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Optimization of Engineering and Process Parameters for Vermicomposting

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Abstract: Urbanization and population rise considerably increase the generation of solid wastes. The recycling of solid wastes through vermicomposting is a sustainable approach. The current study aimed to investigate the effect of earthworm (*Eisenia fetida* and *Eugilius euganiae*)-processed/mixed solid waste manure (vermicompost) on the development, productivity, and chemical characteristics of chili and brinjal in different wooden reactors (R). A mixture of palash leaf litter, biogas slurry, food wastes from a hostel kitchen and households, and municipal solid waste (MSW) were used during the study. The effects of different reactors; process parameters; earthworm cultures, such as R1–R9 with different widths and lengths at a constant height (30 cm); pH, salt, and moisture content; temperature; C:N ratios; N, P, K, and pathogen content; and the type of mono/-polyculture on vermicompost were tested with respect to chili and brinjal production. The average net increase in the worms' zoomass in reactor R1 at different mixed worm densities (*E. fetida* + *E. eugeniae*) under optimum conditions was observed. Compared to a monoculture reactor, the yield of both chili and brinjal were significantly greater in the polyculture reactor with vermicompost soil.

Keywords: biogas slurry; reactors; manure; vermicompost; soil supplement

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1. Introduction

An estimated 38 billion tons/annum of solid organic waste (SOW) is generated globally, challenging waste management researchers to determine methods for its safe, effective, and economical disposal. Generally, SOW is composed of municipal, vegetable-market-derived, institutional, household, and hostel kitchen wastes (mainly food waste) [1]. Palash (*Butea monosperma*) is a native tree of the tropical and sub-tropical climate zones of the Indian sub-continent and Southeast Asia. On the campus of the Maulana Azad National Institute of Technology (MANIT), a large number of palash trees are available. These trees generate massive amounts of leaf litter. Currently, at the MANIT campus, waste is collected in bins and disposed at the Bhopal dumping yard, and a portion of this waste is incinerated in an open dump [2]. However, this malpractice is of concern as it is very harmful to both humans and animals. It can contaminate atmospheric air by generating greenhouse gases and dioxins. Usually, cattle manure undergoes a stabilization process before being used for soil enrichment [3]. During this stabilization process, bulking agents such as crop and wood wastes are introduced into the manure to improve its moisture content and C:N ratio. Studies have reported the successful transformation of wastes from the paper [4], textile [5], guar gum [6], sugar [7], distillery [8], leather [9], beverage [10], agro- [1], and tannery [11] industries into nutrient-rich manure.

Composting and vermicomposting are well-established techniques for biologically stabilizing SOWs. Researchers [12,13] have suggested that the treatment of MSW, leaf litter, or biowaste through composting–vermicomposting and/or anaerobic digestion appears to be the most sustainable option as it improves the physico-chemical properties of soil. While considering technical and environmental perspectives, studies have analyzed MSW composting on an industrial scale [14]. However, the resulting long conversion times, unfeasibility for bulk composting, nutrient losses during prolonged composting periods, and the heterogeneous final product [15] have limited its wide range usage. On the other hand, vermicomposting is an efficient, sustainable, and ecologically appealing process for transforming SOWs into hygienic and value-added products [2]. Under field conditions, vermicomposting has shown significantly impressive effects on different crops [16–22]. The biological activity of earthworms provides nutrient-rich vermicompost for plant growth, thus facilitating the transfer of nutrients to plants [23]. Chili and brinjal are two common plants selected in studies as they grow rapidly and fructify early. However, even though vermicompost is beneficial for plant growth, controlled studies have scientifically established that these benefits have certain limitations. The literature rarely reports studies on vermicompost derived from MSW, specifically with respect to palash leaf litter. Thus, to bridge the knowledge gap, the authors of the current study undertook a series of experiments for generating vermicompost from different sources and testing its impact on plant growth. Among the various earthworm species, *Eisenia andrei* and *Eisenia fetida*, because of their fertility, better growth rates, and temperature tolerance, are the most frequently used for MSW treatment [24].

Thus, the novelty of the current work lies in its foregrounding of the effect of a vermireactor's geometry (particularly its aspect ratio) on the efficiency of vermicast production. Improved vermicast production in different vermireactors of identical volume with surface area/height ratios varying from 4 to 250 is reported using *E. fetida* and *E. eugeniae* [25–33]. The effects of areal loading [34], earthworm densities, and feeding rate [35] on vermicast production in fixed dimension reactors are also explored. In addition, the current study uses reactors of identical volume but widely varying surface areas in order to assess the impact of a reactor's surface area on its efficiency while keeping other variables constant. Moreover, in the current study, several different sets of experiments are performed with these reactors. In these experimental sets, the effect of reactor geometry on the vermicast production rate is assessed as a function of different earthworm species and different stocking densities. In sharp contrast to the research conducted by Ndegwa et al. [35] and Clarke et al. [34], the current study does not concern the effects induced by different feed loading rates. Notably, when Ndegwa et al. [35] and Clarke et al. [34] provided different quantities of feed to reactors with an identical surface area, there must have been some variation in the area/volume ratio even though the area was unchanged. Thus, a tenuous connection might be noted. However, neither of the authors quantified, reported, or discussed the impact of the area/volume ratio. On the other hand, the effect of area/volume ratio was the very raison deterge of the current study.

Regardless of the advances in composting/vermicomposting techniques, a number of limiting factors are still ambiguous. Thus, the current study focuses on identifying and possibly eliminating the factors that can affect composting/vermicomposting, thus rendering it an efficient method for sustainable organic waste management. Considering the above facts, this study was carried out to estimate the potential of *E. fetida* and *E. euganiae* with respect to composting different types of organic substrates (namely, Bhopal MSW, single-household waste, vegetable market waste, institutional waste (MANIT hostel food and palash leaf litter), and digested biogas slurry (DBS)).

2. Materials and Methods

2.1. Waste Collection

The on-farm biogas plant at Sharda Vihar campus, Bhopal, Madhya Pradesh, India, was used to collect digested biogas slurry (DBS). Dried DBS was collected from a storage

tank after being piled on the ground for a week. Hostel kitchen waste (containing bread, cooked rice, eggshells, fruit and vegetable pieces, and milk products) was collected from MANIT campus, Bhopal, India. Palash leaf litter and single-household wastes were also collected from MANIT campus. The litter was manually homogenized in a 25 L wooden reactor. Thereafter, the reactor was sealed until the litter substrate was utilized for vermicomposting. Bhopal's MSW was obtained from a Bhanpura dumping yard, Bhopal, India. The MSW sample was manually segregated into different physical components, including paper, plastics, rubber, leather, glass, metals, textiles, and polyethylene bags. The segregated materials were weighed to determine their respective fractions. The leftover material (after segregation) was a uniform mixture of organic matter along with soil, mud, sand, and other inert materials. All other chemicals used during the study were of analytical reagent grade.

2.2. Pre-Treatment of Fresh Different Solid Wastes for Vermicomposting

The details of pre-treatment are given in Supplementary Information (Text S1).

2.3. Types of Vermireactor Systems

Regarding the preparation of the bedding, various types of bedding materials are available due to their widespread availability. Figure S1a displays different vermireactors. An ideal vermibed has a basal layer that consists of broken (to varying degrees) bricks or pebbles along with a layer of coarse sand (up to 6–7.5 cm thickness) to ensure proper drainage. The basal layer is covered by a loamy soil layer (up to a height >15 cm), which is then moistened. Worms can inoculate over this layer. A small lump of cattle dung is scattered over this layer, and up to 10 cm of the dung is covered with hay. Finally, broad leaves are used to cover the unit, and a net can be used to prevent the intrusion of any unwanted worms or other predators [2]. In the current study, the vermireactors were modified using sawdust, cloth layer, and biogas slurry layer instead of pebbles, core sand, and cattle dung layer used in conventional vermireactors (illustrated in Figure S1b).

2.3.1. Experimental Design for Vermicomposting Reactors

Vermicomposting was performed in wooden reactors (nos. R1–R9) with a height of 30 cm (Figure S1 and Table S1). The upper end was wrapped with a cloth to maintain dark conditions at 30 ± 2 °C during the day and 28 ± 2 °C during the night, to prevent the earthworms from escaping, and for partial aeration. The physical and chemical quality of vermicast from the reactors was analyzed after 24 days. Mature earthworms were introduced into the reactors and fed at the four selected worm densities of 62.5, 125, 250, and 350 animals/lit. Enough feedstock (dry weight basis), consisting of DBS and different solid waste mixtures having C:N ratios of 30 or 45, was provided to meet the needs of the earthworms for the entire eight-week period. Moisture content was maintained at about 80%. At the end of the eighth week, the worms were separated from the vermicompost.

Throughout the experiments, the substrate moisture content in the vermibeds was maintained between 75 and 80% by periodically sprinkling the beds with a sufficient amount of distilled water. Earthworm mortality was monitored on a daily basis for the critical initial period (up to the first three weeks), and mortality data were recorded for different experimental vermibeds. From each experimental reactor, the homogenized substrate samples were drawn at 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 24 days. The samples were oven-dried at 60 °C for 2 days, ground in a stainless-steel blender, and stored in sterilized plastic airtight containers for further physico-chemical analysis. In each experimental reactor, the changes occurring in the individual biomass of the inoculated earthworms and cocoon production were continually measured on a weekly basis for eight weeks.

2.3.2. Earthworm (*E. fetida* and *E. eugeniae*)

Earthworms were precultured at Advanced Research Laboratory, Chemical Engineering Department, MANIT, Bhopal, India. Six-week old *E. fetida* and *E. eugeniae* weighing 0.25–0.4 g and measuring 2.5–5.0 cm/worm in length were randomly chosen from DBS culture for experiments (illustrated in Figure S2a,b). Figure S2c displays biomanure. The earthworm biomass was determined by removing fifty worms from each reactor, washing them in distilled water, and drying them on paper towels. They were then weighed in a weighing boat with water using a balance. This was executed to prevent worms from desiccating, which, in turn, would affect the weight of the earthworms.

2.3.3. Monoculture and Polyculture Vermicomposting of *E. fetida* and *E. eugeniae*

Vermicomposting of the different wastes (palash leaf litter and hostel kitchen/food wastes) was examined during this experimental study. The feeding substrate employed was DBS. Physicochemical parameters, such as moisture content (MC), pH, electrical conductivity (EC), temperature (T), carbon-to-nitrogen (C:N) ratio, nitrogen (N%), phosphorus (P%), potassium (K%), and pathogen content, were identified, and effects of these parameters on worms' survival rate was observed. Fresh DBS and different waste composts were used to develop suitable feed for worms. The mixtures of *E. fetida* and *E. eugeniae* were incubated for polyculture treatment for comparison with monoculture treatment (*E. fetida*) for vermicomposting experiments.

2.3.4. Control

For control experiments, mixtures of DBS and different solid wastes having C:N ratios of 30 and 45 were placed into vermicomposting reactors (with sizes similar to those used for composting) and watered to 80% moisture level (recommended for vermicomposting) without introducing earthworms. The waste mixtures were allowed to incubate for 7–8 weeks without any treatment. Only moisture content of waste mixtures was adjusted.

2.4. Physico-Chemical Analysis

The MC, pH, EC, T, C:N ratio, N%, P%, K%, and pathogen content of materials and compost/vermicompost were determined according to a standard procedure. Organic carbon was measured using the partial oxidation methodology [36], and total nitrogen content was determined as per APHA [37], from which C:N ratio was determined. Plant-available P content was extracted using the Bray method [38], and the P concentration was measured colorimetrically using the molybdate blue method at 712 nm using UV-Vis spectrophotometer (HACH, USA). Exchangeable P was extracted with ammonium acetate. The K concentrations were measured with a flame photometer (Shimadzu, Japan), and particle sizes were analyzed through sieve methods. For microbial analysis, 1 g of compost was weighed and added to 9 mL of distilled water. Thereafter, it was mixed in a rotatory mixer at 4000 rpm for 10 min. Then, 1 mL of the mixture was then added to 10 mL of distilled water and mixed in a similar fashion. All samples were stored in sealed plastic bags to avoid contamination. The concentrations of *E. coli* and *E. faecalis* were analyzed using the most probable number (MPN) method. Lactose broth medium was used in MPN test. The biochemical conformation of *E. coli* and *E. faecalis* was carried out as reported elsewhere (APHA, 1995). The vermicast output (V in mg/L.d) per liter of reactor volume per day was calculated using Equation (1):

$$V = \frac{\text{Average vermicast produced, per run (g} \times 1000)}{\text{Number of days in the run} \times \text{ Volume of the reactor (L)}} \quad (1)$$

2.5. Plant Growth

For control experiments with chili (*Capsicum annuum*) and brinjal (*Solanum melongena*) plants, three pots, one each for chili and brinjal saplings and a third one for control experiment, were designated and employed. Mud pots with 3 L capacity were used

in this study. A total of 750 g of vermicompost was added to each pot. Ten-day-old saplings were planted in each pot. Two pots were supplemented with compost and vermicompost and the other pot was left untreated. Loamy soil was used for plant growth experiments. After two months, as with the test pot, the untreated control pot was also supplemented with palash vermicompost. Daily, both pots were uniformly irrigated, and plants' height, root length, days until first flowering, number of flowers and fruits, and fruit size were observed. In addition, total plant and fruit biomass, root/shoot ratio, fertility coefficient, and harvest index were studied on 80th and 160th days of the experiment by sacrificing five randomly picked samples from each set. Similarly, all other wastes were processed using the same procedures.

The harvest index (h_i) and the fertility coefficient (f_c) were calculated using Equations (2) and (3), respectively:

$$h_i = \frac{\text{Total fruit biomass}}{\text{Total plant biomass}} \times 100 \quad (2)$$

$$f_c = \frac{\text{Number of fruits produced per plant}}{\text{Total number of flowers per plant}} \times 100 \quad (3)$$

Statistical Analysis

All the experiments were carried out in triplicate (n = 3). Multiple regression and standard mean tests were carried out to evaluate differences between treatments at a significance level of 95% ($p < 0.05$) using MS Excel 2007. The figures and plots were developed using MS Excel 2007. The significance of enhancement (E) or suppression (S) in chili and brinjal plant growth in compost- and vermicompost-treated pots compared to control was assessed using Student's *t*-test. For all the parameters used to assess performance, statistical significance (or otherwise) of the difference was calculated in terms of the confidence level (%) associated with the change. The standard Student's *t*-test was used to perform all the tests [39].

3. Results and Discussion

The results and discussion are presented in the following sequence: physico-chemical characterization of different solid wastes, variation in C:N ratio, vermicast recovery and zoomass study, pathogen content study, and, finally, a feasibility study (growing of chili and brinjal plants) concerning pre-composted vermicompost.

Information on the chemical constituents of waste is useful for assessing alternative processing and recovery options. A previous study reported the physical and chemical constituents of Bhopal's MSW [2]. Organic matter contributes the highest (69.39%) share in this waste. The physico-chemical characteristics of different wastes and bulking agents, i.e., for the digested biogas slurry such as EC (dS/m), pH, MC (%), C:N ratios, and N, P, and K content, were determined. Table S2 displays the physico-chemical characteristics of the different waste samples. The respective MC (%), values were 76.3 ± 6.21, 14.4 ± 5.32, 61.5 ± 4.21, 31.1 ± 5.26, and 41.6 ± 7.2 for the freshly digested biogas slurry (FDBS), palash leaf litter, hostel kitchen waste, Bhopal municipal waste, and household waste. Analyses of the other parameters are shown in Table S2. The C:N ratios of different wastes and FDBS were found to be 16.3 ± 0.02, 26.2 ± 1.08, 23.5 ± 1.02, 23.1 ± 1.07, and 22.1 ± 0.04. The EC values of the different wastes and FDBS were found to be 0.94 ± 0.03, 0.44 ± 0.08, 0.68 ± 0.07, 3.7 ± 0.05, and 3.1 ± 0.04. The values regarding N, P, and K content are presented in Table S2. An earthworm requires about 60–70% moisture for their growth and development [2]; thus, maintaining an adequate amount of moisture in feedstock during composting and vermicomposting is essential, as excessive moisture may create anaerobic conditions that could be fatal for earthworms.

The DBS with pH 8.4 ± 0.5 has plenty of N, P, and K. The other wastes were also enriched with nutrients. The major chemical properties of our substrate (DBS with different

wastes) processed by composting–vermicomposting are shown in Table 1. The data reveal that the synergistic employment of the composting and vermicomposting of different wastes induces significant changes in chemical composition compared to solo composting. The observed pH values for the vermicompost were comparatively lower than those of the compost. The control treatment and active phase of composting did not significantly alter the wastes' pH, whereas a significant drop in pH was observed during vermicomposting. The data clearly indicate that compared to composting, vermicomposting different wastes causes significant changes in their chemical composition, which agrees well with previous studies [40,41]. The results reveal that N and P fractions' mineralization, the release of carbon dioxide, and organic acids from microbial metabolism might be responsible for these changes.

Table 1. Physico-chemical properties of different solid wastes treated through composting/vermicomposting (mean ± SD, n = 3).

Parameter	Bhopal Municipal Waste	MANIT Campus Waste	Single-Household Waste
	Composting		
MC (%)	40.50 ± 3.9	50.55 ± 4.2	60 ± 3
C:N	14.99 ± 0.35	14.30 ± 0.21	15.79 ± 0.33
pH	7.3 ± 0.8	6.7 ± 0.3	7.8 ± 0.34
EC (dS/m)	1.37 ± 0.08	1.69 ± 0.03	2.78 ± 0.02
N (%)	1.08 ± 0.6	1.102 ± 0.7	1.13 ± 0.5
P (%)	0.308 ± 0.2	0.411 ± 2.2	0.413 ± 0.6
K (%)	0.689 ± 0.2	0.611 ± 1.3	0.789 ± 0.5
	E. fetida		
MC (%)	55 ± 5.2	53 ± 6.3	58 ± 6.2
C:N	9.98 ± 0.41	9.73 ± 0.31	10.01 ± 0.23
pH	7.0 ± 0.2	6.5 ± 0.3	7.8 ± 0.6
EC (dS/m)	1.25 ± 0.08	1.06 ± 0.02	2.05 ± 0.02
N (%)	1.601 ± 4	1.57 ± 5	1.701 ± 4
P (%)	1.011 ± 1	1.19 ± 2	1.01 ± 1
K (%)	1.250 ± 3	1.109 ± 4	1.301 ± 4
	E. eugeniae		
MC (%)	53 ± 6.3	52 ± 6.1	55 ± 6.5
C:N	10.39 ± 0.41	10.89 ± 0.3	10.72 ± 0.32
pH	7.0 ± 0.02	6.99 ± 0.1	7.7 ± 0.02
EC(dS/m)	1.76 ± 0.01	1.07 ± 0.01	2.10 ± 0.02
N (%)	1.52 ± 1	1.57 ± 5	1.69 ± 2
P (%)	1.11 ± 3	1.02 ± 2	0.987 ± 1
K (%)	1.20 ± 3	1.109 ± 3	1.301 ± 1

The salinity of an organic amendment is measured through its EC. High salt concentrations may cause phytotoxicity. Thus, in agronomy, EC is an indicator of the suitability and safety of compost or vermicompost. In this study, EC was affected in numerous ways by the application of the different treatments. The value of this parameter decreased after vermicomposting compared to that following composting (Table 1). Kalamdhad et al. [42] reported a drop in EC at the end of composting, which could be attributed to ammonia volatilization and the precipitation of mineral salts. During vermicomposting, the production of soluble metabolites such as ammonium and the precipitation of dissolved salts in modest amounts may lead to lower EC values [43,44]. After different treatments, the vermicompost's EC did not exceed the threshold limit of 3 dS/m. This indicates that it is a material that can be safely applied for soil amendment.

The data on pH changes are given in Table 1. Composting and vermicomposting significantly altered the properties of the different feed mixtures tested in the current study. Lower pH was recorded for the final products, which might have been due to the production of carbon dioxide and organic acids via microbial metabolism during the decomposition

of the different substrates in the feed mixtures [45]. The results are in line with those regarding the vermicomposting of cattle manure [43] and fruit and vegetable wastes [44]. It was found that the use of different substrates could result in the production of different intermediate species resulting in different behaviors with pH shifts. Ndegwa et al. [35] observed that the shifting of pH to lower levels could be attributed to the mineralization of nitrogen and orthophosphates and the bioconversion of organic materials into intermediate species of organic acids.

Moisture loss during composting and vermicomposting reflects the decomposition rate since the heat generation that accompanies decomposition drives vaporization. However, the moisture content in composting material is essential for the survival of organisms. After thorough mixing due to a change in moisture levels, the differences in the moisture content leveled out, and the temperatures dropped again. This indicates that the composting process still proceeded very actively. Table 1 shows the MC after the maturation of the primarily stabilized compost. The respective decreases in MC were 10–27% and 12–32% after maturation in the composting and vermicomposting processes compared to the MC present in fresh waste (Table S2). Therefore, vermicomposting can be viewed as an effective process for the maturation of primarily stabilized compost.

Figure 1 displays the evolution of temperature during the composting process. Microbial activity that started during the early hours of operation resulted in an increase in temperature. Initially, the compost temperature was 27–35 °C, which increased to 50–55 °C through composting with different wastes. Temperature fluctuation was more pronounced for the initial 16 days; thereafter, only minor changes were measured until 24 days. Depending on the ambient temperature conditions, the inlet zone temperature of the reactor generally varied between 40 and 55 °C. During composting, the temperature occasionally surpassed 55 °C. Temperatures between 52 and 60 °C are considered to facilitate the greatest thermophilic activity in composting systems [46], and in continuously thermophilic composting systems, carbon dioxide evolution has been witnessed to be submaximal at higher temperatures [47–49]. The temperature in the reactor's mid zone varied between 35 and 50 °C, indicating comparatively lower microbial activity. The reactor's outer zone temperature was equal to ambient temperature or was slightly higher (4–10 °C), indicated the conclusion of the active thermophilic phase. The general observations regarding the temperature variations in the different wastes within the reactor over 24 days are presented in Figure 1.

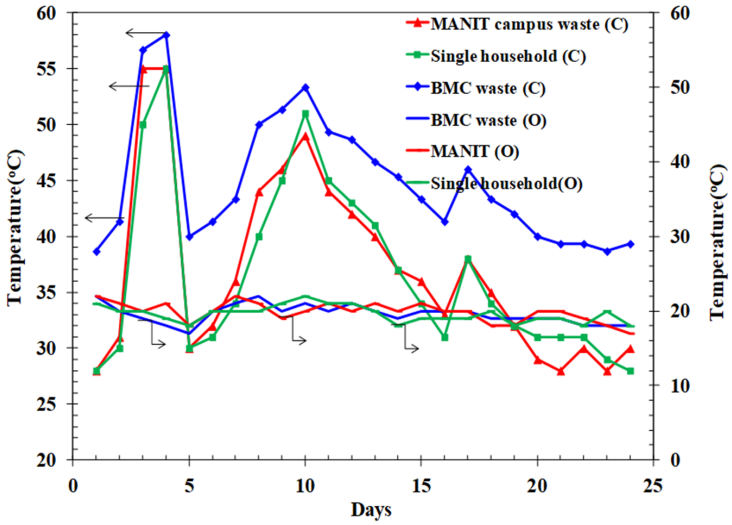


Figure 1. Temperature of the different solid waste over the period of composting. C: compositing; O: outside temperature. The arrow in figure: Indicating temperature.

Previous studies concerning the optimization of the design and operation of vermireactors for the economic improvement of vermicomposting systems have been reported [2,25].

This study also explored the possibility of utilizing different types of solid wastes in generating vermicast in order to provide a wider base of feedstock for vermiconversion systems. Studies conducted to determine whether the vermicast obtained from different feeds stimulates plant growth have also been performed. One of the major issues while designing and optimizing vermireactors has been the acquisition of accurate information on vermicast production per unit feed and per adult animal under different rates of feed inputs, worm densities, and in reactors of different geometries. In conventional vermireactor experiments, the natural biodegradation of feed and the utilization of some of the feed by worm offspring interfere with these determinations because the processing time is only a few months. With time, such interference intensifies, making it impossible to accurately assess the long-term performance of earthworms in vermiconversion.

To reduce the vermicomposting time, mixed wastes were first composted and then vermicomposted. To study the effects of the surface area-to-volume ratio (reactor geometry), nine reactors of different sizes were prepared (R1–R9). Reactor R1 presented the highest surface area-to-volume ratio, while reactor R9 presented the lowest. MANIT campus waste consists of hostel kitchen waste, palash leaf litter, and DBS. Hostel kitchen waste and palash leaf litter were mixed in a 1:2 w/w. When comparing the critical parameters observed during the composting and vermicomposting of different wastes, the results for the MANIT campus waste were relatively better, with lower C:N ratios and higher NPK values. In view of this, the MANIT campus waste was selected as the feed waste to be used in further study. Table 2 displays the physical and chemical parameters of the MANIT campus waste for vermicomposting (after a pre-composting period of 24 days). The MC (%), pH, C:N ratios, EC, and NPK (%) of nine reactors were analyzed.

Compared to feedstock, vermicompost was darker in color and had been processed into a roughly homogenous mixture after 24 days of earthworm activity. Vermicomposting significantly altered the physio-chemical properties of the different tested feed mixtures, inducing minor variations in the final pH (Table 2). The pH dropped from alkaline to near neutral (7.6 $\pm$ 0.04), which was attributed to the mineralization of N and P into nitrates/nitrites and orthro-phosphates and the bioconversion of organic materials into intermediate species of organic acids [35,50]. During vermicomposting, the production of carbon dioxide and organic acid via microbial decomposition lowers the pH of the substrate [51]. A similar pattern of change in EC was found during all the treatments. The initial EC in the feed mixture was in the 0.64 $\pm$ 0.04–0.94 $\pm$ 0.14 dS/m range, while the final EC was in the 1.2 $\pm$ 0.05–1.90 $\pm$ 0.02 dS/m range. The increase in EC might have been due to the loss of weight of organic matter and the release of different mineral salts in available forms [52].

Initially, the MANIT campus waste had higher MC and C:N ratios. Adequate MC (60–70% range) is the foremost requirement of earthworms during vermicomposting [53,54]. The feed mixtures tested in the current research had moisture content within the suggested range. During vermicomposting, significant changes in the physico-chemical characteristics of the feed mixtures occurred. Worms can survive in environments with a pH range of 5 to 9 [55]. However, a 7.5–8.0 pH range is considered optimal. Initially, the pH of the feed mixtures varied from acidic to alkaline. However, the final pH of the vermicomposts was near a neutral pH value. In addition, organic matter decomposition generates ammonium ions and humic acids [56,57]. The presence of carboxylic and phenolic groups in humic acids resulted in a decrease in pH, while the presence of ammonium ions increased the pH of the system. The synergic effect of these two processes regulates the pH of vermicompost, leading to a shift in pH towards neutrality. In general, the pH of worm beds, due to the fragmentation of organic matter under a series of chemical reactions, tends to drop over time. Thus, if the food sources are alkaline, the effect is moderate, tending toward neutral or slightly acidic values, and if acidic (e.g., coffee grounds, peat moss, etc.), the pH of the beds can drop well below 7. Under such acidic conditions, pests such as mites may become abundant. A drop in pH might be another important factor for N retention as this element is lost as volatile ammonia at higher pH values [58].

Table 2. Physico-chemical properties of MANIT campus waste for vermicomposting (pre-composted) (mean ± SD, n = 3.43).

Parameter	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5	Reactor 6	Reactor 7	Reactor 8	Reactor 9
					E. fetida				
MC(%)	62 ± 5.2	60 ± 0.2	63 ± 4.0	63 ± 5.6	65 ± 6.0	68 ± 6.0	67 ± 6.0	69 ± 4.0	70 ± 4.0
C/N	9.2 ± 0.3	9.0 ± 0.2	9.5 ± 0.4	10.1 ± 0.2	9.5 ± 0.3	9.6 ± 0.2	9.3 ± 0.1	9.2 ± 0.3	9.5 ± 0.3
pH	7.5 ± 0.3	7.8 ± 0.2	7.6 ± 0.3	7.5 ± 0.5	7.8 ± 0.6	7.0 ± 0.2	7.3 ± 0.2	7.2 ± 0.2	7.5 ± 0.3
EC (dS/m)	1.98 ± 0.07	1.68 ± 0.02	1.79 ± 0.03	1.86 ± 0.02	1.98 ± 0.07	1.93 ± 0.06	1.98 ± 0.03	1.97 ± 0.02	1.99 ± 0.02
N (%)	1.502 ± 0.02	1.313 ± 0.04	1.308 ± 0.03	1.302 ± 0.02	1.278 ± 0.03	1.379 ± 0.04	1.179 ± 3.0	1.220 ± 0.03	1.108 ± 0.02
P (%)	1.28 ± 0.02	1.27 ± 0.01	1.22 ± 0.02	1.108 ± 0.01	1.07 ± 0.01	1.09 ± 0.01	1.08 ± 0.02	1.07 ± 0.02	1.07 ± 0.03
K (%)	1.381 ± 0.01	1.38 ± 1.0	1.38 ± 0.02	1.27 ± 0.01	1.27 ± 0.01	1.2 ± 0.02	1.10 ± 0.03	1.08 ± 0.03	1.081 ± 0.04
					E. eugeniae				
MC (%)	59 ± 2.5	58 ± 6.0	62 ± 5.0	65 ± 4.9	68 ± 4.0	72 ± 3.0	72 ± 2.9	73 ± 2.8	75 ± 4.0
C/N	10.2 ± 0.31	10.8 ± 0.41	10.7 ± 0.32	10.79 ± 0.35	10.72 ± 0.25	10.72 ± 0.22	10.71 ± 0.25	10.5 ± 0.27	10.7 ± 0.41
pH	7.2 ± 0.07	7.1 ± 0.02	7.5 ± 0.02	7.8 ± 0.03	7.8 ± 0.09	7.0 ± 0.07	7.8 ± 0.08	7.5 ± 0.02	7.0 ± 0.07
EC (dS/m)	1.23 ± 0.02	1.40 ± 0.01	1.52 ± 0.02	1.81 ± 0.07	1.52 ± 0.08	1.40 ± 0.02	1.87 ± 0.07	1.98 ± 0.01	1.7 ± 0.02
N (%)	1.113 ± 0.03	0.895 ± 0.05	0.878 ± 0.04	0.834 ± 0.03	0.798 ± 0.02	0.913 ± 0.03	0.940 ± 0.02	0.934 ± 0.02	0.838 ± 0.03
P (%)	1.090 ± 0.02	1.01 ± 0.03	0.98 ± 0.02	0.79 ± 0.02	0.775 ± 0.03	0.79 ± 0.02	0.708 ± 0.02	0.72 ± 0.03	0.71 ± 0.03
K (%)	1.19 ± 0.02	1.17 ± 0.03	1.12 ± 0.01	1.09 ± 0.03	1.02 ± 0.02	1.0 ± 0.03	0.979 ± 0.04	0.838 ± 0.04	0.923 ± 0.02
					E. fetida + *E. eugeniae*				
MC (%)	62 ± 5.2	60 ± 0.2	63 ± 4.0	63 ± 5.6	65 ± 6.0	68 ± 6.0	67 ± 6.0	69 ± 4.0	70 ± 4.0
C/N	8.30 ± 0.3	9.32 ± 0.3	8.70 ± 0.3	9.98 ± 0.3	8.25 ± 0.2	8.99 ± 0.2	9.20 ± 0.2	8.10 ± 0.3	8.78 ± 0.2
pH	7.5 ± 0.2	7.9 ± 0.3	8.1 ± 0.4	8.0 ± 0.3	7.8 ± 0.4	8.5 ± 0.3	8.3 ± 0.7	7.9 ± 0.6	8.1 ± 0.2
EC (dS/m)	0.98 ± 0.07	1.32 ± 0.02	1.79 ± 0.02	1.20 ± 0.07	1.70 ± 0.02	2.10 ± 0.07	1.79 ± 0.02	0.98 ± 0.07	1.58 ± 0.04
N (%)	1.79 ± 0.03	1.686 ± 0.02	1.685 ± 0.03	1.58 ± 0.04	1.585 ± 0.02	1.68 ± 0.03	1.68 ± 0.04	1.67 ± 0.02	1.68 ± 0.03
P (%)	1.12 ± 0.02	1.19 ± 0.04	1.17 ± 0.04	1.2 ± 2.0	1.18 ± 0.01	1.19 ± 0.02	1.28 ± 0.03	1.17 ± 0.02	1.19 ± 0.01
K (%)	1.5 ± 0.03	1.48 ± 0.01	1.17 ± 0.02	1.28 ± 1.0	1.18 ± 0.03	1.08 ± 0.02	1.17 ± 0.03	1.08 ± 0.02	1.17 ± 0.01

Vermicomposts with a pH range of 6.0–8.5 are suitable for soil application [59]. Worms are highly sensitive to salts. They prefer < 0.5 ds/m (EC) salt content in their feed [60]. After vermicomposting, a rise in EC was recorded, which might have been due to an increased level of soluble salts in available forms due to the mineralization of the feed mixtures by earthworms and micro-organisms [52]. Figure 2a,b display the variation in pH during the vermicomposting process in nine different reactors with *E. fetida*. In all the reactors, the pH dropped from an alkaline range (8.6–8.8) to a near neutral range (7.0–7.6).

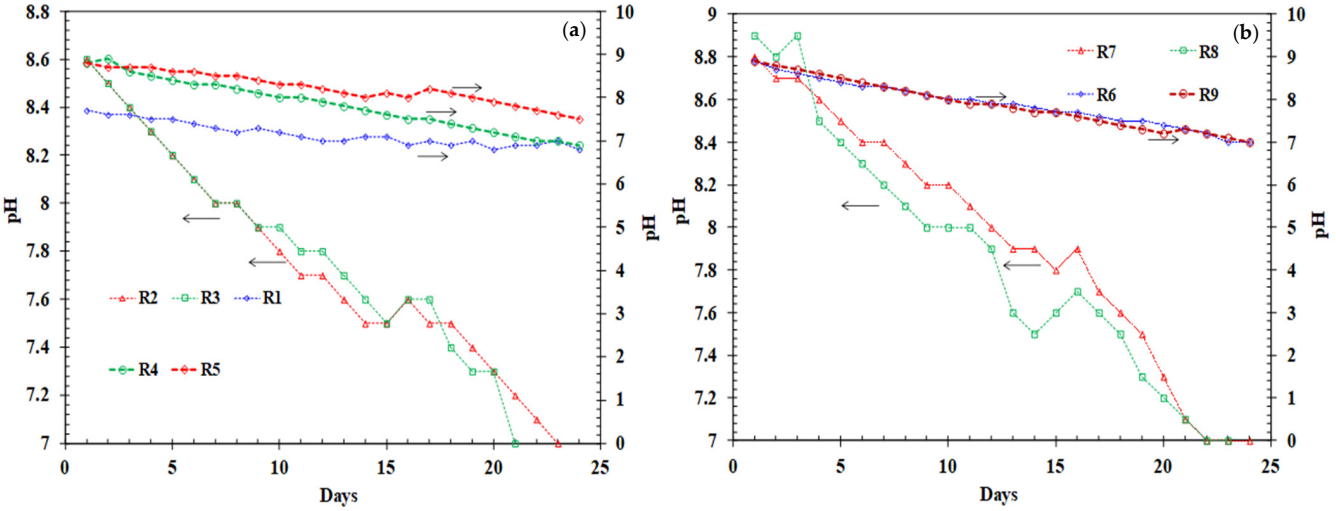


Figure 2. Variation in pH of the substrate in composting-vermicomposting (*E. fetida*) of the different reactors (R1–R5) (**a**) and R6–R9 (**b**) over experimental period (Hostel kitchen waste + Palash leaf litter).

The total N content increased between 1.58 and 1.79% in the final products of the different vermibeds containing *E. fetida* (Table 2). An increase in the nitrate–nitrogen content of cow dung slurry was reported in the presence of *E. fetida* [61]. The organic carbon loss might be due to N addition as mucus nitrogenous excretory substances, growth stimulatory hormones, and enzymes from earthworms' guts [62]. Atiyeh et al. [63] reported that by enhancing N mineralization, earthworms have a great impact on N transformation in manure, allowing N to be retained in a nitrate form.

The total P content was also greater in the final vermicomposts (Table 2). In all reactors, the total P content was between 0.70 and 1.28%, attaining a maximum level (1.28%) in R1 when *E. fetida* was the worm species used. Compared to the values in R1, the P content was 1.07% in R9 (*E. fetida*). The physical breakdown of the earthworms might be a reason behind this result [64]. According to Lee [65], the passage of organic residue through the earthworm gut releases P in an available form. Furthermore, the release of P might be attributed to P-solubilizing microorganisms present in the worm cast.

The total K concentration was increased in the vermicomposts prepared in all the reactors. Benitez et al. [66] found that leachate collected during vermicomposting had higher K concentrations. Kaviraj and Sharma [52] found 10 and 5% increases in total K level when using *E. fetida* and *E. eugeniae*, respectively, during vermicomposting. Suthar [67] observed that earthworm-processed waste material contains high K concentrations due to intensified microbial activity during vermicomposting, which, consequently, raises the mineralization rate. The MANIT campus waste can be ingested by earthworms and converted to humus, for which vermicompost is an example. During conversion, important plant nutrients, such as N, P, and K, present in the feed were converted into forms that were more available to plants than those in the parent substrate, which accords well with previous studies [68]. Due to their high organic content and non-toxicity, food wastes may be a suitable feed for the growth and development of earthworms. The vermicomposting of wastewater treatment plant sludge from industries, institutions, etc., has been reported [2,69]. Earlier, studies had found lower survival rates of earthworms in industrial wastes [70]. Therefore,

it is essential to replace some nutrient-rich organic wastes such as biogas plant slurry, poultry droppings, cow dung, etc., with industrial wastes in order to provide nutrients and inoculums of micro-organisms for vermicomposting [6,69]. This study was carried out to optimize the vermicomposting process of different types of wastes and different sizes of reactors to resolve solid waste disposal issues. The ratio and physico-chemical characteristics of the different constituents of a feed mixture significantly affect the fertilizer value of the vermicompost and the growth and reproduction of worms during the vermicomposting process [45,71].

The P and K content was higher in the vermicomposts compared to the feed mixtures. The P content of the vermicomposts was 42–70% higher than that in the feed mixtures. The K content in the feed mixtures and vermicomposts were in the range of 0.5–1.3% and 0.92–1.38%, respectively. Thus, the K content in the vermicomposts presented a 1.2–1.9-fold increase compared to the feed mixtures. The C:N ratios of the vermicomposts were between 9 and 10. This indicates a high degree of stabilization in all the feed mixtures.

Table 2 shows variation in various physico-chemical parameters in reactors R1 to R9. The parameters studied were MC, C:N ratio, pH, EC, and the N, P, and K content following the conclusion of the composting–vermicomposting period. *E. fetida* and *E. eugeniae* were the worm species analyzed. To examine the effect of reactor geometry on the composts' and vermicomposts' physical and chemical properties, nine wooden reactors with different surface area-to-volume ratios were constructed. The surface area to volume ratios decreased from reactors R1 to R9. When *E. fetida* was the employed species, the C:N ratio was 3.1% lower in R1 compared to R9, while the N content was 7.6% greater in R1 compared to R9. The results regarding the *E. eugeniae* species showed a 4.6% decrease in C:N ratio and an 8.2% increase in N content in R1 compared to R9 (Table 2). Polyculture studies revealed a 5.4% lower C:N ratio and 6.5% greater N content.

Figures 3 and 4 display the variation in pH and moisture content during vermicomposting using the polyculture species in nine different reactors. In all the reactors, the pH dropped from alkaline to a near neutral range. MC also dropped from 80–85 to 55–65%. The excessive application of chemical fertilizers and pesticides has rendered soil toxic and problematic, leading to adverse effects on both human and environmental health. Annually, millions of tons of animal, agricultural, and kitchen wastes are produced. In recent years, considerable attention has been paid to managing different organic waste resources at low inputs and on an eco-friendly basis. Vermicomposting, i.e., composting via earthworms, is an eco-biotechnological process for transforming energy-rich and complex organic substances to stabilized vermicomposts [66].

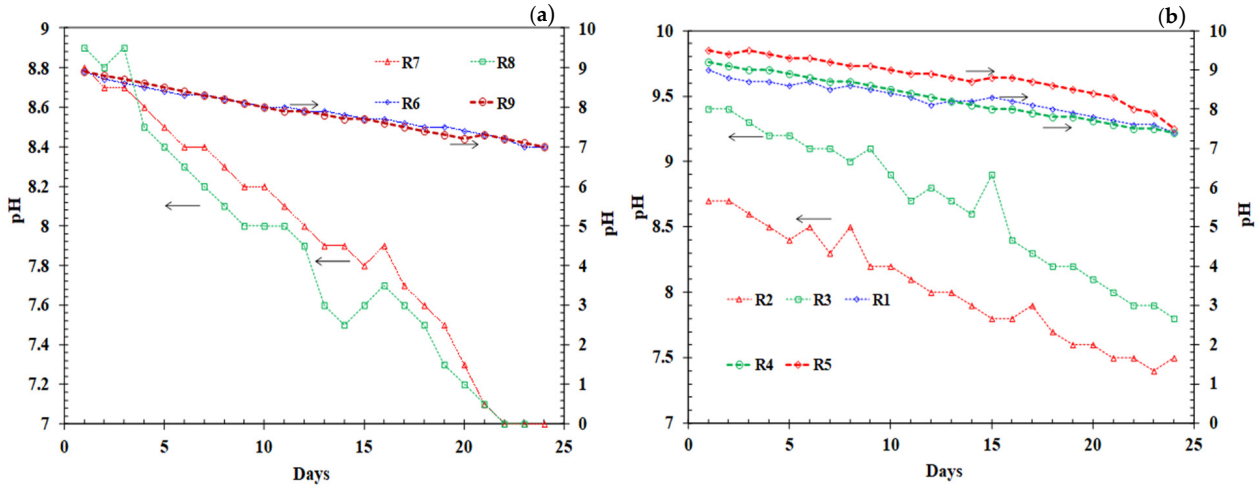


Figure 3. Variation in pH of the substrate in composting-vermicomposting (*E. fetida* + *E. eugeniae*) of the different reactors (R1–R5) (**a**), and R6–R9 (**b**) over experimental period (Hostel kitchen waste + Palash leaf litter).

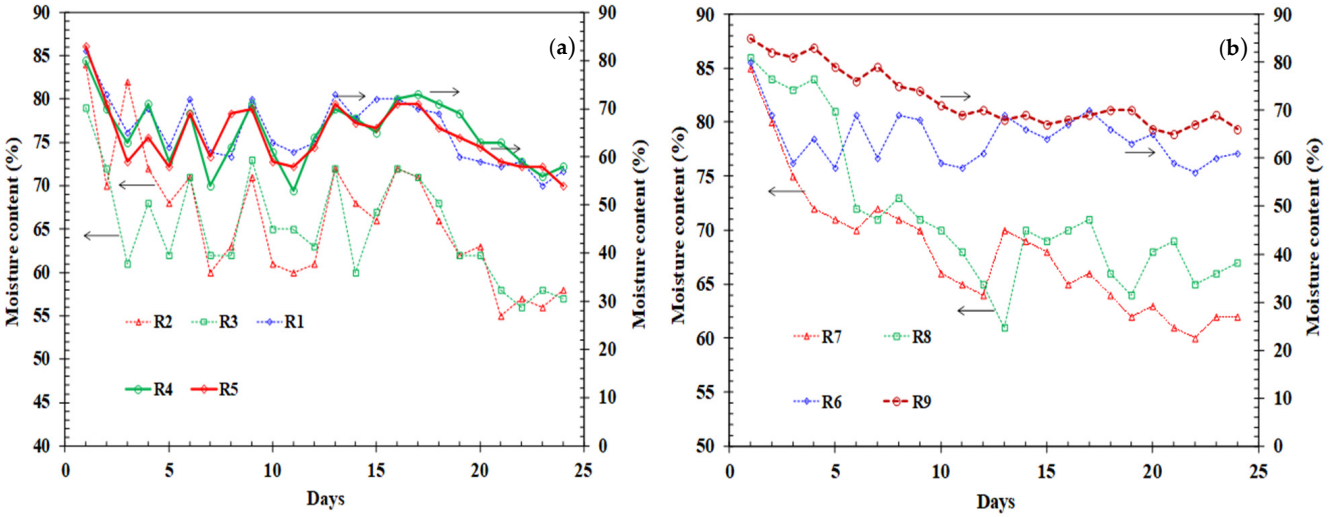


Figure 4. Moisture content of the substrate in different reactor (R1–R5) (**a**), and R6–R9 (**b**) (Hostel kitchen waste + Palash leaf litter) (*E. fetida* + *E. eugeniae*).

Vermicomposting through different earthworm species has been studied. Paper–pulp mill sludge mixed with primary sludge was converted to vermicompost by *Eisenia andrei* [45]. *Eudrilus eugeniae*, an epigenic earthworm, can be used to convert post-harvest crop residues and cattle shed manure into vermicompost [71]. Epigenic earthworms can substantially accelerate the composting process, leading to the production of better-quality vermicomposts [15]. *E. fetida* is suitable for waste management because it can successfully transform wastes into vermicompost [44]. In the current study, the suitability and potential uses of *E. fetida* and *E. eugeniae* were explored with respect to the conversion of MANIT campus waste into vermicompost.

Previous studies have reported the results of using cattle dung and plant-derived waste as substrates, whereas in the current study, different types of solid organic wastes have been used. Therefore, the major difference between the current and past results could be related to the nature of the feed material employed. Suthar [67] demonstrated that *P. sansibaricus* showed better weight gain and reproducibility. In addition, the resulting vermicompost had high N content. The observed difference might be due to the substrate chemistry, the species' feeding behavior, or both. Earthworm mortality is a major concern during the vermicomposting of these waste materials. However, degradation probably causes drastic changes in some environmental characteristics of decomposing vermibeds. These changed conditions influence worms' survival rates. The difference in worm mortality between the studied species could be related to the specific composting behavior or specific tolerance nature of earthworms with respect to a changing microenvironment in the composting subsystem. Overall, *E. fetida* appeared to be more efficient than *E. eugeniae* in terms of organic waste mineralization. Thus, the current study clearly indicates that the vermicomposting of different wastes could be an effective alternate process for converting waste to value-added products.

The earthworm species *E. fetida* and *E. eugeniae* were used for vermicomposting. After 24 days of vermicomposting, the chemical analyses of the substrates worm-worked by both species showed an increase in N, P, and K content, while a decrease in C:N ratio was observed. *E. fetida* produced 68, 8.8, and 12% increases in N, P, and K content as well as 10% decreases in C:N ratios compared to *E. eugeniae*. The use of polyculture species yielded 27, 14, and 36% increases in N, P, and K content and a 4.5% decrease in C:N ratio compared to the monoculture species (*E. fetida*). These results indicate that polyculture may be a better technique for vermicomposting. The recycling of agricultural wastes through vermicomposting can mitigate their disposal issues. Vermicomposting is not only an alternate source of organic fertilizers but can also provide economical animal feed

protein for the fishery and poultry industries globally [72]. Vermicomposts have more available nutrients per weight than their organic waste precursors [73]. Jambhekar [74] reported enhancement in N, P, and K content and improvement in soil fertility through the application of vermicomposts. The nutrients present in vermicomposts are readily available for plant growth. The transplantation of earthworms and mulching facilitate the transfer of nutrients to plants [23].

3.1. Variation in C:N Ratio

The quality and maturity of compost is measured via its C:N ratio. This ratio indicates the degree of decomposition of waste as carbon is lost as carbon dioxide during bio-oxidation, whereas N is lost at a lower rate. Therefore, the more decomposed a waste, the lower its C:N ratio. The C:N ratio of the vermicompost was comparatively lower than that of the compost, while the highest reduction was observed in the vermicompost processed by *E. fetida* + *E. eugeniae*. The difference in C:N ratio significantly varied between the treatments. The C:N ratios of both the compost and vermicompost as a function of time were determined. Composting gradually improved the fraction of N (Table 3), as some of the carbon was lost in the form of bacterial metabolites, principally carbon dioxide. However, the vermicompost presented a decreased C:N ratio (Table 3), thereby confirming the loss of carbon content. The total N content after vermicomposting was comparatively higher than that after composting. Consequently, the C:N ratio was significantly lower in the treatments involving vermicomposting, which indicates that they underwent more intense decomposition.

Table 3. C:N ratio of the compost/vermicompost harvested from each run; C:N ratios of nine samples were analyzed each time (mean ± SD, n = 1.91).

Days	Bhopal Municipal	MANIT Campus	Single-Household
	Compost		
3	14.75 ± 0.5	14.2 ± 0.6	15.7 ± 0.3
6	11.6 ± 1.0	12.3 ± 0.2	14.5 ± 0.6
9	11.2 ± 0.35	11.1 ± 0.8	13.3 ± 0.3
12	10.1 ± 0.3	11.0 ± 0.7	11.3 ± 0.1
15	10.3 ± 0.4	10.9 ± 0.2	11.1 ± 0.3
18	10.0 ± 0.2	10.6 ± 0.2	10.9 ± 0.2
21	10.0 ± 0.25	10.6 ± 0.3	10.7 ± 0.4
24	10.1 ± 0.22	10.7 ± 0.3	10.9 ± 0.3
	E. fetida		
3	10.1 ± 0.16	10.6 ± 0.90	10.67 ± 0.81
6	10.1 ± 0.22	9.9 ± 0.155	10.5 ± 0.77
9	9.8 ± 0.3	10.2 ± 0.13	10.2 ± 0.85
12	9.7 ± 0.22	10.3 ± 0.80	10.1 ± 0.77
15	9.7 ± 0.12	10.2 ± 0.95	9.9 ± 0.53
18	9.7 ± 0.13	9.9 ± 0.86	9.7 ± 0.50
21	9.6 ± 0.02	9.7 ± 0.19	9.8 ± 0.95
24	10.1 ± 0.03	9.2 ± 0.79	9.0 ± 0.88
	E. eugeniae		
3	9.9 ± 0.12	10.71 ± 0.10	9.92 ± 0.16
6	9.8 ± 0.15	9.7 ± 0.13	9.7 ± 0.7
9	9.0 ± 0.27	9.2 ± 0.11	8.9 ± 0.6
12	9.7 ± 0.12	9.2 ± 0.8	9.5 ± 0.6
15	9.2 ± 0.31	9.1 ± 0.10	9.2 ± 0.31
18	9.1 ± 0.12	9.6 ± 0.11	8.8 ± 0.11
21	9.1 ± 0.11	9.5 ± 0.12	9.3 ± 0.7
24	9.9 ± 0.15	9.6 ± 0.10	9.5 ± 0.14

The C:N ratio decreased by 50–60% for different wastes. This is an indicator of the wastes' stabilization. The C:N ratio was measured every third day. Table 3 displays

its variation during the vermicomposting process. The performance of the combination of composting–vermicomposting was tested to improve treatment efficiency and assess the optimum period required in each method to produce better-quality compost. The results show that pre-composting improved the vermicomposting of MANIT campus waste, while achieving a 24.64% reduction in C:N ratio during composting and 13.20% during vermicomposting.

Leaf litter, such as that from palash trees, poses disposal issues in urban/suburban locations in India and several other countries in the southern hemisphere. They are often piled up and set on fire. This practice deteriorates air quality. Hostel kitchen waste and leaf litter (from the palash tree) can be composted and utilized as a fertilizer or soil conditioner; however, the market value of such compost is low. Conversely, vermicompost has high market value (about three times higher than compost). In developed countries, it is a preferred soil conditioner for farmers. Apart from enriching soil with organic carbon and NPK, which regular compost can achieve, vermicompost is believed to confer additional benefits by providing enzymes and hormones that stimulate plant growth [75]. A detailed investigation of the possible causes of this phenomenon revealed that while the C:N ratio of palash compost was comparable with those of other substrates, such as mango [76], neem [77], and acacia [25], studies on leaf litter consumption by earthworms in natural or manmade forests have revealed that palash compost is rich in polyphenols and lignin, which are not preferred by many worm species.

A high nitrogen content is desirable in vermicompost. Results have shown a significant increase in the N content of vermicomposts upon mixing appropriate quantities of DBS. According to Crawford [78], the N content in vermicompost is dependent on the initial N present in the feedstock and the degree of decomposition. Viel et al. [79] have reported that losses in organic carbon might be responsible for N addition. The addition of N in the form of mucus, nitrogenous excretory substances, growth-stimulating hormones, and enzymes from earthworms has also been reported [62]. The mineralization of carbon-rich materials and the activity of N-fixing bacteria can invoke a substantial rise in N content [80]. During vermicomposting's initial stage, the rapid increase in nutrients that occurs may be due to higher degradation and mineralization rates due to the increased availability of food [81].

During vermicomposting, the C:N ratio (an index of waste maturity) in the reactors was monitored. A decrease in C:N ratio over time due to decomposition was observed during the experiments (Table 4). The initial C:N ratio was in the range of 14.01 $\pm$ 0.42–15.79 $\pm$ 0.33 for composting, while the final ratio was in the range of 9.0 $\pm$ 0.2–12.8 $\pm$ 0.17. With regard to vermicomposting with *E. eugeniae*, the initial C:N ratio was 9.9–11.8 and the final C:N ratio was 9.0–10.1, while with *E. fetida*, it varied from 12.8–10.2. According to Senesi [82], a decline in the C:N ratio to <20 indicates an advanced degree of organic matter stabilization and reflects a satisfactory degree of treatment. Suthar [71] reported that the C:N ratio of a substrate material reflects the mineralization and stabilization of organic waste during decomposition. The loss of carbon as carbon dioxide through microbial respiration and the addition of nitrogenous excretory material changes the C:N ratio of the substrate. A sharp decline in the C:N ratio during vermicomposting by *E. fetida* was observed. Similar results have been reported by Gupta and Garg [83] and Suther [71].

Polyculture species were used in reactors R1–R9 for the vermicomposting process. During the vermicomposting process, a variation in the C:N ratio with time was observed (shown in Table 4). A significant decrease in the C:N ratio was noticed. The initial value was in the range of 13.4–16.9, while the final value was in the range of 7.4–10.3.

Table 4. C:N ratio of the vermicompost harvested from each run; C:N ratios of nine samples were analyzed each time (MANIT campus waste) (mean ± SD, n = 2.19).

Days	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Reactor 5	Reactor 6	Reactor 7	Reactor 8	Reactor 9
					E. fetida				
3	12.3 ± 0.16	11.2 ±0.6	10.8 ± 0.12	12.2 ± 0.15	12.9 ± 0.7	11.9 ± 0.15	11.9 ± 0.17	12.7 ± 0.18	10.8 ± 0.19
6	12.7 ± 0.12	12.9 ± 0.19	11.5 ± 0.11	11.7 ± 0.7	12.8 ± 0.4	10.2 ± 0.7	12.8 ± 0.9	10.2 ± 0.2	10.7 ± 0.2
9	11.7 ± 0.15	11.6 ± 0.13	10.7 ± 0.7	11.8 ± 0.2	11.2 ± 0.4	11.2 ± 0.2	12.2 ± 0.2	10.9 ± 0.6	11.8 ± 0.2
12	11.2 ± 0.01	10.8 ± 0.03	10.8 ± 0.2	11.2 ± 0.3	11.2 ± 0.5	12.9 ± 0.2	11.2 ± 0.7	11.2 ± 0.7	10.8 ± 0.3
15	10.2 ± 0.6	10.7 ± 0.7	11.9 ± 0.7	11.2 ± 0.4	10.2 ± 0.7	12.8 ± 0.3	10.2 ± 0.7	10.7 ± 0.7	11.8 ± 0.5
18	12.8 ± 0.17	11.9 ± 0.19	11.7 ± 0.3	11.8 ± 0.3	11.2 ± 0.1	10.2 ± 0.5	11.7 ± 0.8	10.8 ± 0.7	10.8 ± 0.7
21	11.8 ± 0.17	11.2 ± 0.18	12.8 ± 0.1	10.2 ± 0.2	10.2 ± 0.3	10.3 ± 0.7	10.9 ± 0.6	11.2 ± 0.9	10.2 ± 0.8
24	10.7 ± 0.16	10.8 ± 0.13	10.9 ± 0.9	10.2 ± 0.2	10.3 ± 0.2	10.9 ± 0.9	10.2 ± 0.5	10.7 ± 0.5	10.0 ± 0.5
					E. eugeniae				
3	10.2 ± 0.12	11.8 ± 0.23	10.2 ± 0.5	11.5 ± 0.3	11.7 ± 0.4	10.8 ± 0.30	9.9 ± 0.17	10.8 ± 0.19	11.8 ± 0.17
6	10.7 ± 0.7	11.2 ± 0.7	9.0 ± 0.2	11.2 ± 0.7	11.2 ± 0.7	11.2 ± 0.3	10.8 ± 0.3	10.7 ± 0.3	10.2 ± 0.2
9	10.9 ± 0.2	10.2 ± 0.6	9.7 ± 0.3	10.9 ± 0.2	10.8 ± 0.6	11.2 ± 0.2	11.2 ± 0.3	11.8 ± 0.5	10.5 ± 0.1
12	11.2 ± 0.3	10.8 ± 0.7	10.2 ± 0.4	10.7 ± 0.2	10.2 ± 0.2	10.8 ± 0.2	10.2 ± 0.2	9.2 ± 0.4	10.6 ± 0.7
15	10.2 ± 0.2	11.2 ± 0.2	11.2 ± 0.2	11.2 ± 0.7	9.7 ± 0.2	9.9 ± 0.3	10.3 ± 0.2	11.2 ± 0.5	9.9 ± 0.6
18	9.3 ± 0.5	9.0 ± 0.4	9.8 ± 0.2	10.5 ± 0.2	9.3 ± 0.3	9.8 ± 0.2	10.0 ± 0.2	10.8 ± 0.7	9.5 ± 0.4
21	9.8 ± 0.9	9.2 ± 0.2	9.7 ± 0.7	10.2 ± 0.3	9.2 ± 0.3	9.7 ± 0.3	9.5 ± 0.4	10.7 ± 0.6	9.6 ± 0.3
24	9.2 ± 0.2	9.0 ± 0.2	9.5 ± 0.6	10.1 ± 0.2	9.5 ± 0.2	9.6 ± 0.2	9.3 ± 0.3	9.2 ± 0.2	9.5 ± 0.3
					E. fetida + *E. eugeniae*				
3	13.4 ± 0.8	13.7 ± 0.2	14.1 ± 0.3	14.7 ± 0.2	14.2 ± 0.3	15.8 ± 0.3	15.8 ± 0.7	16.6 ± 0.6	16.9 ± 0.2
6	13.8 ± 0.9	10.2 ± 0.3	13.7 ± 0.4	13.2 ± 0.4	13.5 ± 0.3	14.3 ± 0.2	14.2 ± 0.5	15.3 ± 0.7	16.3 ± 0.3
9	12.7 ± 0.6	9.7 ± 0.4	12.8 ± 0.6	12.2 ± 0.5	12.1 ± 0.5	13.2 ± 0.1	13.6 ± 0.4	14.4 ± 0.8	15.2 ± 0.4
12	12.8 ± 0.3	9.4 ± 0.5	11.3 ± 0.3	11.7 ± 0.3	11.8 ± 0.2	12.8 ± 0.4	12.4 ± 0.8	13.2 ± 0.6	14.3 ± 0.5
15	10.8 ± 0.7	9.0 ± 0.3	10.2 ± 0.3	10.3 ± 0.2	11.3 ± 0.5	11.2 ± 0.7	12.8 ± 0.6	13.8 ± 0.5	13.9 ± 0.3
18	9.7 ± 0.6	8.9 ± 0.5	9.3 ± 0.5	9.8 ± 0.1	9.9 ± 0.2	11.2 ± 0.5	10.3 ± 0.8	11.7 ± 0.3	13.8 ± 0.6
21	8.2 ± 0.4	8.7 ± 0.6	8.4 ± 0.7	9.2 ± 0.5	9.9 ± 0.1	10.8 ± 0.7	9.8 ± 0.6	10.2 ± 0.2	12.2 ± 0.4
24	7.4 ± 0.3	8.9 ± 0.7	8.3 ± 0.8	8.1 ± 0.4	8.5 ± 0.4	9.3 ± 0.9	8.2 ± 0.7	9.4 ± 0.3	10.3 ± 0.3

3.2. Vermicast and Zoomass Studies

The effect of the worm loading on vermicast production has been examined (shown in Figures S3–S6). In the reactor in which the loading was 62.5 animals per liter, 64.4% vermicast recovery was achieved when *E. fetida* was the earthworm species employed. Similarly, a 45.6% level of vermicast recovery was achieved when *E. eugeniae* was the earthworm species employed. When the animal density increased to 125 animals per liter, 89.7% and 68.2% vermicast recovery values were found in the *E. fetida*- and *E. eugeniae*-based reactors, respectively. The results are similar to those reported in previous studies on the effect of worm loading on vermicast recovery [34]. In light of this result, to further study the optimization of the process, parameters and worm density were kept constant (125 animals per liter for *E. fetida*). According to the results, maximum recovery was achieved in 20 days, which was about 90% for *E. fetida* and 84% for *E. eugeniae*. Thereafter, a slight decrease in recovery was observed, which is strongly supported by previous results [25]. The factors that may contribute to vermicomposting recovery include acceleration, wherein worms consume larger quantities of the composted manure as they become acclimatized to a feed, and an increasing worm body weight, wherein worms feed more voraciously because of their larger size. Through the influence of both factors, vermicast production reaches its peak. Thereafter, a reduction in vermicast recovery is observed. This may be the result of old worms dying while new ones gradually grow. The vermicompost generated by different wastes using an earthworm density of 125 animals per liter of reactor volume is shown in Figure S3. The improvement in vermireactor efficiency was even more dramatic in the vegetable-waste-based reactors. Inside the reactors, the worms grow and increase in weight. In addition, they reproduce. Figure S3 shows the vermicast recovery for the six different types of wastes used in this study. The market waste yielded 65–70% recovery, which is superior to the values yielded by the other wastes, for which recovery was in the range of 55–65%.

Figures S4–S6 show the vermicast recovery values in the R1 to R9 reactors for the monoculture (*E. fetida* and *E. eugeniae*) and polyculture species. The recovery using *E. fetida* was in the range of 70–84% and the recovery with *E. eugeniae* was 60–80%, while the percentage recovery for the polyculture species was 72–85%. The highest recovery was obtained in reactor R1, which was attributed to its higher surface area to volume ratio. The lowest recovery was observed in reactor R9. The results also show higher acceptability of these wastes as feed by the earthworms. Similar trends in the *E. fetida* + *E. eugeniae* growth rate were obtained in different vermireactors.

The overcrowding of worms is thought to adversely affect their access to feed and, consequently, retard their growth and reproduction. In addition, a reactor's geometry possibly contributes to the loss of efficiency. Feeding, mating, and resting activities are largely confined to the reactor's surface. Thus, an increase in the surface to volume ratio of the reactors will influence the worms' access to feed, thereby contributing to better worm-cast production, growth, and reproduction per worm. The studies have demonstrated that worms can survive, grow, and breed in the reactors fed with different materials. A rising trend in worm-cast output, despite the death of a few worms after 48 days of reactor operation, indicates the sustainability of this type of worm reactor. This work also indicates that an alteration in reactor geometry can uplift its efficiency.

Figure 5a–c show the effect of worm density on the increase in zoomass. Studies were initially conducted with a monoculture species and then with a polyculture species. The highest percentage increase in zoomass was observed for the worm density of 125 per liter. With a further increase in worm density, the zoomass percentage decreased. Comparing the zoomass studies in two reactors i.e., R1 and R9, the result shows that with the *E. fetida* species, a 66.7% increase was observed in reactor R1, while a 56.7% increase was observed in reactor R9. The studies with the polyculture species show a much better zoomass increase, namely, 72.3% in reactor R1 and 61.2% in reactor R9.

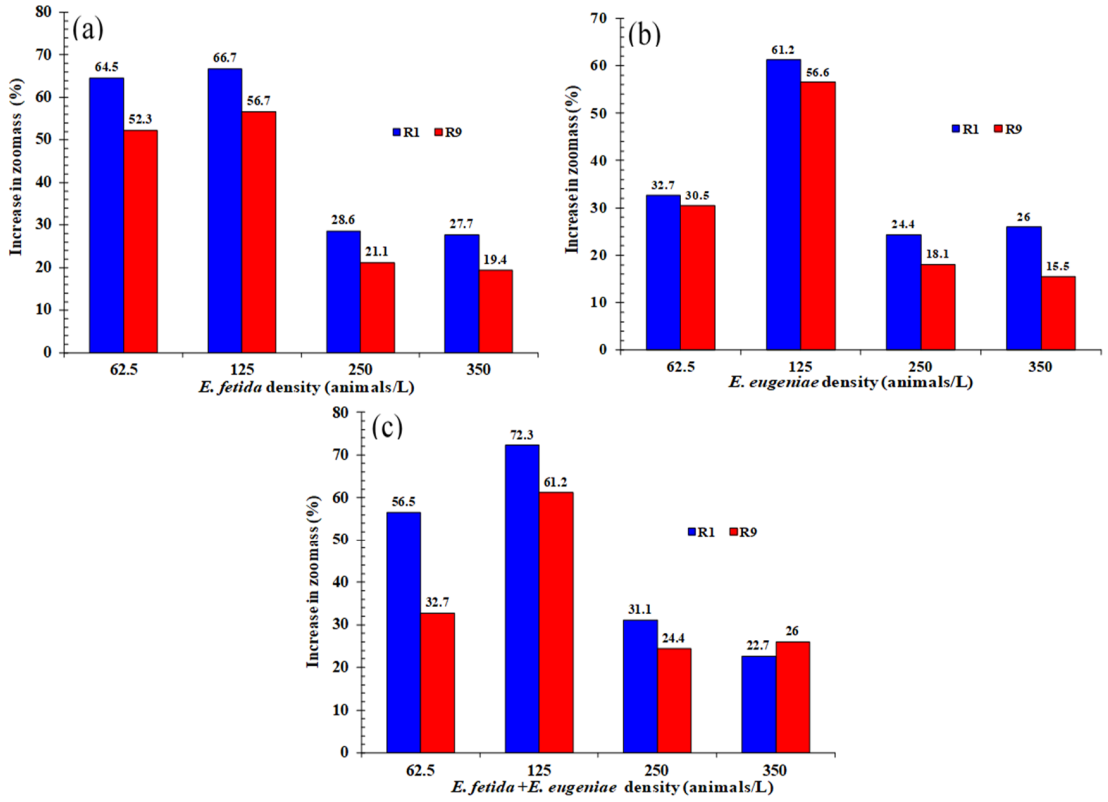


Figure 5. Average net increase in worm zoomass in R1 and R9 reactors at different *E. fetida* (**a**), *E. eugeniae* (**b**), and *E. fetida* + *E. eugeniae* (**c**) densities, (Hostel kitchen waste + Palash leaf litter).

Tables 5 and 6 show the pathogen counts in terms of *E. coli* and *E. faecalis* for the composting and composting–vermicomposting processes. Though good-quality vermicompost was achieved during the 48 days of the composting–vermicomposting process, the substrate needed to be left in a vermicomposting system for at least two months (60 days) to ensure the microbial safety of the vermicompost. The final products (compost–vermicast) were sanitarily tested, yielding negative results for *E. coli* and *E.feacelis*. Table 5 shows the pathogen content measured for compost-vermicomposting processes; it was possible to achieve very low pathogen content (<6 MPN/g) after the vermicomposting process. Similar results were obtained when we prepared the vermicompost using different types of waste (BMC waste, MANIT campus waste, and single-household waste) (shown in Table 6). A significant reduction in pathogen content was achieved in the monoculture- and polyculture-fed vermireactors (R1–R9). A comparison between the two shows that the use of two species is beneficial for pathogen reduction compared to the use of a single species (shown in Table 6).

Table 5. Pathogen content in terms of *E. coli* (MPN/g) and *E. faecalis* (MPN/g) over composting and vermicomposting period.

Process	Bhopal Municipality Waste		MANIT Campus Waste		Single-Household Waste	
	E. coli	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*
Composting	>95	>93	>93	>91	>72	>75
Vermicomposting (*E. fetida*)	5.4	5.6	5.0	5.5	5.0	5.7
Vermicomposting (*E. eugeniae*)	6.7	6.9	6.0	6.5	6.3	5.8

Table 6. Pathogen content in terms of *E. coli* (MPN/g) and *E. faecalis* (MPN/g) over the composting–vermicomposting period (hostel kitchen waste + palash leaf litter).

Process	Reactor 1		Reactor 2		Reactor 3		Reactor 4		Reactor 5		Reactor 6		Reactor 7		Reactor 8		Reactor 9	
	E. coli	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*	*E. coli*	*E. faecalis*
Vermicomposting (*E. fetida*)	6.8	6.7	6.9	6.9	7.0	7.3	7.1	7.2	7.0	7.8	9.1	9.7	7.7	9.4	8.0	8.0	6.9	6.7
Vermicomposting (*E. eugeniae*)	9.9	9.8	9.0	8.6	8.2	8.0	8.1	7.4	8.4	8.6	6.0	5.9	8.0	8.0	9.5	8.0	7.0	8.0
Vermicomposting (*E. fetida* + *E. eugeniae*)	5.7	6.0	7.8	7.4	4.1	7.0	7.0	7.3	7.4	7.7	6.1	5.7	6.2	6.6	6.3	5.7	6.2	6.7

3.3. Feasibility Study (Growing of Chilli and Brinjal Plants) over Composting/Vermicomposting Period

The experimental findings on the plant growth of the chili and brinjal plants using compost and vermicompost are summarized in this section. Initially, for three months, compared to the control pot (without compost–vermicompost), the pot supplemented with compost–vermicompost showed improved growth for both chili and brinjal plants. The plants achieve significantly better height, root length, greater biomass per unit time, quicker onset of flowering, and enhancement in fruit yield. Tables S3–S10 show the effects of compost and vermicompost application prepared from different wastes in terms of the fertility coefficient and harvest index. In the treated pots, there was a statistically significant enhancement in performance. Therefore, when vermicompost was introduced to a control pot as well, plant growth was significantly enhanced. At four months, the difference in plant height, root length, total biomass, and number of flowers/fruits produced between the two pots had lowered. By the end of the experiment on the 160th day, the control plants had revived to such a high degree that in terms of all parameters except the total plant weight, the difference between the test and the control plants became statistically insignificant. The significance of enhancement (E) or suppression (S) in the performance of the chili and brinjal plants grown in the compost/vermicompost-treated pots compared to the controls was assessed via Student's *t*-test (Suresh and Keshav, 2012). For each of the nine parameters used to assess performance, the statistical significance or otherwise of the difference was assessed in terms of the confidence level (%) associated with the change. Observation of the pots also revealed the total absence of any harmful effect of the compost–vermicompost.

Tables S3–S10 show the growth and yield of chili and brinjal plants using compost as well as vermicompost. The different parameters assessed were plant height, number of leaves, root length, shoot/root ratio, total dry weight, number of flowers/fruits, length of inflorescence, and harvest index. For the vermicompost studies, the vermicompost obtained from both monoculture and polyculture worm species was assessed. Compost and vermicompost were obtained using six different types of waste. Then, in the nine reactors, only one type of waste, i.e., the MANIT campus waste, was selected as feed. The various parameters were measured on the 80th and 160th day. The results regarding the different types of waste revealed that the plant growth parameters were better for the compost and vermicompost prepared from the MANIT campus waste. Thereafter, the MANIT campus waste was selected for studies conducted in different sizes of reactors (R1–R9). The surface area to volume ratio for these reactors varied, i.e., the highest was presented in the case of reactor R1 and lowest in the case of reactor R9.

The results for the pots supplemented with compost/vermicompost prepared using MANIT campus waste were better in terms of the various plant growth parameters. Upon comparison of the products prepared in the different reactors, the growth of the plants taken from reactor R1 was superior in terms of many parameters.

4. Conclusions and Scope of Future Work

4.1. Conclusions

A process has been developed for the composting–vermicomposting of different solid wastes. The EC of the wastes does not appear to be a toxic factor for *E. fetida* and *E. eugeniae*. The earthworms seem to be rather tolerant in a solution, which had an EC value of up to 3 dS/m in a pH range of 5.0–8.0, showing no negative effects on *E. fetida* and *E. eugeniae*. After the 48-day composting–vermicomposting treatment, most of the waste materials seemed to be converted to mature vermicomposts with low C:N ratios (<11). A mixture of DBS, hostel kitchen waste, and palash leaf litter with a C:N ratio of 30 was favorable for composting as it produced mature and humified compost and vermicompost with higher NPK content. During composting, the temperature increase during the thermophilic stage could have been responsible for pathogen elimination. For efficient composting and pathogen reduction, a temperature of 55 °C must be maintained for 15 consecutive

days. The vermicast recoveries using *E. fetida* and *E. eugeniae* were 70–84% and 60–80%, respectively. However, when both species were used (polyculture), the vermicast recovery in different reactors was 72–85%. In addition, in the polyculture, the NPK content of the final product had increased. The NPK content was in the range of 1.58–1.79%, 1.12–1.28%, and 1.08–1.5%. Reactor R1, having a higher surface area to volume ratio, showed the highest N and K content, i.e., 1.79% and 1.5%, respectively, when using the polyculture species. The zoomass values in R1 were 66.7, 61.2, and 72.3%, with comparatively higher low surface area to volume ratios for reactor (R9), i.e., 56.7, 56.6, and 61.2% for *E. fetida*, *E. eugeniae*, and polyculture, respectively.

Studies on the effect of worm density on the increase in zoomass showed the highest increase for a worm density of 125 animals per liter when compared with 62.5 animals per liter, 250 animals per liter, and 350 animals per liter worm densities. The final NPK values were in the range of 1.5–1.7%, 0.98–1.19%, and 1.1–1.49%, respectively, for the different waste-based compost–vermicompost. The final product, vermicompost, could be marketed as a fertilizer-cum-soil conditioner. The effect of worm loading on vermicast production has been explored. In the reactor consisting of 62.5 animals per liter, 64.4% vermicast recovery was achieved when *E. fetida* was the earthworm employed. Similarly, 45.6% vermicast recovery was achieved when *E. eugeniae* was the earthworm employed. When the animal density increased to 125 animals per liter, 89.7% and 68.2% vermicast recovery values were found in the *E. fetida*- and *E.eugeniae*-based reactors. In view of this result, for the further study of worm loading, the process parameters were kept constant (125 animals per liter).

4.2. Scope of Future Work

A reactor's dimensions play a significant role in its efficiency as quantified by the percentage of the conversion of the substrate to vermicast. For a given substrate quantity and earthworm density, the vermireactor efficiency increases with an increase in the reactor's surface area/volume ratio. Quite often, the litter cast by different trees is mixed with other compostable substances and used to generate compost. However, the use of such compost for vermicomposting or vermiculture is only possible after ensuring that the species are tolerant to the substrate. Indeed, it is advisable to screen common tree litter for its earthworm compatibility before its use. The mere fact that earthworms voraciously feed upon a substance and produce significant quantities of vermicast is not in itself an indicator of the suitability of that substance as earthworm feed. Suitable feed for earthworms must ensure their survival, weight gain, and reproduction.

The use of *E. fetida* and *E. eugeniae* for the vermicomposting of palash leaf litter, DBS, and kitchen food waste based on their nutrient content is an important indication that this technique will reduce the burden of synthetic fertilizers by provoking the development of organic fertilizers. In addition, it may also act as good soil conditioner and a source of plant nutrients in agriculture.

The overcrowding of worms has an adverse effect on their access to feed and hence their growth and reproduction. It is also possible that a reactor's geometry may be responsible for the loss of efficiency per worm (*E. fetida* and *E. eugeniae*), whose feeding, mating, and resting activities are largely confined to the reactor's surface. An increase in the surface area to volume ratio of the reactors might influence the worms' access to feed, thereby leading to better worm-cast production, growth, and reproduction. The conducted studies have demonstrated that earthworms can survive, grow, and breed in vermireactors fed with composted MANIT campus waste. The rise in vermicast output, despite a few worms' deaths during the reactor's operation, indicates the process's sustainability. The studies also indicate that even better vermireactor efficiency may be possible via modifying the reactor geometry.

The study revealed that a 24-day pre-composting period resulted in more detectable levels of *E. coli* in waste mixtures compared to vermicomposting, which significantly reduced pathogen numbers. A pre-composting period of 24 days was suitable for a combined system for stabilizing DBS, hostel kitchen waste, and palash leaf litter. Pre-composting

of waste for 24 days reduced fecal coliforms below 100 MPN per gram after composting. Thus, it was ideal for combining composting–vermicomposting waste mixtures. The results for the pots supplemented with compost/vermicompost prepared using MANIT campus waste were better in terms of various plant growth parameters. Upon comparison of the products prepared in the different reactors, the growth of the plants taken from reactor R1 was superior in terms of many parameters.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15108090/s1.

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