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Article

Vermicomposting of food waste: A step toward circular bioeconomy

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Abstract: The rapid expansion of the population, urbanization, industrial activities, and the intensification of agriculture and food production have significantly increased food waste generation in recent years. Vermicomposting has the potential to transform food waste into nutrient-rich organic fertilizer, making it a highly promising method for biological waste treatment. This review furnishes an in-depth review of the key patterns and mechanisms involved in food waste decomposition, nutrient recovery, and pollutant detoxification through vermicomposting, approaching a circular bioeconomy. The synergistic interaction between earthworms and microorganisms facilitates the breakdown and transformation of pollutants in the substrate, enriches nutrients, and underscores the crucial role of the earthworm gut in the process. Vermicomposting offers numerous benefits; however, several constraints limit its effectiveness and widespread adoption in agriculture. To promote its development, efforts should focus on advancing technology, increasing governmental awareness and policy support, and establishing standardized guidelines for implementation. Vermicompost plays a vital role in the circular bioeconomy, with applications in agricultural sustainability, waste management, pollutant remediation, biogas generation, and animal feed production.

Keywords: circular bioeconomy; earthworm; food waste; sustainable agriculture; vermicompost

1. Introduction

Food waste is increasing significantly due to rising food demand driven by population growth, agricultural expansion, and urbanization. India ranks second globally in fruit and vegetable production, contributing 10% and 14% of the total output, respectively [1]. Additionally, mechanical damage during storage, mishandling in transportation, and food processing activities such as washing, peeling, and boiling generate substantial food waste [2]. Improper disposal of food waste negatively impacts the environment. For instance, runoff can carry food waste into water bodies, causing pollution, while decomposition in open spaces deteriorates environmental health. Various strategies have been implemented for food waste disposal, including landfill dumping, curbside recycling, incineration, and composting [3]. However, some methods pose environmental risks, including landfill decomposition releasing greenhouse gases like methane and carbon dioxide, contributing to global warming and climate change [4]. Tukker and Jansen [5] revealed that the food sector accounts for approximately 22% of the global warming potential in the EU. Thus, it is necessary to adopt effective technologies to counteract the negative impact of perishable food waste. The best strategy should focus on resource recovery and reuse of organic waste. Recently, vermicompost technology has received a great deal of attention for providing a better solution compared to its counterpart methods. In vermicomposting, synergistic action of earthworms and microbiota can transform food waste into stabilized, nutrient-rich vermicompost [6]. It is a low-cost, energy-efficient process that requires minimum space and produces an odor-free end product [7]. Vermicompost serves as valuable organic fertilizer, enhancing soil health and boosting agricultural productivity. In addition to this, cultivation of earthworms in organic substrates, known as vermiculture, plays a significant role in sustainable agriculture. Vermicomposting not only enhances agricultural productivity but also generates revenue and reduces the dependence on agrochemicals, promoting eco-friendly farming practices. Based on its operational approach, vermicomposting is classified into batch and continuous feed systems. In batch vermicomposting, organic waste is added to the reactor in single or multiple batches, depending on operational conditions and reactor capacity. In some cases, waste is arranged in windrows on the ground and manually turned to enhance aeration and decomposition [8]. Conversely, continuous feed systems allow for manual operation, where trays containing organic waste at different decomposition stages are periodically removed upon maturity, and fresh waste trays are introduced into the system to maintain the process.

The World Economic Forum recognizes the circular bioeconomy as a transformative model that redefines “waste” as a “resource.” By reintegrating waste into the food production chain, these approaches help minimize environmental impact and lower production costs. In line with this shift, the zero-waste program aims to increase waste reuse up to 70% by 2030, addressing critical environmental challenges such as soil degradation, erosion, and climate change [9]. Vermicomposting has the potential to transform the linear economy to a circular bioeconomy by converting waste to energy, adhering to the 3Rs principle (reuse, recycle, and reduce). Recycling aligns with the principles of the circular bioeconomy, transforming waste into valuable resources for consumers [3]. The significant advantages of vermicompost have attracted farmers, offering a more eco-friendly and sustainable solution for chemical fertilizers, contributing to the principles of sustainable economy. This review highlights vermicomposting technology and its crucial role in advancing the circular bioeconomy.

2. Methodology

A systematic literature review involves collecting, identifying, assessing, and interpreting research findings to evaluate specific research problems. In this study, relevant literature was sourced from the Google Scholar database, with publications selected from the period 2015 to 2025. Research results were obtained using specific keywords, including ‘vermicomposting technology’ and ‘circular bioeconomy’, to ensure comprehensive coverage. While Google Scholar provided valuable insights, additional databases such as Scopus and Web of Science were also utilized to enhance the breadth of the review.

3. Circular bioeconomy and its importance

The concept of circular bioeconomy promotes zero-waste management by minimizing waste input and closing material loops. It supports sustainable development by preventing waste leakage and maintaining a circular system [10]. However, most waste management strategies follow a linear economy model, widely adopted by industries. The linear economy operates on a ‘make-use-dispose’ consumption pattern, where manufactured products are used and discarded, failing to align with sustainable development goals. To address this, the circular economy law was enacted in 2008 by China, followed by Germany and Japan [3]. This approach helps reduce industrial waste and environmental burdens [11]. According to the 2030 circular bioeconomy strategy, food waste must be reduced by 50% per capita [12]. Additionally, the circular bioeconomy fosters job creation in emerging businesses and adheres to waste management principles. It enables food waste recycling for compost production [13], bio-energy generation [14], and various value-added products [15].

Currently, circular bioeconomy is replacing the linear model by recycling waste materials and closing the system [16]. For instance, vegetable oils are converted into biodegradable detergents [17], wheat bran is used to manufacture biodegradable tableware [18], grape skins and seeds are processed into bio-compost [19], and household food waste is transformed into compost for agricultural use [20]. These product transformation processes emphasize the circular bioeconomy model, focusing on reducing, recycling, and reusing materials at the consumption level [21]. Despite its advantages, economic, socio-cultural, and institutional factors pose challenges to achieving a circular bioeconomy [22].

Circular bioeconomy indicators assess the environmental impact of recycling and material recovery. These indicators are categorized into three scopes (0, 1, and 2) and incorporate both specific and non-specific strategies, following the life cycle thinking model [10]. Scope 0 indicator does not follow the life cycle thinking approach to measure the recycling rate [23]. On the contrary, scope 1 indicators assess the full life cycle approach, including reusing, recycling, and material recovery [24]. Scope 2 indicators evaluate technological aspects alongside social, economic, and environmental disquiets. Both scope 1 and 2 indicators are used to assess the impact of recycling on food waste management, especially in compost production from perishable food waste, with the expenses being easily measured.

4. An overview of vermicomposting: Process, benefits and applications

Vermicomposting is accomplished by the cooperative activity of earthworms and microorganisms. During this mechanism, earthworms are the sole organisms of making aeration, turning and fragmentation of waste substances [25]. Taking into account vermicomposting, various earthworm species have different modes of nutrition and thrive under varying climatic conditions, both of which significantly influence the degradation rate of organic matter. For instance, Sharma and Garg [26] introduced several earthworm species used in vermicomposting. These include temperate species such as *Eisenia fetida, Dendrobaena veneta* and *Lumbricus rubellus,* as well as tropical species like *Eudrilus eugeniae* and *Perionyx excavatus*. These species displayed greater potential in the production of vermicompost. The earthworm and its anaerobic and aerobic gut microflora perform physical and chemical actions during metabolism. They are involved in aeration, mixing, and grinding of organic matter and biochemically decompose the substrates in the earthworm’s intestine and convert the unstable organic matter into a stable product [27].

Additionally, earthworms, the soil dwellers, can engulf the organic matter mixed in soil and can easily hydrolyze it in their intestines by the action of digestive enzymes. The nutrient-rich fecal substance is excreted (**Figure 1**). In general, vermicompost consists of excreta of earthworm, also known as vermicast, which can improve the biological, chemical, and physical properties of the soil [28]. It has been reported that vermicompost provides a large surface area and avails the nutrition that can intensify the growth of microbial population as compared to thermophilic compost [4]. Additionally, soil amended with vermicompost has high porosity and water-carrying capacity, enhancing aeration that facilitates decreasing C/N ratios [26]. The gut microorganisms of earthworms produce acids that convert the insoluble nutrients into their soluble form [29]. Earthworms can strongly improve soil fertility by increasing the phosphorus, potassium, and nitrogen concentration in soil. Besides this, vermicomposting involves bioremediation in which earthworms can eliminate toxic metals from the waste substrates and convert them into non-toxic forms by absorbing heavy metals through the skin and intestine [30]. According to Gajalakshmi and Abbasi's [31] report, earthworm castings contain a higher amount of ammonium and phosphorous content as compared to bulk soil. Vermicast is also fortified with several enzymes and hormones; on the other hand, it discourages pathogens. For instance, vermicast inhibited the infection of tomato plants caused by *Fusarium oxysporium* f. sp. *lycopersici*.

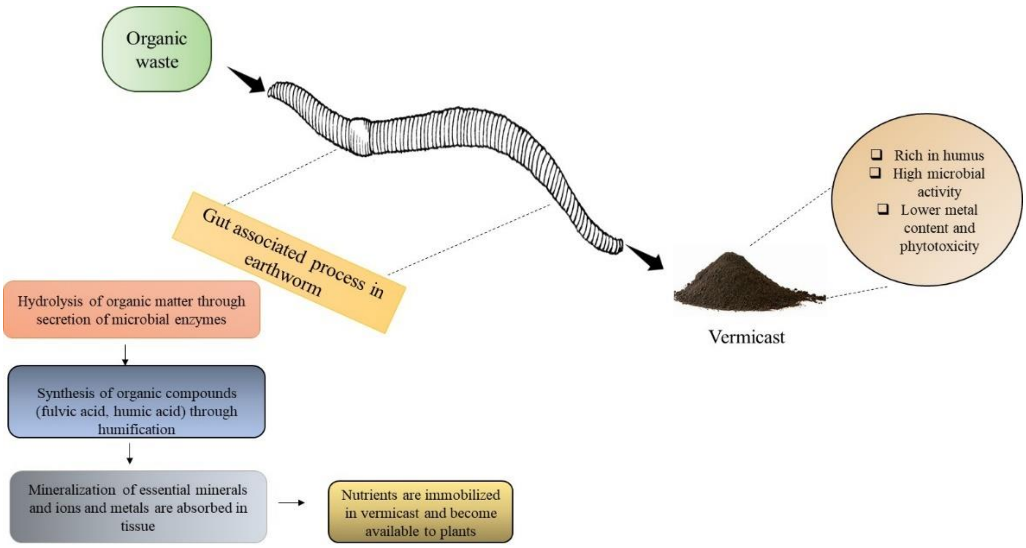

Figure 1. Synergistic action of earthworm and its gut microflora in vermicomposting.

5. Vermicomposting efficiency: Integration of microbial activity and environmental factors

The growth of worms during vermicomposting depends on several crucial factors, such as temperature, feeding, moisture, aeration, pH, and C/N ratio. **Table 1** outlines the key parameters that influence vermicomposting. Feeding is the main factor in vermicomposting, which enhances the reproduction ability of earthworms and the production rate of cocoons (vermicast). Feed percentage also determines the degradation efficiency of earthworms. According to Gupta et al. [32], 60% fly ash feed improved vermicomposting efficiency, but it gradually decreased when the percentage reached up to 80%. Sharma and Garg [26] used different types of feeding substrates like the dung of cows, sheep, horses, and goats fed with organic stocks, which were implemented as the best fertilizers as compared to the dung of camels, buffaloes, and donkeys.

Table 1. Key parameters influencing vermicomposting efficiency.

Parameters	Optimum range	Sources
Temperature	25–37 °C	[26]
Moisture	50%–80%	[4]
pH	5.5–8.5	[6]
C:N ratio	25–30	[33]
Stocking density	1.60 kg worms/m^2	[26]
Feeding rate	1.25 kg feed/kg worm/day	[27]

Moisture level controls vermicomposting productivity, and the optimum range of moisture varies between 50%–80% and is well suited for composting [4]. For example, *Eisenia fetida* requires about 70%–80% moisture content for its growth [34]. However, a high moisture level can negatively impact microbial activity and hinder the growth of earthworms. Similarly, stocking density is another regulating factor that controls vermicomposting by influencing earthworm biomass. It has been observed that the optimum density for better vermicomposting is 1.60 kg worms/m^2 [26]. High population density decreases the copulation frequency of earthworms [35]. Ali et al. [27] reported that *Eisenia andrei* exhibited slow growth under conditions of higher population density.

Vermicomposting efficiency and earthworm sensitivity depend on maintaining an optimum pH range of 5.5–8.5 [6]. pH changes in vermicomposting are influenced by substrate composition, as the decomposition of organic feedstocks gradually lowers the overall pH of the vermicomposting piles [4]. This finding can be further clarified by mineralization and bioconversion of organic materials into CO_2 and intermediate organic acids through microbial decomposition. Excess moisture in organic substrates can reduce the pH level of the composting pile, potentially affecting microbial activity and decomposition efficiency. Furthermore, quality and composition play a significant role in substrate alkalinization throughout the composting process, influencing compost stability and nutrient availability [36]. Song et al. [37] revealed that the pH of the mushroom vermicomposting pile decreased by 9.5% and stabilized at a final pH of 7.6.

In addition to this, the optimum temperature for vermicomposting is maintained at 25–37 °C, which is suitable for earthworms and helps them to improve their activity, growth, metabolism, respiration, and cocoon production [26]. Vermicomposting is non-thermophilic, where temperature is carefully monitored under controlled conditions. Earthworm species residing in vermicompost are susceptible to different temperature conditions. For instance, *Eisenia Fetida* can withstand temperatures ranging from 0 to 35 °C, with optimal growth occurring at 25 °C. On the other hand, *Dendrobaena veneta* can survive in low temperatures but is more susceptible to high temperatures. Similarly, *Eudrilus eugeniae* and *Perionyx excavatus* displayed higher growth rates at an optimal temperature of 25 °C, while they can tolerate a broader range between 9 and 35 °C [6]. The C/N ratio is a crucial factor regulating the growth and development of earthworms. Food waste contains significant proportions of carbon and nitrogen, with an initial C/N ratio of 25–30, which gradually decreases below 20 at the mature stage [33]. This reduction happens due to rapid mineralization and decomposition of organic matter, where carbon is lost as CO_2 through microbial respiration. Meanwhile, nitrogen content increases due to mucus secretion by worms, which is later excreted, lowering the C/N ratio [27].

Microbial communities play a crucial role in vermicomposting, influencing decomposition dynamics and final product characteristics. Studies indicate that bacterial succession throughout the process is closely linked to earthworm species, highlighting their interrelationship with microbes. Understanding this interaction can provide insights into vermicompost quality. Additionally, the microbial composition of earthworms and soil determines the rate of organic matter decomposition. In-depth research on bacterial communities involved in the degradation process is essential for optimizing vermicomposting efficiency. For example, during vermicomposting of Scotch broom (*Cytisus scoparius*), bacterial communities underwent distinct phases of succession. Domínguez et al. [38] categorized them into three groups: bacteria present in freshly cut Scotch broom (day 0), bacteria that passed through earthworm intestine and were excreted (day 14), and bacteria associated with the aging process of worm casts (days 42 and 91). The bacterial composition primarily consisted of Proteobacteria, Bacteroidetes, Actinobacteria, Firmicutes, and Verrucomicrobia. Proteobacteria dominated the early phase but declined after day 14, while other phyla emerged, varying in abundance across different vermicomposting stages. A similar pattern was observed by Kolbe et al. [39] in the vermicomposting of grape marc over 91 days. Significant shifts in bacterial community composition occurred from day 7 to day 91, with increasing taxonomic, phylogenetic, and functional diversity throughout the experiment. Compared to Scotch broom, fresh grape marc exhibited a high abundance of Firmicutes, alongside Proteobacteria. The starting substrate and earthworm species play a crucial role in shaping bacterial diversity and succession. In both Scotch broom and grape marc, initial bacterial diversity was relatively low but increased significantly as vermicomposting progressed.

Vermicomposting relies on the activity of earthworms, which maintain an aerobic environment in vermi beds by facilitating oxygen flow, thereby reducing greenhouse gas emissions. These emissions can be regulated by key factors such as moisture content and temperature. If moisture levels exceed the optimal range, earthworms experience dermal respiration failure, leading to their death. Excessive moisture in vermi beds produces anaerobiosis, promoting the growth of methanogenic bacteria that generate methane. Additionally, nitrous oxide emission increases due to the simultaneous processes of nitrification and denitrification during the mesophilic stage [40]. The denitrification process is facilitated by the gut microflora of worms, including certain fungi and *Nitrosomonas* species, leading to the anaerobic reduction of NO_2^- to N_2O [8]. Besides this, the addition of manure, a source of carbon and nitrogen, as a conditioner in vermicomposting has been reported to enhance greenhouse gas emissions. Studies have observed that composting spent mycelia of *Penicillium notatum* and pharmaceutical sludge from effluent treatment plants resulted in methane emissions ranging from 21.6 to 231.7 μg/m^2 per day, while carbon dioxide emissions increased significantly, ranging from 39.8 to 894.8 mg/m^2 per day. Notably, no live earthworms were found in the vermi beds under these conditions [41].

In addition to the above facts, researchers also have highlighted the advantages of vermicomposting, reporting that the burrowing action of earthworms reduces anaerobic denitrification and lowers the emissions of nitrous oxide and methane (39.0–81.1 g/kg). Additionally, perforations at the bottom of vermi beds allow oxygen to enter, maintaining aerobic conditions and mitigating greenhouse gas emissions during vermicomposting. Earthworm activity enhances methane oxidation through methanotrophic bacteria, which helps stabilize waste and further reduces greenhouse gas emissions compared to traditional composting [42]. The incorporation of reed straw into vermicomposting significantly reduces NH_3 emission [4]. Moreover, earthworms influence microbial abundance in a dual manner, depending on the composition of the starting material.

Vermicompost is predominated with plant-beneficial microbes, which promote plant growth and development. The application of vermicompost enhances soil fertility and structure, supports the propagation of beneficial bacteria, and helps combat toxic pollutants in the soil. These benefits make vermicompost essential for promoting soil health and maintaining ecological balance.

6. Advancement of vermicomposting technology

Vermicomposting is operated under a small-scale domestic system, a large-scale industrial system, a windrow system, and a medium- and high-technology system [8]. Small-scale vermicomposting is more feasible when taking into consideration additional measures like pretreatment of organic substrates, additive supplementation, and optimization of pH and temperature. These factors enhance process efficiency and earthworm activity and improve compost quality. On the other hand, large-scale vermicomposting is a labor-intensive process of manually extracting earthworms, which can hinder the process's efficiency and scalability. In this context, new emerging technology has emerged where earthworms can be easily separated through centrifugation with a high rate of worm recovery (84%) [43]. Vermi-reactors offer a viable technological solution for enhancing the biodegradation process, ensuring optimal parameter control, and facilitating the production of nutrient-rich vermicompost. For example, Ghorbani and Sabour [44] proposed a vermi-reactor that reduces composting time by 50% while simultaneously increasing worm growth by 30% compared to conventional containers. Additionally, large-scale vermicomposting can be enhanced by integrating thermal cameras instead of traditional temperature monitoring sensors and machine learning-controlled microcontrollers for efficient water supply [33]. These advanced technologies could optimize the composting condition and improve overall process efficiency. Furthermore, incorporation of additives such as zeolites, biochar, vermiculites, and ashes enhances microbial activity during vermicomposting, improving soil nutrient dynamics and compost quality [33].

Vermi-reactors are constructed with plastic materials designed with several compartments with the same dimensions (length, width, and height), which are perforated at the bottom for easy circulation of earthworms from one chamber to another during decomposition (**Figure 2**). This setup facilitates earthworms thriving in the substrate layers. Earthworms are introduced into the substrate layer appropriately so that younger ones reside over the older ones, depending on vermicomposting time and maturity. The vermi bed of this reactor is filled with earthworms and vermicompost to protect earthworms from the environmental shock [45]. Earthworms migrate from the bedding material to the fresh waste compartment and aid in decomposition along with its associated symbiotic microbes. New waste biomass of the same amount will be added into the waste chamber at certain time intervals [46]. At the end of vermicomposting, the entire material of the vermi-reactor will be unloaded, separated, and packaged for further agricultural application. Vermicomposting also can be carried out as either a continuous or batch process, depending on operational preferences and efficiency goals. In the batch process, feeding materials are added only once at the beginning of the experiment. The waste material is then left for twelve months to undergo biomass conversion into vermicompost. Batch vermi-reactors can be made of plastic, concrete, or wood. Batch systems processing fresh, non-pre-composted waste tend to produce vermicompost with lower macronutrient availability, whereas those utilizing pre-composted substrates yield significantly higher nutrient concentrations [47]. Additionally, wooden batch vermicomposting reactors have proven effective in biomass waste treatment. In a batch experiment utilizing a rectangular plastic vermi-reactor to process banana waste, which had undergone three weeks of pre-composting before 105 days of vermicomposting, researchers observed significant nutrient variations. Nitrogen content across different reactors ranged from 30.76% to 102.41%, phosphorus levels varied between 16.05% and 37.14%, while potassium concentrations increased from 13.1% to 25.85% following vermicomposting [48]. The rise in nitrogen, phosphorus, and potassium in the vermicompost was attributed to enhanced earthworm activity, extracellular enzyme production, and the secretion of nitrogenous compounds [8]. However, a major limitation of batch-scale reactors is the buildup of anaerobic conditions due to the stacking of waste materials, which can lead to earthworm mortality. Additionally, operating batch-scale vermi-reactors is labor-intensive.

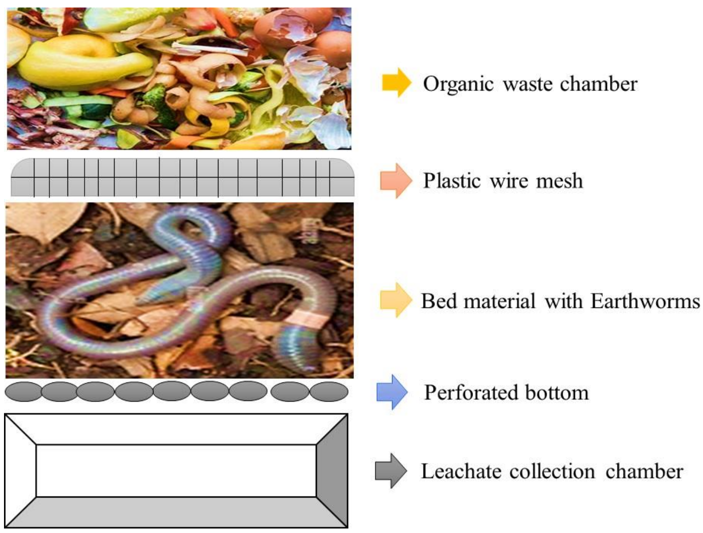

Figure 2. Diagrammatic representation of a small-scale vermi-reactor for vermicomposting.

The continuous feeding system efficiently contributes to waste valorization, enhancing the nutrient content of vermicompost in both plastic and metallic reactors. Pre-composting before vermicomposting significantly reduces waste biomass while improving microbial activity, earthworm viability, and reproductive ability [8]. Santana et al. [49] reported that in a continuous metallic vermi-reactor, grape marc underwent vermicomposting following a 720-days pre-composting period. The study observed an increase in nutrient content, with nitrogen content at 39.42 ± 2.84 g/kg, phosphorus at 3.71 ± 0.99 g/kg, and potassium at 15.62 ± 4.40 g/kg in the final vermicompost. Zziwa et al. [50] also found that pre-composting pineapple peel for three weeks and cattle manure for one week before vermicomposting influenced the nutrient composition of the processed waste. Over a 60-days period, the continuous system exhibited higher nutrient retention and greater earthworm biomass compared to the batch system. Specifically, the continuous system retained 91.2% phosphorus, 32.6% nitrogen, 79.3% potassium, and 46.1% carbon, whereas the batch system retained 24.2% nitrogen, 90.4% phosphorus, 67.5% potassium, and 41.1% carbon. Based on these findings, the authors recommend continuous vermicomposting as a more effective method for processing pineapple waste. The continuous feeding system enhances organic waste stabilization during vermicomposting while allowing new substrate layers to be added to existing ones. This approach facilitates the assessment of earthworms' contribution to waste stabilization by analyzing the chemical and microbiological properties of the treatment system [8]. **Table 2** presents additional findings on batch and continuous-scale vermicomposting, highlighting its effectiveness in achieving high nutrient recovery.

Table 2. Assessing nutrient enhancement in batch and continuous Vermi-reactors.

Reactors	Treatment process	Waste type	Pre-composting	Earthworm species used	Nutrition content	Sources
Continuous feeding vermi reactors (40 cm × 40 cm × 18 cm)	Continuous substrate fed-batch process	Apple pomace, Digestate, Grape pomace	-	*Eisenia andrei*	Nitrogen content was increased with increased duration of vermicomposting	[46]
Continuous feeding vermi composter	Continuous feeding type	Spent mushroom substrate	-	*Eisenia andrei*	Phosphorous (676 ± 95 mg/kg); potassium (16,834 ± 693 mg/kg) content was found high.	[51]
Metallic vermi reactors (1.5 m × 4 m × 1 m)	Continuous process	Grape marc	-	*Eisenia andrei*	Nitrogen (39.42 ± 2.84 g kg^{-1}); phosphorous (3.71 ± 0.99 g kg^{-1}); potassium (15.62 ± 4.40 g kg^{-1}) content increased at the end of vermicomposting	[49]
Earthen vermi composter (0.45 m × 0.15 m × 0.30 m)	Batch process	Vegetable kitchen waste, cow dung and paddy straw	5 days	*Eudrilus eugeniae*, *Eisenia fetida*, *Perionyx excavatus*	Nitrogen content increased up to 5.86–6.67 folds; phosphorous content increased by 5 folds and potassium content was increased by 4.3 folds	[52]
Plastic buckets (50 L capacity with 0.52 m in diameter and 0.63 m in height)	Batch scale	Pineapple waste and cattle manure	3 weeks	*Eudrilus eugeniae*	Nitrogen content (24.2%); phosphorous content (90.4%) and potassium concentration (67.5%) was found	[50]

Table 2. (*Continued*).

Reactors	Treatment process	Waste type	Pre-composting	Earthworm species used	Nutrition content	Sources
Plastic containers (52 cm × 68 cm × 39 cm)	Batch scale	Garden waste, spent mushroom and cattle manure	21 days	*Eisenia fetida*	45.5%–77.8% of nitrogen content; 29.2%–68.3% of phosphorous; 45.1%–92.9% of potassium content was increased during vermicomposting	[53]
Wooden vermibeds (0.65 × 0.60 × 0.25 m^3)	Batch scale	Food, paper and yard waste	14 days	*Eudrilus eugeniae*	-	[54]
Cement pots (10 kg capacity)	Batch scale	Vegetable waste, leaf litter, maize strover	45 days	*Eudrilus eugeniae*	Total nitrogen content (1.43%–1.99%); phosphorous content (0.82%–2.10%) and potassium content (1.1%–1.8%) of vermicompost was increased	[55]

7. Advantages of vermicomposting technology

Vermicomposting actively contributes to multiple benefits, categorized into physical, chemical, and biological aspects. As a soil conditioner, vermicompost improves water-holding capacity, fertility, and bulk density [56, **Figure 3**]. Additionally, it enhances soil chemical properties by optimizing pH, cation exchange capacity, and organic matter content. Furthermore, it has been reported that vermicompost produced from food waste is enriched with organic matter, phosphorous, nitrogen and micronutrients that improves microbial activity and stimulates plant growth [56]. Beyond its role as an organic amendment, vermicompost exhibits biocontrol potential, surpassing traditional compost in effectiveness. Research suggests that vermicompost application significantly reduces disease occurrence in crops by suppressing soil-borne pathogens such as *Fusarium, Acanthamoeba*, and *Verticillium dahlia* [57]. Studies indicate that vermicompost enhances microbial diversity, which competes with harmful pathogens, leading to a 70% reduction in disease incidence in crops like tomato, melon, and asparagus [6]. Additionally, a meta-analysis by Blouin et al. [58] revealed that vermicompost application increased crop production by 26%, overall biomass by 13%, and root and shoot biomass by 57% and 78%, respectively.

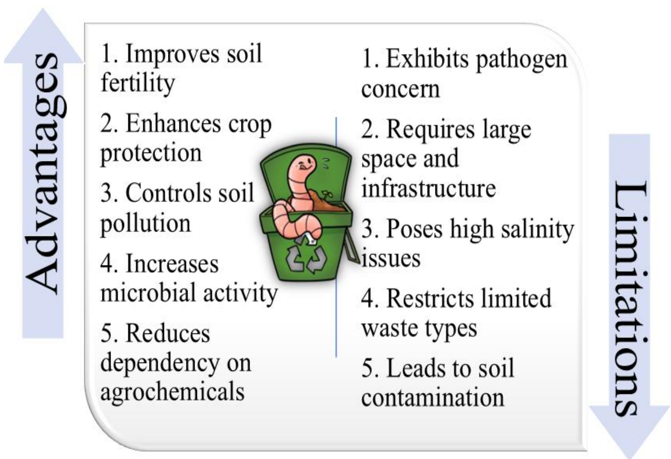

Figure 3. Advantages and limitations of vermicomposting.

Researchers have revealed that a 25% application of vermicompost increased nitrate-N concentration to 580 mg kg^{-1}. This value doubled to 1001 mg kg^{-1} when vermicompost application reached 100%. In addition to this, it is established that vermicompost addition enhances electric conductivity (EC) and dehydrogenase activity. Conversely, NH_4^+ content become decreases after application of vermicompost [56]. Thus, vermicompost is become an adorable option to increase the plant growth promoting attributes of soil. The microbial community in vermicompost, particularly bacteria, fungi, and actinomycetes, enhances nutrient availability by converting phosphates, nitrates, calcium, and potassium into accessible forms for plants [25]. Additionally, earthworms produce phytohormones such as auxin and cytokinin, which stimulate plant growth and development. The humus content in vermicompost plays a crucial role in the synthesis of flavonoids and anthocyanins, significantly promoting plant growth while inhibiting phytopathogens [59]. Earthworms have the ability to secrete enzymes, efficiently transforming waste into stabilized vermicompost. After vermicompost production, they introduced as natural soil drillers, enhancing soil porosity, promoting aggregate formation, and improving soil nutritional status [4]. In addition to this, heavy metals in waste materials tend to aggregate with humic acids, forming polymerized fractions. This process can help reduce contamination by stabilizing heavy metals and limiting their mobility in the environment. Value addition to vermicompost leads to the production of vermicompost tea, which serves as a liquid biofertilizer and enhances plant disease resistance [33].

8. Challenges and limitations of vermicomposting technology

Vermicomposting plays a crucial role in waste recycling and resource recovery, promoting sustainable waste management. However, certain critical factors need to be addressed for improving the efficiency of vermicomposting. Several greenhouse gases are produced from vermicomposting that not only hamper environmental health but also lead to loss of nutrients and energy [60]. Besides this, vermicomposting faces challenges such as phytotoxic substances and low decomposition quality, while high saline content of vermicompost can limit its effectiveness as an organic fertilizer [61, **Figure 3**]. The microbial activity and quality of the final product are significantly affected by the composition of substrates and unsuitable composting environments. For instance, kitchen waste often contains highly oily and saline materials, making degradation challenging. To improve decomposition efficiency, co-vermicomposting kitchen waste with vermicompost is recommended [6]. Lim et al. [62] reported that salinity issues in vermicomposting can be mitigated by adjusting physicochemical factors and optimizing the substrate ratio.

The key constraint of vermicomposting is its inability to remove pathogens, as it lacks the thermal sanitation phase. To address this issue, high-temperature composting is necessary to reduce pathogen contamination before vermicomposting. Pre-composting at the thermophilic stage (60 ℃), effectively eliminates pathogens, ensuring a safer final product. Additionally, incorporating organic matter from this stage into the vermicomposting pile enhances decomposition efficiency while reducing costs and processing time [57]. Moreover, the incorporation of metallic species in vermicompost can subsequently damage soil health and contaminate food chains. They interrupt soil structure; for example, high sodium content renders microbial death and soil erosion. Additionally, toxic metals like lead can deteriorate soil quality. Therefore, extensive research is needed to address the challenges posed by immature and contaminated vermicompost [25]. Additionally, the marketing and application of vermicompost face several challenges, including the slow release of nutrients compared to chemical fertilizers, which makes farmers hesitant to adopt vermicomposting at the field scale. Additionally, large-scale production encounters difficulties due to limited availability of organic waste and water supply. Moreover, high transportation costs further burden the feasibility of this technology [6,25]. To address these bottlenecks, financial and policy support, along with stronger promotion efforts, are essential. Additionally, clarifying the optimal quantity of vermicompost application is crucial, as studies indicate that a 10%–50% application is beneficial, whereas excessive use may lead to adverse effects [63].

9. Harnessing vermicomposting in circular bioeconomy system

Vermicomposting is a conversion technology that transforms food and organic waste into nutrient-rich compost for plants. The by-products generated from this process contribute to the circular bioeconomy by closing material loops and adhering to cleaner production principles for sustainable waste management (**Figure 4**). Its primary goal is to promote global sustainability by minimizing environmental burdens [64]. Vermicompost provides an alternate solution to agrochemicals to increase crop productivity and soil fertility. It is considered the best waste management strategy with multiple benefits. Vermicomposting provides a sustainable alternative to agrochemicals, enhancing crop productivity and soil fertility while promoting waste recycling. As a key component of the circular bioeconomy, it transforms organic waste into nutrient-rich compost, reducing environmental impact and supporting regenerative agricultural practices [6]. Additionally, the end product, earthworm biomass, consists of approximately 60%–70% protein, along with essential amino acids such as niacin, lysine, methionine, and phenylalanine, as well as vitamins, including B12 [3]. These nutritional properties make them highly suitable as feedstocks for both aquaculture and poultry farming. For instance, in Japan, more than 3000 vermicomposting facilities provide earthworms as fish feed for intensive eel aquaculture systems (*Anguilla japonica*) [3]. In the current scenario, biological pre-treatment processes such as vermicomposting have gained attention as an economically viable technology for biogas production. Food waste primarily consists of lignocellulosic materials, including cellulose, hemicellulose, and pectin. Pectin is particularly difficult for microorganisms to degrade during anaerobic digestion [65]. Therefore, enzymatic hydrolysis is required to break down organic materials. Earthworms secrete hydrolytic enzymes to decompose the organic matter and reduce the recalcitrance of organic feedstocks. The consecutive action of two enzymes, like pectinase and N-acetyl-D-glucosaminidase, facilitates the hydrolysis of pectin and N-acetyl-D-glucosamine, respectively, thereby increasing methane production. Chen et al. [65] reported that methane production was significantly higher (63%–65%) in the co-digestion process of corn stalk with vermicompost compared to the digestion of corn stalk alone. Vermicomposting enhances cellulose degradation, improves biogas production, and offers a new perspective for biofuel generation and environmental sustainability. The by-product of biogas production is known as biogas slurry. Yadav and Garg [66] utilized biogas plant slurry as an amendment and nutritional source for earthworms in vermicomposting. This aligns with circular bioeconomy principles by repurposing discarded materials from biogas plants, enhancing sustainability and resource efficiency. India is a leading country in vermicomposting implementation. For example, in Maharashtra, solid waste from temples has been successfully decomposed through vermicomposting, turning it into a profitable venture [67]. However, factors such as substrate availability, compost quality, processing costs, and transportation influence profitability. Despite these considerations, the financial returns from vermicomposting have been remarkable, with selling prices ranging from Rs. 155,325 to Rs. 171,057.63 per ton [68].

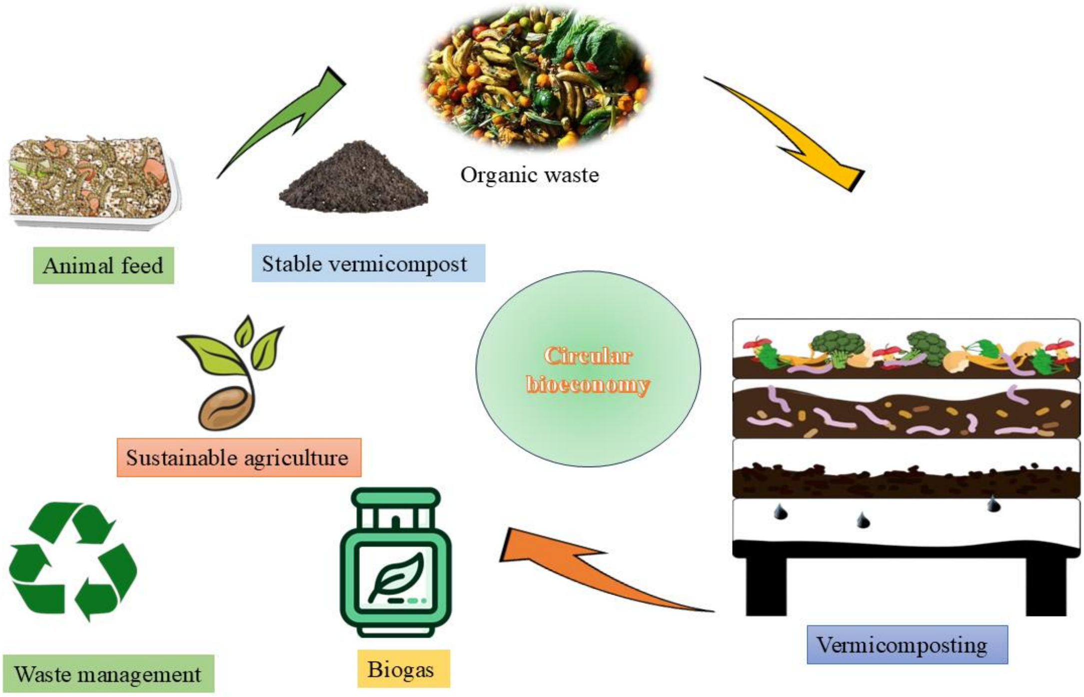

Figure 4. Role of vermicomposting in waste management and the circular bioeconomy.

10. Future perspective

The foresight of a circular bioeconomy has the efficacy to significantly mitigate climate change through composting technology. The vermicomposting process should be empowered by industrial infrastructure, which can create job opportunities and contribute to national economic growth [69]. Additionally, advanced technology of vermicomposting is also accessible for bioremediation. It has the potency to remove various pollutants like pesticides and polycyclic hydrocarbons from soil. The role of microorganisms in vermicomposting presents a promising avenue for further research in bioremediation [70]. Further investigations are needed to explore the key aspects, including the composition of bacterial communities, vermicompost quantity, its impact on heavy metal content, plant pathogens, diseases, and organic waste selection. In-depth analysis should focus on enhancing vermicomposting efficiency, developing pollutant control strategies, and advancing vermicompost utilization. Key research directions include the formulation of additives, the application of mathematical models, and the design of vermi-reactors. The widespread adoption of vermicomposting relies on technological advancements, increased public awareness, and the establishment of unified standards.

11. Conclusion

This review elucidates the potential of vermicomposting in enhancing food waste management, promoting agricultural sustainability, and supporting bioremediation, thereby contributing to a circular bioeconomy. Additionally, it explores economic opportunities, technological advancements in vermicomposting, and its role in mitigating climate change. Earthworms and their associated microbiota play a crucial role in neutralizing waste materials, while biogas production during vermicomposting serves as an auxiliary biofuel resource. One of the most notable advancements in this field is the vermi-reactor, which is being explored to enhance vermicomposting efficiency. Understanding the mechanisms by which vermicomposting factors influence pests and disease suppression is crucial for stimulating their effectiveness and integrating them into eco-friendly, sustainable crop production systems. Additionally, optimizing the production and utilization of vermicast products while ensuring food safety is vital for enhancing crop quality. By incorporating circular bioeconomy indicators, closed-loop systems, and circular models, vermiculture minimizes waste leakage while creating job opportunities and increasing profitability. Recycling and regeneration technologies transform the linear economy model into a circular one, with vermicomposting by-products utilized as animal feed and valuable products. Despite its benefits, several uncertainties remain that require further investigation and optimization to maximize the effectiveness of vermicompost products in sustainable agriculture. Addressing these knowledge gaps will improve the understanding of key variables and parameters in vermicomposting, ultimately enabling broader application and utilization of vermicompost products.

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