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A Review on Optimizing Organic Waste Management and Income Generation through Vermicomposting and AI-Powered Vermicomposting: Insights from Guwahati, Assam

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ABSTRACT

Urban India faces significant challenges in managing organic waste due to limited disposal facilities. Guwahati, a city in Northeast India, illustrates the potential of converting municipal solid waste (MSW) into energy. With an MSW generation rate of 0.7 kg per capita per day, the city could generate up to 30 MW of power. Guwahati's waste, which is 42.2% organic, is well-suited for composting. Composting, particularly through vermicomposting, offers a cost-effective solution supported by regional demand for organic fertilizer. This eco-friendly method not only diverts waste from landfills but also produces nutrient-rich manure, promoting sustainable agricultural practices and improving the city's waste management system.

This paper examines municipal solid waste (MSW) management in Guwahati city, emphasizing vermicomposting as an eco-friendly solution for household organic waste. By diverting waste from landfills, vermicomposting not only enhances sustainability but also fosters micro-entrepreneurship. Additionally, the paper explores how integrating Artificial intelligence (AI) into vermicomposting is a promising advancement, offering the potential to optimize processes, increase productivity, and improve compost quality. It describes traditional vermicomposting practices and the integration of AI-powered technologies for enhanced efficiency. This is an effort to explore how use of AI-driven systems invite improvement in composting conditions, boost productivity, and support small-scale farmers.

Keywords: Artificial Intelligence Deep Learning, Machine Learning , Vermicomposting, Waste Management.

1.INTRODUCTION

The rapid increase in global population has escalated two major challenges: food production and waste management. One of the most visible effects of fast-paced urbanization and economic growth is the accumulation for MSW i.e. Municipal Solid Waste [1]. The inefficiency of local authorities in managing this waste has worsened the situation. According to study [2], food and organic waste account for 32% of the total waste of high-income countries, 53% in middle-income countries, and a striking 57% in low-income countries. Moreover, while 51% of waste is recyclable in developed nations, only 20% of waste in low-income regions can be recycled, highlighting the critical need for improving the management of organic waste in such areas [2].

At present, one of the major global challenges is the evolving issue of waste management. In 2000 Ascia generated more than 3 million tons of solid waste, and projections suggest that this amount cloud rise to almost 9 billion tones within 2050. Before 1998, the region produced 0.76 MSW per day. Developing nations saw their MSW increase at a rate of 2-3% annually, while developed countries experienced even sharper growth, ranging from 3.2% to 4.5% [3]. These trends underscore the mounting pressure on waste management systems across Asia.

Indian cities generate approximately 0.115 million metric tonnes of waste daily, equating to 42 million metric tonnes annually [4], which is reported by PIB, 2016 as to 62 million tonnes per year already. Waste production has increased by 50% in the past decade and continues to rise, with the potential for a 70% surge. Per capita waste generation, currently between 0.2 and 0.6 kg per day, is growing by 1.3% annually due to urbanization and economic growth. By 2047, waste generation is projected to surpass 260 million tonnes annually (TERI). Larger cities, home to over 0.1 million people, contribute 72.5% of the total waste, while smaller urban centers generate only 17.5%. MSWM (Municipal solid waste management) in India is still largely focused on collection and disposal, with little emphasis on processing or treatment.

MSW generation in the North-Eastern part of India is increasing at 3% annual rate (Ministry of New and Renewable Energy, 2017-18). In Assam alone, MSW production amounts to approximately 1,124 tons daily (Assam Urban Solid Waste Management Policy Report, 2018).

In Guwahati, the gateway to North-East India, solid waste generation is approximately 550 tons per day, with a weight density ranging from 41 to 327 kg/m³ (Assam Urban Solid Waste Management Policy Report, 2018). This figure is concerning, highlighting the urgent requirement of effective SWM i.e. Solid Waste Management in the city. Due to increasing rate of population and economic development, the volume of waste rises rapidly, putting increasing pressure on local authorities and policymakers to discourse the issue. Furthermore, Guwahati has the potential to generate about 30 Mega-Watt of power from its solid waste, presenting a scope to transform this challenge into a resource for sustainable energy.

Given the high organic and moisture content of Guwahati's municipal solid waste (MSW), composting emerges as an efficient and eco-friendly treatment option. The surrounding areas have a strong demand for organic fertilizers, bolstered by government efforts to promote traditional farming practices in the North-East. Composting, compared to other waste treatment technologies, requires lower capital investment and operating costs, making it a practical choice [5, 6, 7]. Both centralized and decentralized composting systems can offer sustainable solutions.

Using kitchen waste as the fuel for the vermicompost process means that a certain quantity of waste is diverted from the waste stream. This is an environmental benefit in that less waste goes to the landfill.

Recently, automated systems that utilize artificial intelligence technology for efficient vermicompost generation have gained popularity. These systems are designed to create optimal conditions for composting by precisely managing humidity and temperature. By collecting and analyzing relevant data, these automated solutions help maintain ideal pit conditions, ultimately enhancing the composting process. This noble tactic streamlines vermicomposting as well as ensures a higher quality of organic fertilizer, contributing to more sustainable waste management practices.

In summary, this paper offers a comprehensive overview of generation of waste along with the related challenges met by Guwahati city. It also examines the advantages of vermicomposting as a viable waste management solution and highlights the integration of artificial intelligence technologies with vermicomposting methods to enhance efficiency and effectiveness in waste management practices.

2.MATERIALS AND METHOD

A comprehensive review of vermicomposting-related research, primarily original studies, was conducted based on several key criteria. These included the origin, sources, and generation of waste in relation to Guwahati city, along with various waste management strategies such as waste-to-energy initiatives and composting. The review also covered the benefits of functional compost, eco-friendly vermi-transformation technologies, and the selection of suitable earthworm species for vermicomposting. Additionally, it explored the role of artificial intelligence in enhancing vermi-technology, the economic aspects of vermi-biotechnology for sustainable SWM, and the contribution of earthworms in managing waste and environmental sustainability.

3.MANAGEMENT OF SOLID WASTE IN GUWAHATI CITY

Guwahati is the largest city in North-East India. It is a country's fastest-growing urban areas and is situated at a latitude of 26° 11' North and a longitude of 91° 44' East. The city experiences a generally cool and dry climate, with a mean air temperature of 24°C, a mean maximum of 42°C, a mean minimum of 5°C, and an annual precipitation of approximately 1,800 mm. According to the latest census from 2011, Guwahati has a population of 1.8 million spread across 320,000 households, resulting in an average population density of about 6,047 inhabitants per km² (Census of India, 2011).

However, the city faces significant waste management challenges, with municipal solid waste accumulating on the streets due to ineffective disposal systems. Many residents clean their homes and litter their immediate surroundings, which negatively effects to their own communities and neighbors. The Guwahati Municipal Corporation (GMC) oversees 60 wards within its 296 km² jurisdiction, supported by 26 non-governmental organizations (NGOs) that assist in daily waste collection. Currently, the city generates around 800 metric tonnes of MSW each day [8].

Waste collection is carried out by the GMC, which manages both primary and secondary collection processes. Primary collection involves door-to-door waste collection, with source segregation into wet (biodegradable and inert) and dries (recyclable) waste. After this initial collection, waste is transported to the nearest community bin or transfer station using tricycles and mini-tipper trucks. The secondary collection process involves the collection of MSW from community bins, storage depots, and transfer stations using garbage compactor trucks. Thanks to a strong local awareness of solid waste management (SWM), a commendable amount of source-segregated waste is collected from households, reflecting the community's engagement in addressing waste management.

In Guwahati, several local non-government organizations (NGOs) play a significant role in primary waste collection, also generating employment scopes for local residents. However, a significant issue arises during the secondary waste collection phase, where all waste is combined and placed into a single community bin, as there are no separate bins for segregated waste. This leads to a lack of effective waste segregation practices, with waste being stored in general dustbins designed for this purpose. Waste collection occurs regularly and is facilitated using various vehicles, including tractors, trucks, tippers, and hand carts. Unfortunately, the city currently lacks proper waste treatment and sorting facilities, resulting in all waste being dumped at the Boragaon dumpsite, which operates as an open dumping ground. This method of disposal allows biodegradable materials to decompose in uncontrolled and unsanitary conditions, leading to several environmental and health issues. The open dumpsite emits foul odors and creates breeding grounds for various insects and pathogens, contributing to the spread of vector-borne diseases. Additionally, the release of toxic gases from decomposing waste poses serious health risks to the local population, further compromising the quality of the environment. This situation highlights the essential necessity for improving the practices of waste management, including proper segregation, treatment, and disposal systems in Guwahati [9].

In the study [10] highlights the significant challenge that Guwahati faces due to the escalating generation of municipal waste; a concern shared by many urban areas. Her research explores public preferences of services offered by ISWM (Integrated Solid Waste Management) compared to collection of local waste and their disposal options. Dutta recommends implementing a Public-Private Partnership (PPP) model involving NGOs and community organizations to enhance waste disposal services.

Similarly, the case study [11] highlighted the critical importance of solid waste management in Guwahati in their study “Municipal Solid Waste Management in Guwahati – A Case Study”. Utilizing a Logistics regression model, it has been observed that residents were ready to bear an expenditure of approximately ₹60.22 for improving the services of management of waste. The residents also support the Public-Private Partnership (PPP) approach as a viable solution to the ongoing waste management challenges in Guwahati.

Moreover, another study [12] argue that every component of solid waste can be transformed into a valuable product through appropriate scientific methods, underscoring the potential for innovative solutions in waste management practices. Together, these studies emphasize the need for collaborative approaches and scientific techniques to address the pressing waste management issues in Guwahati effectively.

Introducing various techniques for recycling and treating waste materials at their source can yield numerous socio-economic and environmental benefits [13, 14]. Organic food waste, in particular, is a renewable energy production resource, such as biogas [15]. Biological processes like composting and vermicomposting have been widely employed for converting organic waste into a resourceful soil amendment [16]. Currently, the application of vermicomposting techniques regrading conversion of organic waste into organic fertilizers with high-quality is being reported globally [17, 18].

Organic wastes, including animal manure [18], biosolids [19], and kitchen waste [20] can be transformed into nutrient-rich organic fertilizers containing essential elements like nitrogen (N), phosphorus (P), and potassium (K) by vermicomposting technology. This strategy not only improves soil fertility but also supports sustainable agricultural practices and waste management efforts.

Researchers at IIT-Guwahati have pioneered a novel two-stage biodegradation technique that offers a long-term solution for managing organic waste. This innovative method enables municipal corporations and governing bodies to handle organic waste in an environmentally friendly manner while also producing high-quality vermicompost and organic compost enriched with nitrogen, phosphorus, and potassium (NPK) and other essential micronutrients for agricultural use. Significantly, this technique reduces the biodegradation time to just 27 days, yielding vermicompost with a total nitrogen content of 4.2%. This is a remarkable improvement compared to the standard biodegradation period of 45 to 60 days. Additionally, the process effectively decreases the amount of waste by 71%, showcasing its potential to enhance urban waste management methods while promoting sustainable agriculture [21]. Figure 1 shows a typical solid waste management system in Guwahati city :

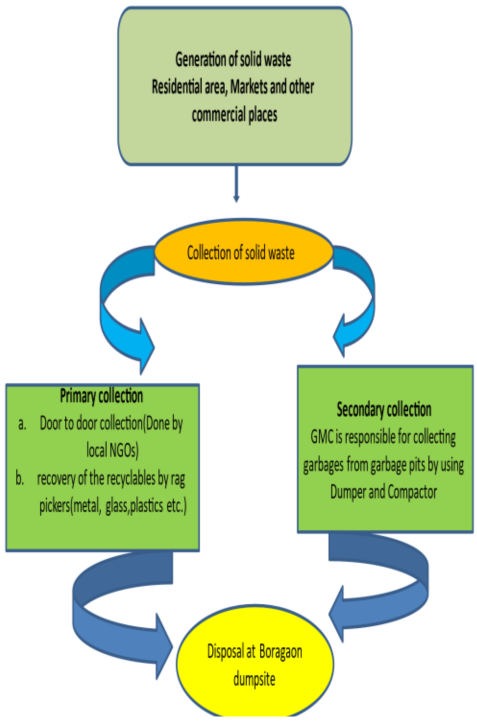

Figure 1: Solid Waste Management System of Guwahati

Waste generation per day in Guwahati city from different sources has been shown in the Table 1 given below:

Table 1: Waste generation in Guwahati City

Sl. No	Source	Unit Generate per day	Total Waste (Tones/Day)
1	Domestic Source	2.66 Kg/House hold	490.64
2	Markets	3.0 Kg/Unit	4.72
3	Commercial Establishment	1.62 Kg/Unit	62.97
4	Hotels and Restaurant	83.89 Kg/Unit	11.4
5	School and Institutions	2.5 Kg/Unit	2.5
6	Street Sweeping and drain Cleaning	---------	48.00
7	Others	---------	6.61
Total waste generated per day			626.84

4.AN OVERVIEW ON VERMICOMPOSTING

Vermicomposting is an eco-friendly waste management method that breaks down the organic portion of waste materials into a stable, easy-to-handle form which may be applied to agricultural fields without causing harm [22,23,24]. This process involves both earthworms and microorganisms working together under controlled conditions, leading to non-thermophilic breakdown of organic materials [25,26,27,28,29]. Earthworms serve a crucial function in conditioning the waste and influencing biological activity, while microbes carry out the biochemical degradation. This low-cost technology is particularly effective for treating organic waste [30,31]. The process is especially useful to handle MSW due to its ability to safely decompose large amounts of organic material [22]. It is regarded as a cost-effective, rapid, and viable method for utilizing organic waste and crop residues. Earthworms act like mechanical blenders, disintegrating organic matter and modifying its physical, chemical, and biological characteristics such as reducing its carbon-to-nitrogen (C: N) ratio. They enhance the area of surface the waste, rendering it more accessible to microbes, which accelerates decomposition [32,33,34]. Vermicomposting is faster than traditional composting as earthworms processes the material through their digestive systems. The resulting worm castings, or vermicompost, are rich in plant growth hormones, microbial activity, and offer natural pest-repellent qualities [35].

Vermicomposting is increasingly emerging as a favored approach for recycling organic waste and has been tested in numerous countries for a variety of purposes and operational scales. It is explored for managing municipal solid waste in Argentina [36,37], the Philippines [38], India [39, 40, 41], and Spain [42]. Vermicomposting offers a viable approach to waste management, rural advancement, and eco-friendly agricultural improvement by utilizing earthworms' digestive processes to convert waste into valuable resources.

The benefits of vermicomposting are plentiful. As a waste management method, it reduces the volume of organic waste by about 50% [43], is safe, hygienic, and adaptable to varying scales of waste volumes [44]. Research suggests it is often preferable to traditional composting, more significant reduction of heavy metals [44], offering faster decomposition rates [45], better pathogen stabilization, and minimal odors [46].

Changes in the structure and function of bacterial communities during the vermicomposting of coconut leaves has been observed [47]. Investigation has been made [48] also for the conversion of leaf litter into valuable compost through vermicomposting. Study [49] reviewed the bioavailability and fate of heavy metals during the vermicomposting of different organic wastes. Comparetive study made by [50] on the quality of vermicompost generated from rice straw and paper waste using the earthworm Eisenia *fetida*. [51] emphasized the role of vermicompost as crucial for sustainable agriculture. Study [52] highlighted how changes in bacterial communities during vermicomposting contribute to its beneficial properties.

Study [53] explored vermicomposting of a mixture of citronella bagasse and paper mill sludge using *Eisenia foetida*. The environmental and food security impacts of vermicomposting technology were examined by the study [54]. The study [55] reported that vermicomposting with *Eisenia fetida* enhances soil nutrient content. It is reviewed by the study [56] about vermicomposting methods as an eco-friendly, economically viable, and socially accepted method for crop nutrition. Again, from the study [57], vermicomposting is found as an implement for solid waste management, while the study [58] reviewed the role of vermicompost and vermicompost tea in sustainably managing crop diseases and pests.

Recently the study [57] highlighted the growing interest in using vermicomposting to process the organic fraction of municipal solid waste (OFMSW) in urban areas. With evolving regulations, such as the European Union's 2018 mandate to treat OFMSW as a resource by 2023, there is a requirement for environmentally friendly processes suited to urban environments, considering challenges like high population density and pollution. Although limited research has concentrated on the agronomic potential of vermicompost from OFMSW, research on vermicompost from manures has shown promising results. These include improved plant growth [59, 60], the development of beneficial bacteria [61, 62, 43], and reduced plant diseases and pest infestations [63, 64, 65]. Vermicompost also enhances soil quality by reducing bulk density, increasing porosity and water retention, and improving aeration [66, 67]. A meta-analysis further revealed that adding manure-based vermicompost boosts crop yield and total biomass [68].

4.1 Various Stages in the Vermicomposting Process

The vermicomposting process primarily occurs in the mesophilic temperature range (20-35°C) and consists of four stages:

4.1.1Precomposting Stage

This initial stage prepares organic waste for worms by making it semi composted, reducing toxicity, and eliminating harmful substances like heat, salts, ammonia, and pesticides. The waste is composted naturally for 3-4 weeks, allowing decomposable compounds to break down and volatile substances to dissipate, making it safer for earthworms [69, 70].

4.1.2Mixing Stage

In this stage, different organic materials are combined to make the feed more suitable for earthworms or to enhance vermicompost quality. For instance, crop residues that contain with high cellulose can be mixed with nitrogen-rich animal dung. Some waste materials, like sludge from paper or sugar mills, can be unfavorable for worms in their raw form but become acceptable when blended with other organic matter [71,72,73]. This step can be skipped if the original waste is already favorable for the worms.

4.1.3Vermicomposting Stage

This is the core phase, lasting 8-10 weeks, where worms feed on the waste in bins or beds, enhancing microbial activity and decomposing the material. During this time, biochemical and physical changes, such as adjustments in pH and nutrient content (NPK), take place. Proper moisture and temperature are critical for maximizing worm activity [73].

4.1.4 Maturation Stage

In this final stage, the vermicompost stabilizes and matures over 3-4 weeks. The quality of vermicompost depends on its maturity, with mature compost offering a balanced nutrient profile (N, P, K) and lower C/N and C/P ratios, which facilitate slow nutrient release. Immature compost with higher ratios may hinder microbial growth and slow down decomposition [74].

4.2 Role of Earthworms in Vermicomposting

Earthworms are key players in the vermicomposting process, serving multiple roles as aerators, grinders, crushers, and decomposers of solid waste [75,76,77]. Their burrowing activity creates aeration channels, which significantly improves oxygen distribution throughout the waste material.

When earthworms consume organic matter, they undergo a mechanical breakdown of the waste in their muscular gizzard, reducing the size of the material by approximately 25-30% [78,79]. This initial mechanical processing is followed by digestion in the intestines, where various enzymes from both the earthworms and the microorganisms they ingest further decompose the organic matter [80]. This process increases the surface area of the waste, thereby facilitating greater microbial activity.

As the vermicomposting process progresses, complex organic compounds are restructured into simpler forms, enhancing the presence of vital nutrients such as nitrogen, phosphorus, and potassium (NPK) for plant uptake [81].

Additionally, earthworms establish a mutualistic relationship with the microorganisms in their gut, which aids in breaking down the organic matter present in their diet [82]. Consequently, the nutrient-rich quality of vermicompost emerges from the synergistic interactions between earthworms and microorganisms, significantly increasing its effectiveness as a fertilizer:

4.2.1Earthworms

Over 4,000 species of earthworms have been recognized, which may lead to broad categorization into three categories: **epigeic, anecic, and endogeic**. Researchers have explored the vermicomposting potential of earthworms from all three categories. Currently, the Indian subcontinent is home to 509 earthworm species, categorized into 67 genera and 10 families [83]. Earthworms in ecological terms are classified according to their capacity to make burrows and the intricacy of burrows:

- Epigeic earthworms that cannot make burrows in the soil strata. They are able to navigate only through the cracks on the surface.
- Endogeic are the subsoil dwellers found in deeper region of the soil and
- Anecic earthworms found in the soil, that are not frequently disturbed.

Although not every earthworm species is suitable for vermicomposting, numerous researchers have examined the effectiveness of the three groups of soil-dwelling earthworms [84,85,86,87]. Among these, certain epigeic earthworm species can be particularly efficient at accelerating the production of organic fertilizer through biodegradation and mineralization in comparison to other species. It is evident from the available literature that epigeic earthworms comprising *Eisenia fetida, Eisenia andrei*, *Eudrilus eugeniae*, and *Perionyx excavatus* are most effective for vermicomposting, owing to the following characteristics:

- high reproduction rates,
- tolerance to a broad spectrum of environmental conditions,
- rapid rate of vermi conversion,
- ability to feed on a diverse range of organic wastes.

4.3 Influence of Process Parameters on Vermicomposting

Several key factors affect the process involved in vermicomposting, including earthworm growth, cocoon production, and microbial diversity. Each of these factors is elaborated upon below:

4.3.1 Moisture

Functioning of both earthworms and microbes relies heavily on adequate moisture levels within the vermicomposting setup. An optimal moisture range of 60% to 80% is typically recommended for effective vermicomposting [88]. Studies [89, 90] indicated that for *Eisenia fetida* and *Eisenia andrei*, the optimal moisture content exceeded 70% in cow manure and 85% in pig manure respectively. Insufficient moisture can delay the growth of clitella in earthworms, while high moisture content can lead to anaerobic environments in vermibins and vermibeds, which may be fatal to the worms [91].

4.3.2Temperature

The optimal temperature range for the vermicomposting process lies between 15°C and 28°C. Earthworms respond variably to temperature fluctuations, requiring that temperatures remain above 10°C in winter and below 35°C in summer [92].

4.3.3 pH

For optimal biological and earthworm activity, the pH should be maintained between 6.5 and 8.5. Throughout the vermicomposting process, significant changes in pH can occur. Initially, a low pH is often observed as a result of the production of carbon dioxide and volatile fatty acids. As the process continues and CO2 is released alongside the consumption of volatile fatty acids, the pH begins to rise [93].

4.3.4 Aeration

Earthworms respire through their vascular skin, where oxygen absorbed diffuses into their blood and is transported throughout their bodies. Oxygen is vital for the oxidation of food, with carbon dioxide produced as a byproduct. This CO2 mixes with the blood and is expelled through the moist skin [94, 95]. Low oxygen levels (55–65%) can reduce respiration rates, slowing feeding activity. High temperatures in the vermicomposting bed can increase microbial oxygen consumption, thereby reducing oxygen availability for the earthworms. Excess moisture may result in poor aeration, further hampering oxygen supply. Eisenia fetida has been noted to migrate from saturated zones to areas with optimal moisture conditions but can endure for prolonged periods in well-aerated water [96].

4.3.5 Light

Earthworms are naturally photophobic. Lacking eyes, they perceive light through their skin, allowing them to detect bright light and avoid it. The study [97] noted that the anterior and posterior ends of earthworms are more responsive to light compare to their central region, with the anterior end being the most responsive. Earthworms are less sensitive to light when contracted rather than extended, as the anterior end contains more light-sensitive cells [98]. They prefer to remain away from sunlight to prevent skin desiccation. Brief exposure towards sunlight can cause paralysis, while prolonged exposure is lethal. Earthworms perceive red light similarly to cloudy conditions, which is less threatening to them.

4.3.6 Feed quality

Feeding quality is crucial for the growth and reproduction of earthworms during the process of vermicomposting. The feeding rate is influenced by factors such as the proportion of organic content, particle size, moisture content, salt content, C:N ratio, etc [99]. Study [100] noted that earthworms consume food at a rate of 100 to 300 mg per gram for body weight per day. Since worms are very sensitive to salts, the feed should contain less than 0.5% salt content [101]. Feed should be free of any nonbiodegradable or harmful substance (e.g., inert materials, plastics, glass, metal objects, detergents, pharmaceuticals, etc.) that poses a threat either directly to the earthworms or via their metabolic byproducts [102]. The C/N ratio of feed material affects the earthworms' growth and reproduction. The optimum C/N ratio for vermicomposting is 30:1. If the C/N is excessively high or excessively low, waste degradation becomes a slow process. Numerous studies have demonstrated that the C/N ratio in soils with litter may be brought down to less than 25:1 by the intervention of earthworms [103]. If the organic feed material is poor in nitrogen and the C/N ratio is high, microbial activity decreases in the feed substrate [104]. The following Table 2 shows the process parameter for vermicomposting:

Table 2: Process Parameters for Vermicomposting [104]

Sl. No.	Factor	Optimum Conditions
1	Moisture content	60-80%
2	Temperature	15-28 0 C
3	pH	6.5-8.5
4	Aeration	• Frequent turning of watse • Excessive moisture should be avoided • Greasy and oily wastes should not prsent
5	Feed Quality	• Should be free from toxic, nonbiodegredable waste • Should be free of salts • Should have optimum C/N ratio
6	Light	Earthworms are light-sensitive, so vermicomposting bins should either be placed in dark places or be covered

The steps invovled in the procedure of vermicomposting has been shown in the Figure 2 given below:

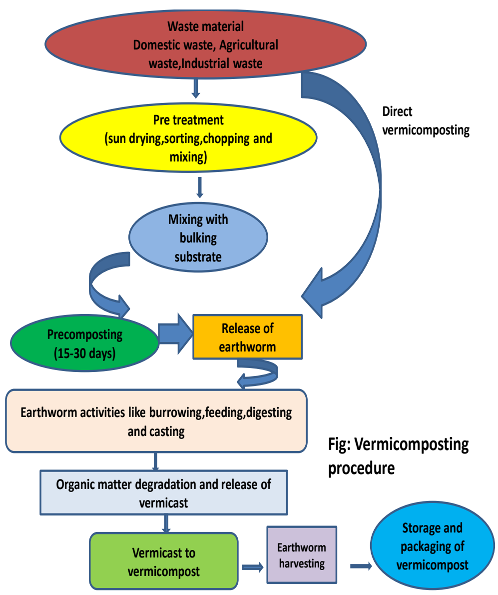

Figure 2: Vermicomposting Procedure

4.4 Advantages of Vermicomposting

4.4.1Environmental Benefits of Verm technology

Vermicomposting offers several potential environmental advantages, including the reduction of noxious properties in organic waste, the elimination or reduction of harmful microorganisms, and the conversion of agricultural waste into high-value fertilizers. Additionally, it facilitates the production of food and feed from food discards [105]. Vermicompost enhances soil fertility over prolonged periods without compromising food quality. Notably, its nutrient content surpasses that of traditional farmyard wastes (FYW): The study [105] furnished the nutrient content of farmyard waste as shown in the Table 3:

Table 3: Nutrient content of farmyard waste [105]

Nutrients	Vermicompost	Farmyard Wastes (FYW)
Nitrogen (N)	0.5%	0.18%
Phosphorus (P)	0.57%	0.2%
Potassium (K)	3.14%	0.5%

Sujatha et al.,2003 [106] noted that earthworm castings in home gardens can contain 5 to 11 times more nitrogen, phosphorus, and potassium than the surrounding soil. Moreover, these castings are rich in vitamins, antibiotics, and enzymes such as proteases, amylases, lipases, cellulases, and chitinases. Vermicomposting can generate employment opportunities for millions, reduce reliance on chemical fertilizers, convert waste into valuable fertilizers, rehabilitate wastelands, address food security, and contribute to a greener, more prosperous nation [107]. This technique also acts an essential action in conserving biodiversity, which is becoming increasingly significant today. Additionally, it provides self-employment prospects for disadvantaged communities while promoting sustainable agricultural waste utilization and maintaining ecological balance.

4.4.2 Vermicomposting in Indian Context

In India, many settlements and metropolitan lack efficient waste management systems, leading to unprocessed solid waste being disposed of in landfills or on roadsides, while liquid waste is often discharged into water bodies. Domestic organic waste constitutes about 50% of total waste, with an average household generating approximately 200 kg of organic solid waste annually. Instead of discarding this waste, it can be repurposed through vermicomposting, transforming it into valuable manure for soil enrichment [83].

4.4.3 Vermicomposting for Rural Development

A significant amount of agro-industrial waste and byproducts remains underutilized by local populations due to a lack of awareness regarding their value. Vermicomposting presents a low-cost, profitable solution for these materials. Unemployed individuals in rural areas can engage in vermicomposting as a part-time or full-time venture, as long as they are furnished with the necessary technical knowledge. Raising awareness about vermiculture and vermicomposting can encourage rural communities to establish their own units, generating a steady income.

4.4.4 Revenue Generation through Vermiculture and Vermicomposting

Verm technology is gaining popularity due to its straightforward methodology, low investment requirements, and lack of need for sophisticated infrastructure. Processing one ton of organic matter daily requires approximately 1,500 square meters of space and about six workers, potentially producing around 70 tons of earthworm castings annually [108]. Innovative and motivated rural individuals can become successful entrepreneurs in vermicompost production, thereby improving their income and quality of life. Engaging in vermicomposting can provide valuable job opportunities, especially through self-employment initiatives. The benefits of vermi technology in terms of revival and survival of biosphere has shown in the Figure 3:

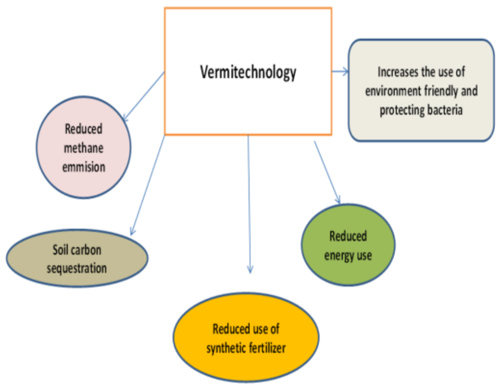

Figure 3: Vermi technology in revival and survival of biosphere

5. ARTIFICIAL INTELLIGENCE (AI) IN MANAGEMENT OF WASTE PARTICULARLY FOCUSING ON COMPOSTING AND VERMICOMPOSTING

AI is a quickly evolving technology which is being progressively incorporated into numerous industries, particularly in waste management [109]. By incorporating AI and robotics into the design and functioning of urban waste treatment facilities, there is potential for a transformative impact on solid waste management, leading to enhanced operational efficiency and more sustainable practices [110, 111]. Numerous developed nations, including Austria, Germany, New Zealand, the USA, the UK, Japan, Singapore, Switzerland, South Korea, and Canada, have begun to embrace AI technologies to optimize resource use, improve efficiency, and enhance recycling capabilities throughout the solid waste management process [112]. AI applications, especially in the sorting and handling of solid waste, are becoming increasingly vital in this domain [113, 114].

The implementation of artificial intelligence in waste recycling has become increasingly prevalent. Key uses include enhancing routes for waste collection trucks, identifying waste management facilities, simulating waste transformation processes, and integrating various technologies such as radio frequency identification (RFID) [115], global positioning systems (GPS) [116], and geographic information systems (GIS) [117] to effectively monitor solid waste collection trucks and containers. Furthermore, machine learning and techniques involved in image processing have been combined with these technologies to enable automatic detection of container fill levels [118].

Machine learning (ML), an essential component of artificial intelligence, has gained widespread acknowledgement for its efficiency and effectiveness. It offers considerable time savings, achieves high accuracy in predicting outcomes for complex nonlinear problems, and significantly cuts down on labor and resource expenditures by eliminating the need for redundant experiments [119, 120].

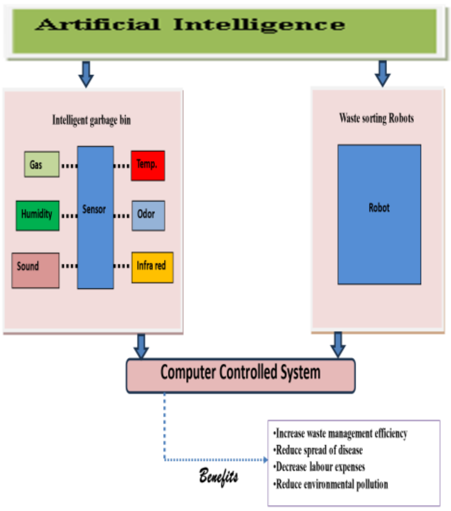

Figure 4: AI powered typical waste management system

In recent years, the application of artificial intelligence (AI) technologies in vermicomposting has emerged as a promising method for enhancing efficiency, boosting productivity, and ensuring high-quality compost output. A typical waste management system powered by AI is shown in the above Figure 4. Composting technology offers a sustainable means of biologically treating organic waste, focusing on organic materials that decompose easily by aerobic bacteria, such as cellulose, proteins, and fats. The resulting compost serves not only as an organic fertilizer that improves soil quality and reduces reliance on chemical fertilizers but also as a soil amendment that lowers heavy metal bioavailability, addresses organic pollutants, and mitigates soil pathogens.

Despite its benefits, conventional composting technology has notable drawbacks, including low humification rates, greenhouse gas outputs, nitrogen depletion, and excessive metal dispersion [121,122, 123]. The limited humification throughout the composting process restricts the agricultural applicability of the resulting compost [124, 125]. Additionally, nitrogen deletion, greenhouse gas outputs, and the dispersal of toxic metals not only degrade compost quality which also considerably contribute to environmental pollution [126,127].

To tackle these challenges, an increasing number of researchers are investigating the scopes of machine learning (ML) to monitor and control composting processes, aiming to improve product quality, optimize operations, and enhance environmental protection [128,129, 130]. Currently, in the limited available literature, ML algorithms, such as ANN, RF, SVM, ANFIS, and KNN, have been used to predict compost maturity and other critical parameters and monitor pollution and greenhouse gas outputs, among aspects of others.

Ensuring the maturity of compost is vital, as partially decomposed compost can contain harmful bacteria, acidic substances, and pollutants that negatively affect plant growth, contaminate the environment, and pose risks to both ecosystems and human health [129, 131]. Compost maturity influences the efficiency of the composting process and determines the final product's quality. Various indicators are used to evaluate compost maturity, including physical criteria such as temperature, color, and odor, in addition to chemical factors such as pH, electrical conductivity (EC), carbon-to-nitrogen (C/N) ratio, moisture content, humic acid, and total organic carbon (TOC). Biological markers like the seed germination index (GI), enzyme activity, and microbial populations are also critical in assessing compost readiness [128, 119].

To enhance the prediction of compost maturity, researchers have implemented Convolutional Neural Network (CNN) models that use compost images for a more precise and efficient assessment. A CNN model has been designed [131] to predict compost maturity by processing compost images through convolutional pooling layers, successfully detecting differences in granularity at various stages and extracting visual features that determine maturity. A CNN-based methods has been explored [132] for early-stage compost maturity classification, with their model achieving classification errors between 0.51% and 17.77%. In another study [133] implemented a rapid region-based CNN model to assess compost maturity by analyzing multilayer image attributes, achieving a 96.4% accuracy rate.

The application of CNN models in compost maturity prediction has significantly improved both the speed and accuracy of these assessments, consistently exceeding 95% accuracy. This image-based method aligns well with practical needs and provides valuable technical support for determining compost maturity in real-world production scenarios. A radial basis functional neural network (RBFNN) was employed [134] to study how the tea waste ratio and composting time affect parameters like moisture content (MC), total nitrogen (TN), and total organic carbon (TOC) loss in the co-composting of food and tea waste. Their RBFNN model identified that a 25% tea waste ratio resulted in the lowest TN and TOC loss during the composting process. Additionally, genetic algorithms (GAs) were used to further optimize co-composting parameters such as temperature, pH, electrical conductivity (EC), carbon-to-nitrogen (C/N) ratio, MC loss, TN loss, and TOC loss.

In a separate study [135], predicted compost maturity parameters—such as temperature, pH, EC, MC, TN, and C/N ratio—using a neural network model that required inputs like natural mineral materials, olive waste ratio, and composting time. This model demonstrated prediction errors of less than 2%. After optimization with GAs, blending pumice and vermiculite effectively achieved optimal temperature conditions and minimized nitrogen loss while adjusting pH, EC, and MC. Furthermore, machine learning (ML) combined with sensor technology was applied to monitor moisture content in large-scale industrial composting systems, as demonstrated by [136]. Study [137] explored how penicillin, pH, and the carbon-to-nitrogen (C/N) ratio affect bacterial communities and the humification process during aerobic composting, using random forest (RF) and logistic regression (LR) models. Their findings revealed that penicillin mainly impacted microbial genera with low abundance, while bacterial communities played a crucial role in regulating the building of humic substances such as fulvic acid and humic acid.

Spectroscopy and other chemical characterization techniques are essential for predicting compost maturity through machine learning (ML) approaches. A study [138] pioneered the use of near-infrared spectroscopy (NIRS) to monitor physicochemical and biochemical changes during composting. By applying principal component analysis (PCA), they identified distinct stages and aging processes in compost based on spectral data. The integration of partial least squares (PLS) models allowed for the prediction of various parameters, including moisture content (MC), temperature, pH, organic carbon (OC), organic nitrogen (ON), the OC/ON ratio, total nitrogen (TN), ammonium nitrogen (NH_4^+-N), and humic and fulvic acid ratios.

Further investigation has been attempted [139] on chemical transformations during composting, such as the degree of humification, cellulose composition, aromaticity, and polymerization, utilizing ultraviolet-visible spectroscopy, X-ray diffraction, and infrared spectroscopy. Through the application of PLS models, they examined the relationship between infrared spectra and the chemical properties of compost.

Additionally, study [140] conducted a quantitative analysis of organic matter, TN, and the C/N ratio under varying composting conditions using NIRS. They developed three nonlinear PLS models, using spectral preprocessing and variable selection techniques. Their findings indicated that, with appropriate spectral preprocessing, NIRS achieved highly accurate predictions for each parameter, showcasing its strong predictive power in compost analysis.

Machine learning (ML) both significantly contributes for predicting compost maturity, optimizing process parameters, controlling pollution, and tracking of greenhouse gas outputs and also shows considerable promise in forecasting nutrient recovery efficiency, nitrogen loss, heat loss, and pressure drop during the composting process. Another study [141] assessed the performance of Artificial Neural Network (ANN) and Multiple Linear Regression (MLR) models in predicting nutrient recovery efficiency in vermicomposting. They utilized seven chemical and biological indicators as input variables to estimate the recovery rates of total nitrogen (TN) and total phosphorus. The results indicated a notable increase in TN and total phosphorus recovery rates due to the composting process. The ANN model outperformed the MLR model in predicting both TN and total phosphorus, identifying TN and the carbon-to-nitrogen (C/N) ratio as critical factors in its predictions. A study [142] examined the effects of physicochemical parameters on nitrogen loss during composting. Their findings demonstrated that nitrogen loss escalated with rising temperatures and was influenced by several factors, including pH, compost mixing, C/N ratio, and moisture content (MC). Consequently, they developed a hybrid tool that combines linear and nonlinear approaches based on a Cascade Feedforward Neural Network (CFNN) to predict nitrogen loss, achieving a mean absolute percentage error of approximately 1% to 2%. Through Genetic Algorithm (GA) optimization, they identified the parameter values that minimize nitrogen loss effectively. An artificial neural network (ANN) model was utilized [143] to estimate heat loss throughout the composting process, demonstrating the model's effectiveness in predicting both heat release and loss throughout the composting cycle. Their sensitivity analysis identified six key parameters impacting heat dynamics, ranked as follows: temperature, mineral mass, oxygen content, flow rate, CO_2 content, and process duration. These insights contribute to a deeper understanding of heat utilization and optimization in composting. Similarly, study [144] employed an ANN model to forecast pressure drops in organic material beds during composting operations. Their multilayer perceptron (MLP) model, structured as 5-9-1, exhibited a strong correlation between predicted and actual outcomes. Key influencing factors included time, density indicators, and hydraulic load, with flow direction having a negligible impact on airflow resistance predictions. Statistical analyses further confirmed the model's robustness, yielding an R^2 value of 0.906 and a standardized residual range of 4.082 to5.453.

The Figure 5 is reflecting the typical AI based composting study and the Table 4 is highlighting the application of Machine Learning to predict composting maturity.

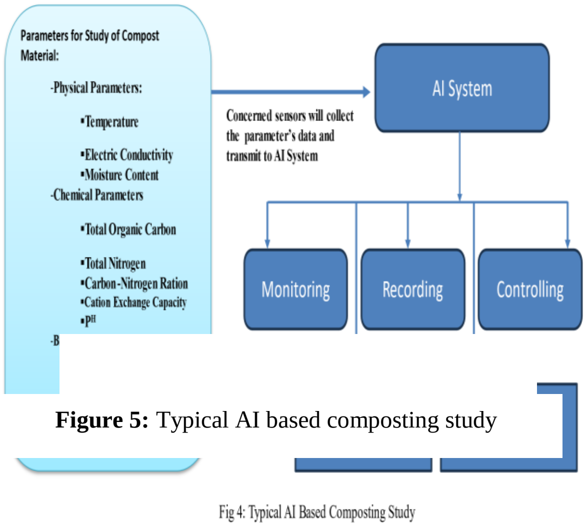

Figure 5: Typical AI based composting study

Table 4: Applications of Machine Learning to predict composting maturity

Biomass	Input variables	Output variables	ML algorithm	Reference
Vegetable waste, straw, livestock waste and mixture,	Image of composting	Composting maturity	CNN	[131]
Sewage sludge, rapeseed straw	Image of composting	Composting maturity	CNN	[132]
Grass, livestock -manure, vegetable-wastes, plastic, glasses	Image of composting	Composting maturity	ReCNN	[133]
Food waste and tea waste	Tea waste ratio, composting time	MC, TN, TOC loss	RBFNN, GA	[134]
Olive mill waste and natural mineral amendments	Natural mineral material types, olive mill waste ratio, composting time	Temperature, pH, EC, MC, TN, and C/N ratio	FF-NN, ER-NN, RSM, GA	[135]
Chicken manure, corn straw	Penicillin, pH, and C/N ratio	Bacterial communities and humification processes	RF and Linear regression on PLS	[137]
Textile waste, green waste, paper & cardboard waste	UV-visible spectroscopy, X-ray diffraction, and infrared spectroscopy	Humification degree, presence of cellulose mixtures, aromaticity, and polymerization degree	PLS	[139]
Rice straw, dried pig manure	NIRS figures	Organics, TN, C/N ratio GI, T-value	PLS	[140]
Food waste, garden waste	Composting time, ambient temperature, ventilation rate, pH. EC	GI, C/N ratio	RF, XGBoost, LightGBM, MLP	[129]

5.1 Some advantages of using AI in vermicomposting process [145] are described below:

- AI-driven monitoring systems in vermicomposting track vital conditions like temperature, moisture, pH, and oxygen. When irregularities arise, AI instantly adjusts the environment, ensuring ideal conditions for worms. This boost composting speed and efficiency, maximizing yields with minimal manual intervention.
- Machine learning transforms vermicomposting by analyzing historical data to uncover key patterns linking inputs to outcomes. AI-powered predictive analytics can forecast ideal feeding times, suggest environmental tweaks, and anticipate problems before they occur. This foresight enables operations to optimize efficiency, reduce waste, and minimize environmental impact, creating smarter, more sustainable composting processes.
- AI-powered image recognition revolutionizes vermicomposting by accurately sorting organic waste, swiftly filtering out non-compostable materials. This automation enhances efficiency, cuts labor costs, and ensures only optimal inputs enter the system. Additionally, AI evaluates compost quality, analyzing nutrient levels, microbial health, and stability to guarantee regulatory compliance and customer satisfaction, delivering superior results with minimal manual oversight.
- AI-driven optimization refines feedstock mixtures for vermicomposting by analyzing factors like carbon-to-nitrogen ratio, moisture, and particle size. By customizing formulations to worm needs, AI accelerates decomposition, reduces

odors, and enriches compost nutrients. This data-centric approach boosts efficiency and cuts the need for expensive additives, ensuring a more effective, streamlined composting process.
- AI's continuous learning in vermicomposting allows it to evolve by analyzing sensor data, historical trends, and user feedback. This self-improving capability refines processes, adapts to changing conditions, and integrates new knowledge, ensuring optimal composting outcomes. By staying agile to environmental shifts, market trends, and regulations, AI fosters innovation and sustainable growth in the industry.

6. ENTREPRENEURSHIP DEVELOPMENT THROUGH VERMICOMPOSTING IN THE NORTHEAST REGION (NER) OF INDIA

The development of entrepreneurship is increasingly recognized as a vital driver for industrial development and a remedy to unemployment, particularly in economically weaker sections of society. In the Northeast region (NER) of India, unemployed youth in rural areas can be encouraged to adopt low-cost vermicomposting technologies, which can serve as a means of micro-entrepreneurship. This initiative not only addresses unemployment but also contributes to the effective management of municipal solid waste (MSW), thereby improving the socio-economic conditions of marginalized communities.

The demand for vermicompost has surged in the Northeast due to various government initiatives promoting organic production. This entrepreneurial venture not only generates income but also enhances crop productivity in the region by improving soil fertility through environmentally friendly farming practices. Furthermore, it supports effective waste management and promotes organic farming, which is increasingly sought after for its benefits. Entrepreneurs can expect a promising return on investment. For instance, with an investment of around ₹3,500, an entrepreneur can earn a net profit of ₹10,000 to ₹20,000 annually. Upon establishing a vermicomposting unit with dimensions of 10x4x2 feet, approximately 400 kg to 450 kg of vermicompost can be harvested every two months.

However, several challenges may hinder vermicomposting entrepreneurs, including:
- Lack of awareness about improved vermicomposting production techniques
- Insufficient knowledge regarding market trends
- Inadequate training facilities
- Financial constraints
- Difficulty in sourcing earthworms
- To support this initiative, the Government of India and various state governments provide financial assistance for establishing vermicomposting units. Programs such as the Paramparagat Krishi Vikas Yojana (PKVY), National Mission for Sustainable Agriculture (NMSA), Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA), and the Mission for Integrated Development of Horticulture (MIDH) offer training and financial aid. Additionally, farmers can seek support from NGOs or form self-help groups to access funds. Some banks also provide loans to help meet investment or working capital needs for establishing vermicomposting units [146]. Through these initiatives, vermicomposting can serve as a sustainable entrepreneurship model, empowering rural youth and contributing to the economic development of the Northeast region.

7. KEY PROSPECTS FOR YOUTH EMPOWERMENT THROUGH VERMICOMPOSTING ENTERPRISES

- **Sustainable Self-Employment**: Young people can establish vermicomposting production as independent microenterprises with minimal startup costs. The primary resources required include available land, animal dung, and biomass [147]. The growing urban demand for organic compost creates ample opportunities for business expansion.
- **Supplemental Income Source**: Small and marginal farmers can enhance their farm incomes by utilizing available labor for vermicomposting, making use of farm waste [148]. Additionally, women farmers can effectively manage vermicomposting units while balancing their household responsibilities.
- **Rural-Urban Linkages**: Youth in peri-urban areas can capitalize on the urban demand for organic waste by collaborating with rural youth groups for sourcing raw materials, thereby developing commercially viable vermicomposting ventures [149].
- **Capacity Building and Training**: Practical training programs focused on vermicomposting techniques and entrepreneurship can empower youth to establish and manage their enterprises more efficiently. Partnerships with agricultural institutions can further enhance technical skills and knowledge [149].
- **Market Linkages**: Establishing connections with government extension services, farmers' associations, and organic product companies can facilitate market access. Participating in rural entrepreneurship fairs and exhibitions also offers valuable exposure and networking opportunities [149].
- **Access to Credit and Subsidies**: Youth involved in vermicomposting can benefit from financial support available through state and national schemes aimed at promoting rural entrepreneurship, self-employment, and environmental protection [150].

8. IMPORTANCE OF THE STUDY

This study assists as a valuable resource for policymakers, waste management authorities, and relevant stakeholders in making well-informed choices regarding effective waste management strategies. It aims to shed light on the environmental, economic, and social impacts of various waste management approaches, facilitating the identification of the most efficient and sustainable solutions. By addressing the critical need for sustainable waste management, this study will serve a crucial role in promoting environmental sustainability and guiding future waste management policies and practices.

This review also explores the applicability and benefits of different machine learning (ML) models in the biological treatment of organic waste. Our analysis shows that artificial neural networks (ANNs), support vector machines (SVM), and genetic algorithms (GAs) are the most commonly used algorithms for modeling biological treatment processes. The detailed evaluation of ML applications in composting underscores the considerable potential of these technologies to optimize processes and facilitate real-time monitoring. Looking ahead, research should emphasis on improving the efficiency of ML in biological treatment by automating model selection, incorporating explainable ML techniques, boosting computational efficiency, and strengthening its practical implementation in engineering applications.

AUTHOR CONTRIBUTIONS

All authors contributed equally to the research and writing of this paper.

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COMPETING INTERESTS

The authors declare that there are no competing financial interests or personal relationships that could have influenced the findings presented in this paper.

DATA AVAILABILITY

The research undertaken for this article did not involve the use of any data.

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