic search, conceptualized the draft, and reviewed the entire manuscript; I.O.: was responsible for formal analysis, investigation, visualization, and software used in this study; M.M: ensure final checking of the manuscript. All authors have accepted responsibility for the entire consent of this manuscript and approved its submission.

Conflict of Interest

The authors declare no conflicts of interest.

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