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Rapid, Clean, and Sustainable Bioprocessing of Toxic Weeds into Benign Organic Fertilizer

Dhandapani Banupriya [1], Tabassum-Abbasi [2,*], Tasneem Abbasi [1] and Shahid Abbas Abbasi [1]

[1] Centre for Pollution Control & Environmental Engineering, Pondicherry University, Puducherry 605 014, India
[2] School of Engineering, Sustainability Cluster, University of Petroleum and Energy Studies, Dehradun 248 007, India
* Correspondence: tab.abbasi@gmail.com

Abstract: A recent report in this journal from these authors, which shows that vermicomposting transforms a toxic weed such as lantana into a benign organic fertilizer, can be of practical utility only if processes can be developed for rapid, inexpensive, and sustainable vermicomposting of these weeds. This paper describes attempts leading to such a process for the vermicomposting of toxic and allelopathic weeds lantana (*Lantana camara*), parthenium (*Parthenium hysterophorus*), and ipomoea (*Ipomoea carnea*). For it, the 'high-rate vermicomposting' concept was employed due to which the weeds could be used for vermicomposting directly in each case without the need for pre-composting or any other form of pretreatment. The manure worm *Eisenia fetida*, which had been cultured on cowdung as feed and habitat, was slow to adapt to the weed-feed but survived and then began to thrive, in all the three weeds, enabling the weeds' sustained and efficient vermicomposting throughout the 16 month's uninterrupted operation of the vermireactors. In all cases the extent of vermicast production per unit time showed a rising trend, indicating that the rate of vermicomposting was set to rise further with time. The vermicomposting was found to accompany a 50 $\pm$ 10% loss of organic carbon of each weed with a 50 $\pm$ 10% increase in the concentration of total nitrogen as also the weed's additional mineralization. The combined effect was a significant lowering of the carbon-nitrogen ratio, and enrichment of all major, medium, and trace nutrients in the vermicomposts relative to their parent substrates. The findings establish that sustained, direct, and rapid transformation to organic fertilizers of even toxic and allelopathic weeds can be accomplished with the high-rate vermicomposting paradigm.

Keywords: toxic weeds; high-rate vermicomposting; organic fertilizer; *Lantana*; *Ipomoea*; *Parthenium*

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1. Introduction

Parthenium *(Parthenium hysterophorus)*, ipomoea *(Ipomoea carnea)*, and lantana *(Lantana camara)* are among three of the world's most pernicious and intransigent of weeds [1–3]. These weeds can be seen growing profusely in open lands, in and around agricultural farms, roadsides, wetlands, and parks [2,4]. They have been invading even forests; for instance, lantana has covered about 87,000 km^2 of forests in India alone and its global invasion potential has been estimated as 11 million km^2 [5]. The estimates of parthenium colonization are even more grim; as much as 350,000 km^2 of land in India has been overtaken by parthenium [6]. Worse, all three weeds are continuing to aggressively invade new areas and colonize them [7]. Their hardiness, invasiveness, and colonizing ability have overcome all attempts so far to control or destroy them, irrespective of whether the attempts were based on chemical, biological, or mechanical methods. If some success has been achieved it has at best been local and temporary—often the weakening of the hold of one invasive species paving the way for another equally invasive species [3,8]. This oft-encountered inability to control the invasion and associated colonization of these weeds results in the production of billions of tonnes of phytomass across the world which has no utility value. Worse, this happens at the expense of soil nutrients and other natural resources which would otherwise have been used by diverse species or for agriculture.

There is another equally serious fall-out. Upon senescence, the phytomass of the weeds decays in the open—part aerobically and part anaerobically. Both processes generate global-warming gases, but the latter process is more harmful than the former because it leads to about 65% of the biodegrading organic carbon being converted to methane. As each molecule of methane has been estimated to have 25–34% greater global warming potential than that of carbon dioxide [9], the contribution to global warming of the latter is several times greater than the former.

Among the possible ways of utilizing the phytomass of invasive plants is vermicomposting. It has the special attribute that it can potentially lead to organic fertilizer of which almost limitless demand exists across the world. But past attempts to vermicompost lantana, parthenium, and ipomoea—indeed any other botanical species—have been unviable. The reasons have been elaborated recently [10–12] and essentially comprise of the inherent drawbacks of the conventional vermicomposting technology which necessitate pre-composting of the weeds and/or augmenting them with animal manure. These factors, together with the slow rate of the conventional vermireactors, make the vermicomposting of phytomass economically unviable. For similar reasons, past attempts in vermicomposting lantana, parthenium, and ipomoea—as summarized in Table 1—have not led to any viable process.

Table 1. A summary of past attempts at the utilization of lantana, parthenium, and ipomoea as feed in vermireactors. All vermireactors were operated in batch mode and no quantifiable measure has been given by any of the authors with which it was decided that vermicomposting had been completed.

Manner of the Weed Utilization; Reactor Size (If Stated)	Earthworm Species Employed	Duration after Which the Vermicompost Was Harvested	Main Findings	Reference
Fly ash was mixed with parthenium in different ratios in square pots of 30 cm × 30 cm × 30 cm	*Eisenia fetida*	Two-three months	Fly ash mixed with parthenium appeared to be a good feed for earthworm	[13]
Parthenium and cowdung were mixed in 1:2 ratio	*Perionyx excavatus*	Two-four months	Weeds can be used as a resource for making vermicompost	[14]
Parthenium was mixed with cowdung in circular plastic containers of 10 kg capacity	*E. fetida*	Three-and-a-half 3 1/2 months	Parthenium and cowdung in 1:3 ratio appeared optimum for the growth and reproduction of *E. fetida*	[15]
Ipomoea, cowdung and soil were mixed in earthen pots 5 kg capacity	*Eudrilus eugeniae*	Two months	Ipomoea can be converted into an 'environment-friendly' nutrient source	[16]
Parthenium was mixed with cowdung and loaded in cement tanks of 1 m depth	*E. eugeniae*	One-and-a-half months	Aromatics, aliphatics, alcohols, phenols, and polysaccharides are significantly decreased while nutritional levels are increased through vermicomposting	[17]
Cow dung, food industry sludge, water hyacinth and parthenium were mixed in a circular plastic tub loaded with 1 kg of the substrate.	*E. fetida*	Three months	Higher ratios of parthenium and water hyacinth resulted in higher vermiprocessing efficiency	[18]
Lantana was mixed with cowdung in different ratios.	*E. fetida*	Two months	Vermibeds with 40–60% of parthenium leaves showed better mineralization	[19]
Partheniumand cow dung mixtures were used incement tanks of 1 m depth.	*E. eugeniae*	The mixture was precomposted for 75 days and then harvesting of the vermicast was carried outonce in 15 days	Appropriate mixing of parthenium with cowdung is essential for the survival of the earthworms	[20]
Parthenium, farm wastes, and animal manure were mixed 10:1:1 in cement tanks of 1 m^3 volume.	*E. fetida*	Two months	Addition of different farm and animal wastes helped to degrade parthenium	[21]
Parthenium was mixed with biogas plant slurry in circular plastic tubs.	*E. fetida*	Two months	Parthenium mixed with biogas plant slurry could be 'profitably' vermicomposted	[22]

To overcome these hurdles the authors have developed the concept of 'high-rate vermicomposting' [10]. The authors have also designed and tested several machines aimed at translating the concept to application [23–26]. Further, as reported in an accompanying paper in this journal [27], the authors have found that upon being vermicomposted, lantana loses its toxicity and is transformed into an organic fertilizer as benign and potent as vermicompost derived from cowdung. However, this finding can be of practical utility only if technology is available to transform weeds such as lantana, parthenium, and ipomoea not only swiftly but also directly—i.e., without any pretreatment and without any fortification with animal manure. This report describes studies carried out with the objective of (a) developing such a process; (b) assessing the robustness and sustainability of the process when used uninterruptedly for several months; and (c) identifying factors, if any, with which process efficiency can be improved further.

2. Material and Method

2.1. Substrate and Vermicomposting

Leaves of each of the species were collected from their respective natural strands situated near the place of the author's work (Pondicherry University campus). They were rinsed with tap water to remove adhering muck and invertebrates—if any—and gently wiped before loading them into the HEVSTOW (high efficiency vertically stocked vermicomposting system for treating organic waste) vermicomposting machine described elsewhere [28]. HEVSTOW is a multi-module semi-continuous vermicomposting machine (Figure 1) designed on the basis of the high-rate vermicomposting concept reported earlier [10].

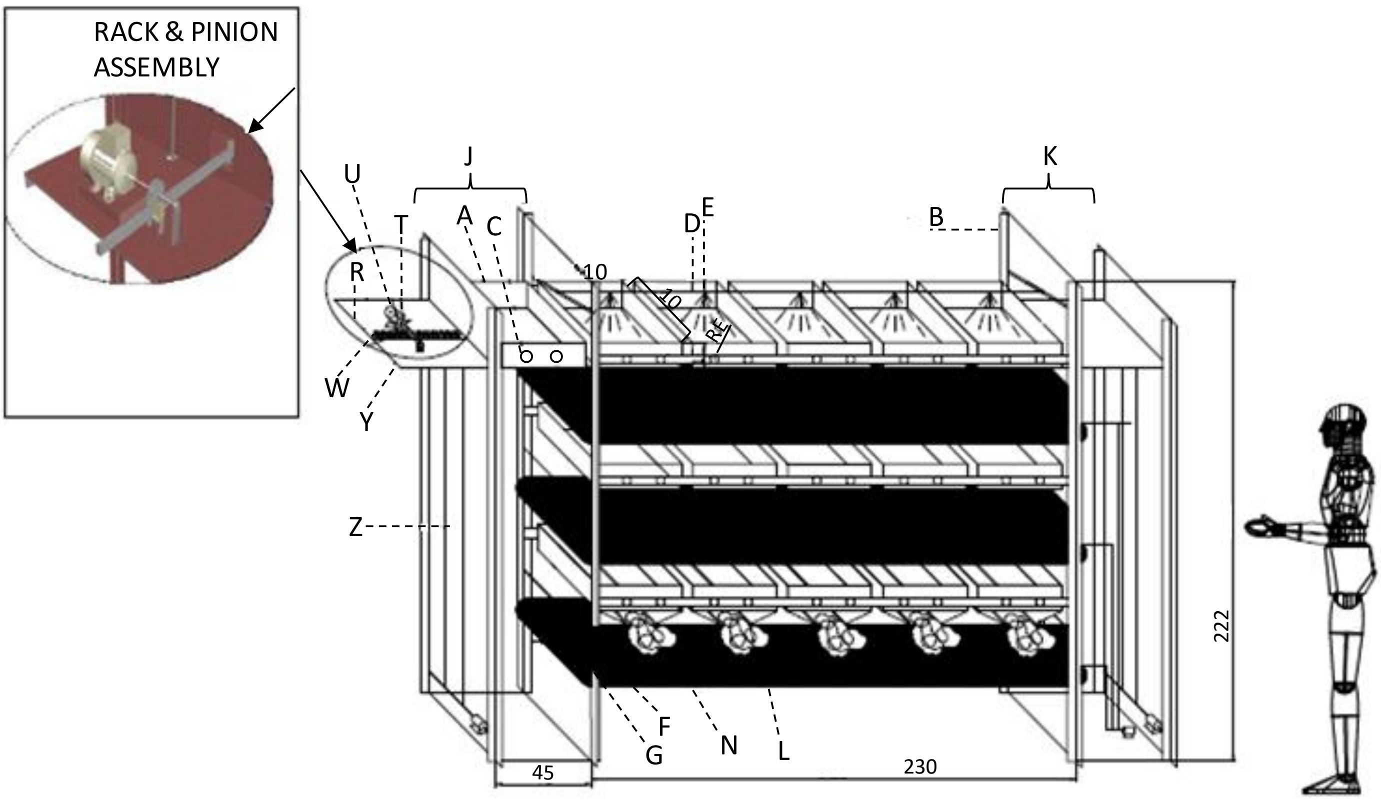

Figure 1. Schematic of the high efficiency vertically stacked vermicomposting system for treating organic waste (HEVSTOW); the human figure has been put to give an indication of the size.

HEVSTOW consists of a set of modular reactors and arrangements for their swift loading and unloading. A **fixed frame B** is provided to hold **modules A** loaded in series as well as in parallel. The modules move over B with the help of **wheels C** present on either side. The wheels are so positioned that they prevent A from moving vertically at the time of harvesting. A **sprinkler system D**, with **nozzles E** positioned above the modules, maintains the moisture content in A. There is a **rod F** placed below A, which can be rotated 180° using **gear mechanism G**. It helps in emptying the contents of the modules onto the **conveyor belt H** placed below each track. The guiding mechanism at one end of H enables the removal of the contents of the modules without any spillage. The **loading J** and **unloading K** systems help in the loading of A onto the fixed frame B or its unloading off B, using **rack and pinion arrangements R and T**. A roller attached to a motor helps in rotating H at the time of harvesting.

During operation, A is filled with substrate and placed on the loading end J. The motor aids in the lifting of the module with the help of a **rope Z**. The rack and pinion R and T arrangements, driven by **motor U**, help in placing module A onto the fixed frames B. In turn, U is supported on a frame and the **rod W** is attached to a **hinge X**. The whole set-up is placed on **frame Y**.

Each module in the HEVSTOW system used by us had 0.4 m × 0.4 m surface area and 0.12 m height. No chopping, pruning, soaking, or any other form of pre-treatment was performed. A jute cloth sheet of 3mm thickness, saturated with water, was provided at the bottom of each module to serve as bedding for the earthworms. The feed was laid over the jute cloth. The HEVSTOW prototypes used by these authors were fabricated from aluminum sheets of appropriate thickness, and steel bars/pipes. However, other appropriate materials such as fiberglass can be used in the manufacture of the HEVSTOW units.

In order to quantify the vermicast generation per adult worm, the modules were operated in the pseudo-discretized continuous reactor operation (PDCOP) mode, conceived by S. A. Abbasi and coworkers, and described elsewhere [29].

Its defining features are as summarized below:

- It enables reactor operation which is not actually continuous but approximates continuity; hence the term 'pseudo-discretized continuous'.
- In PDCOP, the vermireactors are initiated with a pre-set quantity of the substrate and a certain fixed number of adult earthworms. After allowing the earthworms to effect vermicomposting for a set number of days, say 20 or 25, the reactor contents are transferred to another container for determining the extent of conversion of the substrate to vermicast as also assessing the fecundity by counting the offspring in terms of the numbers of juveniles and cocoons produced by the earthworms. Soon after removing the reactor contents, the reactors are restarted with fresh weed feed but with the same adult animals that were deployed initially, while excluding the juveniles and cocoons. This makes it possible to measure the rate of vermicast production per adult animal and per unit of time.
- Since the unused substrate—which, if not removed, would have biodegraded even without the action of the earthworms—is removed every 20–25 days, the effect of factors other than ingestion of the feed by the earthworms is minimized.
- PDCOP thus ensures that the earthworms graze only upon totally fresh, or almost fresh, feed as they would be doing in the 'high-rate' vermireactor operation based on low solid retention times (SRTs) of just 20–25 days. Here SRT implies the time given in each pulse of feeding-harvesting for the earthworms to carry out vermicomposting. The lower the SRT needed for adequate vermicomposting, the higher the process efficiency. Further, since the juveniles and the cocoons that are generated in the vermireactors are separated before they could grow to the stage where they begin consuming significant quantities of the feed, their influence, too, on the reactor performance is sharply dampened.

All of the above enable assessment of the quality of vermicomposting garneted as a function of the number of earthworms and time, thereby providing avenues of process control and monitoring.

In the present work, three series of triplicate modules were started with 20, 50, or 80 earthworms for each weed, respectively, in the concerned modules. Each module was loaded with 1 kg dry weight equivalent of fresh weed. Healthy, adult, individuals of *E. fetida* were picked for this purpose randomly from cowdung-fed cultures maintained by the author. In the first run, all modules were allowed to function for 30 days after which they were emptied and their contents were transferred to separate containers for the assessment of vermicast and production of juveniles and cocoons. Immediately thereafter the reactors were started afresh in which everything else was kept the same as it was at the start of the experiment except that the adult earthworms removed from the previous run, were reintroduced into the fresh feed. Subsequent runs were of 20-day duration.

Throughout the experiments, all the modules were kept under identical ambient conditions of 30 °C ± 5 °C temperature and 60 ± 10% relative humidity. Their moisture level was maintained at 65 ± 5%. Mass balance of feed input and vermicast output was performed separately on the basis of respective dry weights taken after oven-drying their randomly picked and pooled samples at 105 °C to constant weight. To separate castings from other particles, the harvest was sieved through a 3 mm mesh.

2.2. Physical and Chemical Characteristics

Electrical conductivity (EC) and pH of the samples (vermicast and the parent weed) were measured in 1:2 (*v*/*w*) suspensions in water using EI™611E EC meter and Digison™ digital pH meter 7007, respectively. The bulk density and the particle density of the vermicast were measured on undisturbed cores by the graduated cylinder method [30] and the volumetric flask method [31], respectively. The vermicast's total porosity was then computed on the basis of its particle and bulk density values [30].

Total organic carbon was estimated using the modified dichromate redox method for the respective weeds and their vermicastas described by Heanes [32]. Total nitrogen was determined by the modified Kjeldahl method [33] for each vermicast and its parent weed using Kel Plus™ semi-automated digester and distillation units. The inorganic NH_4^+ and NO_3^- were determined by modified indophenol blue and Devarda's alloy methods, respectively [31,34] for vermicast and the weeds after they were extracted from the respective samples into a 2M KCl solution (1:10 *w*/*v*). Extractable/available potassium, calcium, and sodium were determined using Elico™ CL378 flame photometer after extraction from each vermicast or its parent substrate with Mehlich 3 extraction solution [35].Extractable/available copper, manganese, and zinc were determined using atomic emission spectroscopy (AES) by extracting the sample with Mehlich 3 extraction solution in a 1:25 sample-to-extractant ratio [35]. The same Mehlich 3 extract was used to determine the available phosphorus according to the ammonium molybdate–ascorbic acid method [36].

3. Results and Discussion

3.1. Vermicomposting of Lantana

3.1.1. Vermicast Production and Fecundity

The findings on the generation of vermicast and juveniles/cocoons produced during approximately 16 months of uninterrupted HEVSTOW operation in its 9 modules with 20, 50, and 80 adult individuals of *E. fetida* in triplicate sets are presented in Tables 2–4, respectively.

Due to logistics all modules could not be processed on the same day and had to be handled in a space of 2–3 days. As a result, the duration of the pulse varied by a day or two once in a while. Further, in modules with 80 earthworms, some harvests were carried out at 30 days intervals. However, since vermicast has been calculated in terms of per worm, per day, these variations do not cause any difficulty in comparing the observations across different reactors. Even though the vermicast production among triplicates varied from run to run (pulse to pulse), the overall average yield was in remarkably close agreement in all three sets. This reproducibility across triplicates extended to juveniles and cocoons as well, especially the former.

Table 2. Vermicomposting of lantana with 20 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	12.4	32.1	26.3	0	1	4	7	5	4
50	32.2	27.0	28.2	0	0	2	8	12	14
70	19.2	16.3	33.3	6	6	9	5	7	8
90	21.9	21.0	20.5	6	2	4	12	14	9
110	48.4	43.2	41.0	4	7	6	11	9	4
130	39.2	27.0	29.5	2	7	3	14	11	12
150	20.9	22.9	18.6	6	10	4	4	6	7
172	31.0	38.1	36.3	4	2	0	6	3	8
192	26.9	25.7	28.5	4	7	6	6	3	4
212	37.9	34.8	36.0	6	7	8	4	5	4
232	42.5	34.4	38.5	7	10	9	10	16	12
254	28.6	27.5	35.9	4	2	3	7	9	6
276	32.2	38.2	29.0	3	5	6	2	7	3
296	52.3	62.1	44.2	4	6	2	5	3	7
317	50.8	52.2	48.1	3	5	2	6	4	3
337	50.7	48.8	51.0	0	2	2	0	3	4
360	49.2	42.1	44.4	0	2	1	2	1	2
380	52.5	43.3	53.2	2	1	2	0	2	1
400	41.2	31.0	41.0	3	2	4	2	1	3
422	40.9	50.3	37.0	3	1	2	2	5	4
444	32.5	45.9	51.2	3	2	2	4	1	3
464	34.1	37.7	33.3	3	2	0	2	1	2
485	47.2	45.6	54.4	3	4	3	2	5	4
Average $\pm$ SD	36.7 $\pm$ 11.7	36.8 $\pm$ 11.3	35.6 $\pm$ 12.1	3.3 $\pm$ 2.1	4.0 $\pm$ 3.0	3.7 $\pm$ 2.6	5.3 $\pm$ 3.8	5.8 $\pm$ 4.3	5.6 $\pm$ 3.5
Overall average		36.4 $\pm$ 11.5			3.7 $\pm$ 2.5			5.5 $\pm$ 3.8	
Average $\pm$ SD (of the last six month's data)	44.3 $\pm$ 7.5	44.1 $\pm$ 6.6	41.5 $\pm$ 15.8	2.2 $\pm$ 1.3	2.3 $\pm$1.3	2.0 $\pm$ 1.1	2.2 $\pm$ 1.9	2.6 $\pm$ 1.7	2.9 $\pm$ 1.1
Overall average $\pm$ SD (of the last six month's data)		43.3 $\pm$ 10.4			2.2 $\pm$1.2			2.6 $\pm$ 1.6	

Table 3. Vermicomposting of lantana with 50 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	19.0	17.7	17.0	5	4	6	12	11	9
50	20.6	17.2	16.9	3	4	6	14	20	14
70	16.3	15.7	15.6	9	6	7	7	8	5
90	12.1	11.4	12.3	1	7	6	17	23	14
110	27.8	30.9	28.7	10	4	7	14	16	11
130	21.7	23.8	22.3	8	7	4	13	16	21
150	16.9	16.5	18.0	12	16	14	11	10	9
172	21.9	22.8	21.3	5	7	6	4	9	11
192	18.3	16.9	17.8	8	9	5	7	6	4
212	22.8	24.9	25.8	9	8	11	6	5	7
232	22.5	17.9	23.3	12	12	16	21	14	19
254	16.8	17.8	20.2	6	4	6	11	8	9
276	19.3	20.8	18.3	4	7	6	5	9	7
296	30.5	35.5	37.3	6	3	8	4	7	11
317	27.6	32.8	31.8	6	8	4	7	11	8
337	25.9	28.5	30.5	4	3	6	5	4	8
360	25.8	23.9	25.8	4	5	3	3	4	3
380	25.2	23.8	25.3	4	3	5	3	4	6
400	24.1	22.9	19.7	4	6	7	4	5	4
422	33.2	27.0	25.3	4	3	2	6	7	3
444	32.5	30.2	32.3	4	5	3	6	4	2
464	26.4	29.5	25.2	4	5	3	2	4	3
485	37.8	31.3	40.9	6	5	6	5	7	6
Average $\pm$ SD	23.7 $\pm$ 6.2	23.5 $\pm$ 6.4	24.0 $\pm$ 7.1	6 $\pm$ 2.9	6.1 $\pm$ 3.1	6.4 $\pm$3.3	8.1 $\pm$ 5.0	9.2 $\pm$ 5.3	8.4 $\pm$ 5.0
Overall average		23.7 $\pm$ 6.5			6.2 $\pm$ 3.1			8.6 $\pm$ 5.1	
Average $\pm$ SD (of the last six month's data)	28.7 $\pm$ 4.1	27.8 $\pm$ 4.9	28.5 $\pm$ 13.1	4.4 $\pm$ 1.3	4.8 $\pm$ 1.7	4.3 $\pm$ 1.7	4.6 $\pm$ 2.1	5.6 $\pm$ 2.3	4.8 $\pm$ 2.3
Overall average $\pm$ SD (of the last six month's data)		28.3 $\pm$ 4.7			4.5 $\pm$ 1.4			5.0 $\pm$ 2.1	

Table 4. Vermicomposting of lantana with 80 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	23.3	20.0	19.7	9	7	7	38	26	29
50	17.2	15.2	14.0	6	6	4	22	23	18
70	12.6	13.5	16.4	7	9	12	4	10	12
90	10.3	7.2	9.2	4	6	3	48	37	29
110	14.3	15.9	20.8	7	12	9	17	22	14
130	24.7	26.1	24.2	8	7	9	24	20	17
150	14.5	13.3	14.1	20	18	14	42	36	29
172	16.8	14.8	15.1	9	7	12	10	9	7
192	16.1	16.4	17.5	11	14	12	9	7	8
212	20.7	21.9	21.4	13	16	14	10	13	9
232	18.4	17.7	15.7	17	14	9	29	20	18
262	17.8	21.2	18.8	9	6	11	23	17	14
292	17.5	13.7	15.1	8	10	6	11	9	12
322	27.3	24.0	28.1	7	6	8	9	10	7
352	25.3	26.0	25.9	7	6	9	12	7	14
382	21.9	21.9	22.0	6	4	8	5	6	7
412	26.6	27.6	31.0	7	4	6	6	3	4
442	27.6	29.4	23.1	4	5	7	6	7	5
472	27.1	26.9	24.7	7	4	5	5	3	4
Average ± SD	20.0 ± 5.4	19.6 ± 6.1	19.8 ± 5.6	8.7 ± 4.1	8.5 ± 4.3	8.7 ± 3.2	17.4 ± 13.5	15.0 ± 10.3	13.5 ± 8.2
Overall average ± SD		19.8 ± 5.6			8.6 ± 3.8			15.3 ± 10.8	
Average ± SD (of the last six month's data)	24.8 ± 3.8	24.2 ± 5.2	24.3 ± 5.1	6.6 ± 1.3	5.6 ± 2.1	7.0 ± 1.4	7.7 ± 2.9	6.4 ± 2.7	7.6 ± 4.0
Overall average ± SD (of the last six month's data)		24.4 ± 4.5			6.4 ± 1.7			7.2 ± 3.1	

The trends in vermicast production as a function of duration for the three sets of reactors are presented in Figure 2a–c. The statistical trend lines show a rising trend in all three cases, indicating that with time the earthworms—which had been born and grown in cowdung-fed cultures—increasingly adapted to the lantana feed. Indeed, the average vermicast output during the last six months of the experiment was substantially higher than the overall average (Tables 2–4). It also indicates that more prolonged reactor operation as also the use of *E. fetida* offspring, who are born and grown in lantana-fed cultures, are likely to yield higher vermicast per animal than the maximum achieved in our experiments.

As expected, the modules which had just 20 earthworms per kg (fresh weight) of lantana generated the maximum vermicast per worm (per day) due to the most liberal availability of the feed and hence the easiest access to it of the three module types. In modules with $2\frac{1}{2}$ times this population, viz 50 earthworms per kg of lantana, competition for access to food brought the per capita yield down (Table 3). In still more crowded reactors operated with 80 earthworms per kg of lantana, the per capita vermicast production was still lower (Table 3), but the margin of difference was not as pronounced as it was between reactors with 20 earthworms and 50 earthworms per kg of lantana.

In terms of absolute vermicast production, and if the average of the last six month's data is used as the base—which is logical, given that due to the rising trend future yields are likely to be at least as good, possibly better—the situation is as explained below lantana had 22.4% dry weight. Hence, each kg fresh weight of lantana contained 224g of solids.

The modules with 20 earthworms per kg fresh weight (or 224 g dry weight) of lantana generated $(43.3 \times 20 \times 30)/1000 = 25.98$ (rounded to 26) g of vermicast (dry weight equivalent) per month. In other words, converting 11.6% of the feed to vermicast per month.

The modules with 50 earthworms per kg fresh weight (or 224 g dry weight) of lantana generated $(28.3 \times 50 \times 30)/1000 = 42.45$ (rounded to 42.5) g of vermicast (dry weight equivalent) per month. In other words, converting 19% of the feed to vermicast per month.

The modules with 80 earthworms per kg fresh weight (or 224 g dry weight) of lantana generated $(24.4 \times 80 \times 30)/1000 = 58.56$ (rounded to 58.6) g of vermicast (dry weight equivalent) per month. In other words, converting 26.2% of the feed to vermicast per month.

Given that 50 ± 10% of organic carbon contained in any feed is either converted to worm zoomass or is lost as CO_2(due to respiration by earthworms and microorganisms present in the feed) in the course of vermicomposting, the above-mentioned figures reflect the conversion of about twice as much feed as the vermicast produced. Hence the effective conversion of feed to vermicast per month in reactors with 80 earthworms is equivalent to 52.4 ± 10% utilization of the feed per month. But the rising trend in vermicast production with time (Figure 2a–c) means vermicast output is set to increase further with time. Secondly, had we not been removing the juveniles and cocoons from the modules, they would be utilizing substantial parts of the feed. The combination of both these factors is likely to have caused much more than 52.4 ± 10% utilization of lantana per month and the actual vermicast yield would have approached its theoretical maximum at 30–40-day SRTs. This rate is several times faster than the 90–120 days that are taken by conventional vermireactors. Equally important, this rate has been achieved without any pre-composting, cowdung supplementation, or even any pre-treatment of the lantana feed.

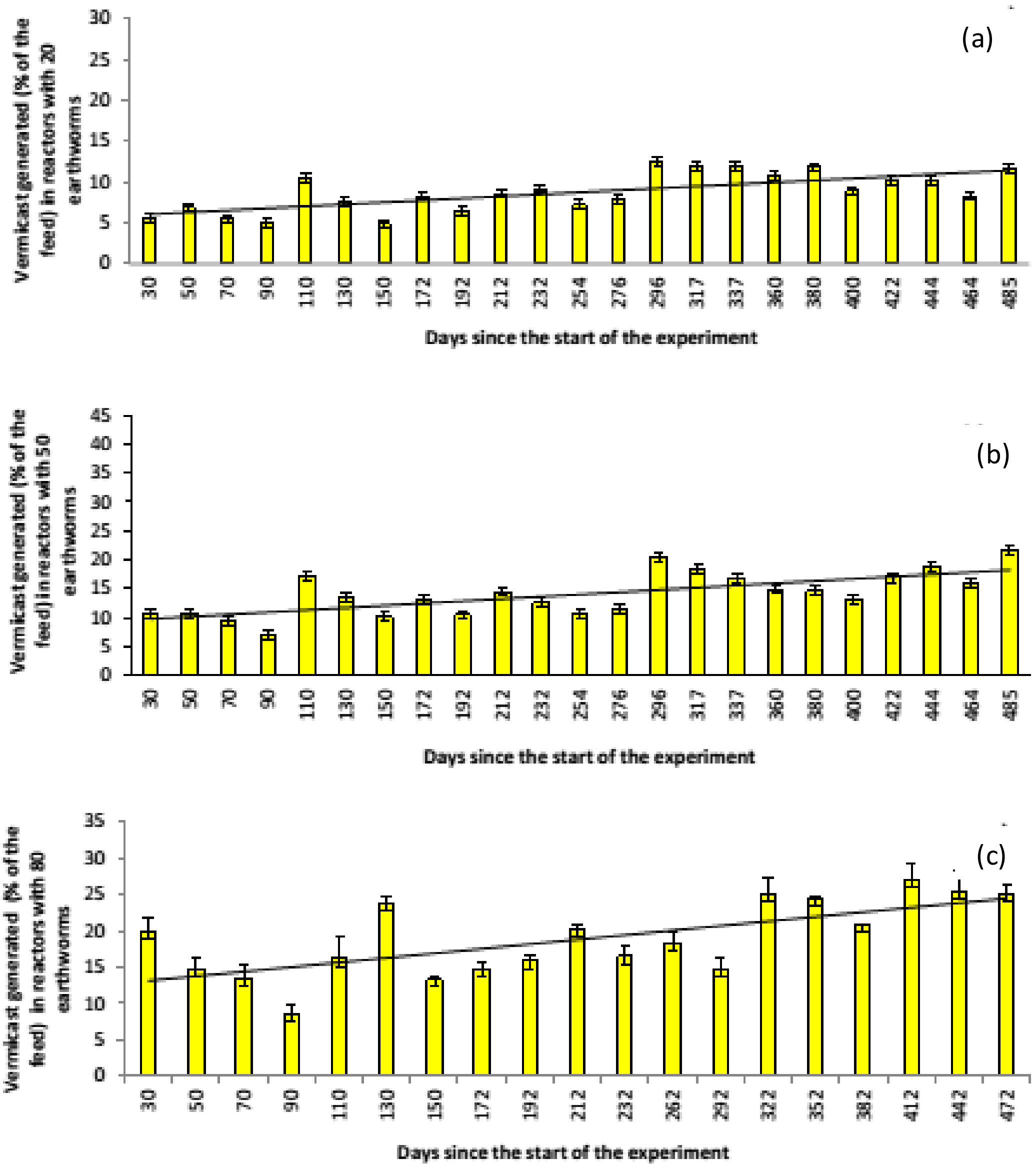

Figure 2. Trend in the generation of vermicast as a function of time in pulse-fed, semi-continuous reactors operated with (**a**) 20, (**b**) 50, and (**c**) 80 earthworms and fed with fresh lantana.

Depending on species and variety, individual earthworms take 6–12h for converting the material they ingest into their vermicast [37]. If a means can be found to immobilize live earthworms in a way that each can be fed individually and its cast harvested, as soon as it is exited, vermicomposting of any substrate should not take more than 6–12h. However, it is not possible to engineer vermicomposting systems which can accomplish this. In a vermireactor each earthworm has to first find food in competition with other earthworms. It then has to leave its casting in the midst of the feed, making its immediate and clean-cut harvesting almost impossible. As a result, the product of vermicomposting becomes fit for harvesting only when a large fraction of the parent substrate has been converted to vermicast. In conventional vermireactors this becomes possible after 90–120 days. The paradigm shift achieved in high-rate vermicomposting shortens this duration to 20–30 days but further improvements in increasing the rate of vermicomposting appear unlikely. This is due to the engineering limits associated with maximizing access to food and speeding up the harvesting of the vermicast.

3.1.2. Chemical Characteristics of the Lantana Vermicompost in Comparison to Lantana

Vermicomposting of lantana is seen to have caused significant differences to arise between the vermicast and its parent substrate (Table 5). The total organic carbon (TOC) content, which was 453.6 g/kg in lantana falls to 248.7 g/kg in the weed's vermicompost, reflecting a 57.4% reduction. Concurrently, there is an increase in total nitrogen from 16 to 18 g/kg, calculated on the basis of initial feed mass, perhaps by way of mucus contributed by the earthworms. The combination of these two factors causes a reduction in the carbon-to-nitrogen (C:N) ratio of the vermicast relative to lantana—from 28 to 14. This plays a major role in making lantana vermicast a highly potent fertilizer because a C/N ratio of less than 20 in an organic fertilizer makes it acceptable for use while a C:N ratio of 15 or less is deemed ideal [38,39]. Vermicomposting thus transforms lantana into a nitrogen-rich fertilizer of the ideal C:N ratio.

Table 5. Chemical characteristics of lantana and its vermicast.

Variables	Values in	
	Lantana	**Vermicast**
Total organic carbon (g/kg)	453.6 ± 12.5	248.7 ± 5
Total nitrogen (g/kg)	16 ± 0.4	18 ± 1.1
C:N ratio	28:1	14:1
Ammoniacal nitrogen (mg/kg)	-	321 ± 5.4
Nitrate nitrogen (g/kg)	1.73 ± 0.05	14 ± 0.5
Available sodium (g/kg)	0.080 ± 0.010	0.260 ± 0.0051
Available potassium (g/kg)	1.023 ± 0.012	4.1 ± 0.2
Available calcium (g/kg)	1.08 ± 0.09	4.3 ± 0.23
Available phosphorous (mg/kg)	79.8 ±2.1	324.38 ± 20.1
Total copper (mg/kg)	21.27 ± 1.86	32.1 ± 7.05
Available copper (mg/kg)	3.33 ± 1.155	13.53 ± 0.73
Total manganese (mg/kg)	128.8 ± 9.73	163.9 ± 18.51
Available manganese (mg/kg)	10.3 ± 2.32	87.9 ± 0.3
Total zinc (mg/kg)	106.33 ± 8.42	123.1 ± 35.18
Available zinc (mg/kg)	18.33 ± 1.33	58.56 ± 0.58

There is an 8-fold increase in nitrate nitrogen reflecting the high degree of mineralization occurring when lantana is transformed into vermicast. There is an equally dramatic increase in available sodium, potassium, calcium, and phosphorous in vermicast relative to lantana. The levels of total copper, total manganese, and total zinc have also increased mildly, while those of available copper, manganese, and zinc have gone up dramatically.

All these characteristics point towards lantana having been converted by vermicomposting into a potential fertilizer.

3.2. Vermicomposting of Parthenium

3.2.1. Vermicast Production and Fecundity

All modules had vermicast production steadily rising with time as seen in the trend lines (Figure 3a–c). There was steady production of juveniles and cocoons in all the reactors.

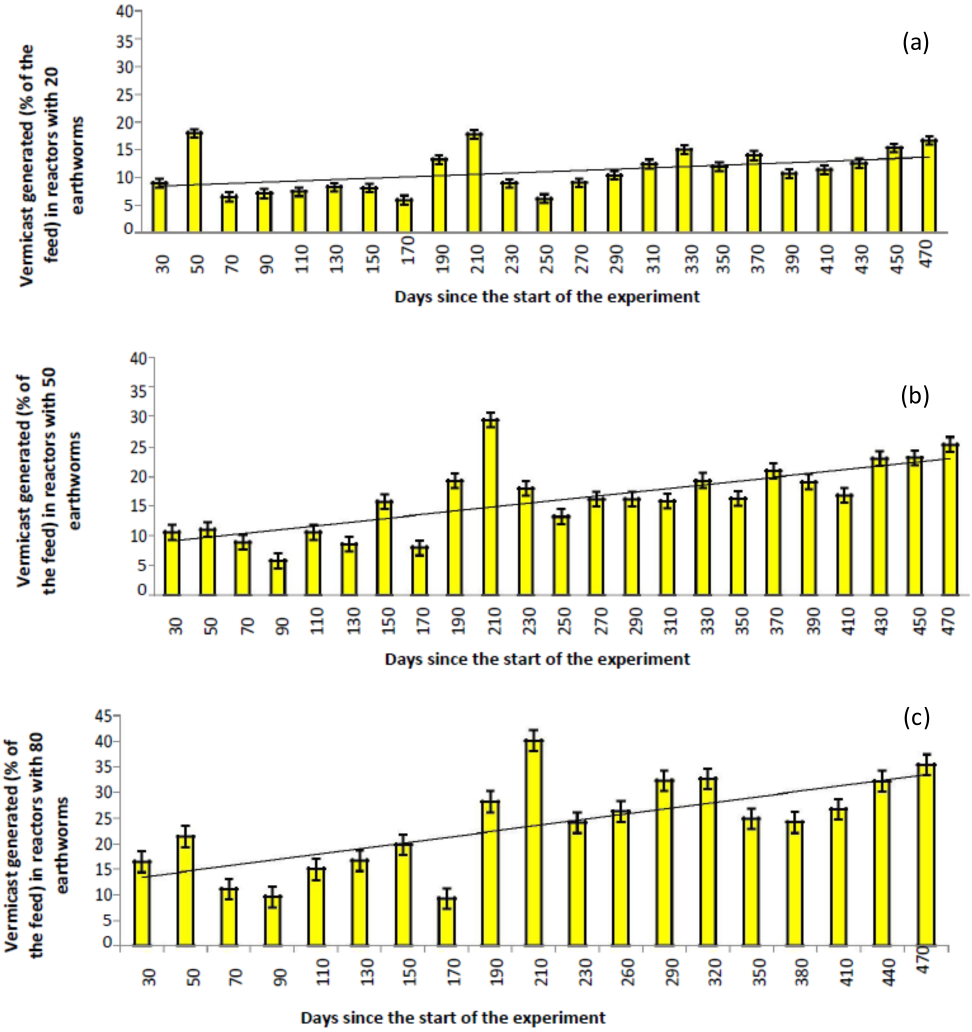

Figure 3. Trend in the generation of vermicast as a function of time in pulse-fed, semi-continuous reactors operated with (**a**) 20, (**b**)50, and (**c**) 80 earthworms with fresh Parthenium.

If figures of average vermicast production per earthworm during the last six months of the system operation per day are used to calculate the fraction of parthenium converted to vermicast per month, in the same manner as illustrated with lantana in Section 3.1.1, the corresponding figures are as follows.

In reactors with 20 earthworms per kg (equivalent to 305 g dry weight) of parthenium, the vermicast generated per month is 7.5% of the feed mass. In reactors with 50 and 80 earthworms per kg (equivalent to 305 g dry weight) of parthenium, the vermicast generated per month is 11.3% and 17.5% of the feed mass. Considering that (a) with time there is increasing adaptation of earthworms to parthenium feed as also to the confines of the HEVSTOW modules; (b) the juveniles and cocoons if not removed from the system would have contributed to even greater utilization of the feed, and (c) the effective utilization of feed is about twice as much as the vermicast produced (due to the loss of about half of the feed in metabolism), it can be safely assumed that with time the rate of parthenium utilization would significantly improve in HEVSTOW to achieve near total conversion to vermicast in 30–40 days.

The results are summarized in Tables 6–8. In the case of Parthenium-fed modules also, the averages of the vermicast yield in the triplicates were in close agreement even as the output of constituent runs varied. The per worm output of vermicast in modules with 20 earthworms per kg (equivalent to 305 g dry weight) of parthenium was significantly higher than the per animal output in reactors with 50 earthworms per kg of parthenium, evidently due to the liberal availability of the feed in the former case. However, a further increase in earthworm density to 80 animals per kg (Table 8) did not cause any significant change in per capita vermicast production. The greater crowding did seem to affect the rate of vermicomposting in the initial months due to which the overall average vermicast output in reactors with 50 earthworms—18.8 ± 7.4 mg/worm/day—is higher than the overall average—17.6 ± 6.9 mg/worm day in reactors with 80 earthworms. However, this difference has disappeared during the last six months of the system operation and the average output during the last six months in the two types of modules is almost the same. This indicates a possible adaptation with time not only with parthenium as the sole feed but also with the higher earthworm density. It also indicates that the overall vermicast production in reactors with 80 earthworm/kg will be much higher than in reactors with 50 earthworms/kg because the per capita vermicast production in the reactors of these two animal densities become close to each other once the adaptation to higher animal density is over.

Table 6. Vermicomposting of parthenium with 20 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	19.9	35.8	22.7	1	3	0	2	3	3
50	55.4	54.2	48.3	3	0	4	0	2	2
70	20.8	18.1	18.5	2	6	4	4	3	5
90	23.5	17.1	21.5	0	3	0	4	6	3
110	19.2	23.5	22.1	2	0	1	3	4	3
130	20.0	27.1	24.8	0	0	0	0	0	0
150	22.1	24.2	24.4	4	3	6	0	0	0
170	18.1	15.4	18.5	4	0	2	2	1	2
190	34.2	39.2	42.1	3	5	3	4	2	2
210	53.3	42.1	60.2	3	6	2	4	5	5
230	18.1	24.0	36.0	0	2	0	2	0	0
250	12.1	25.4	17.1	2	0	0	1	2	0
270	24.2	18.3	36.5	0	2	1	0	1	0
290	38.8	25.2	27.1	0	3	2	1	2	4
310	36.7	41.3	31.0	0	2	2	0	0	1
330	46.0	46.5	38.8	0	0	2	0	2	3
350	34.4	35.0	35.6	0	0	0	2	0	3
370	40.4	42.5	39.4	0	1	0	0	2	0
390	37.3	31.9	24.6	0	0	0	1	0	2
410	35.4	32.1	32.3	0	1	2	0	2	1
430	39.4	29.4	40.8	0	2	0	0	1	0
450	49.2	43.1	41.9	0	0	2	0	0	1
470	47.3	46.5	52.5	2	3	3	2	2	3
Average ± SD	32.4 ± 12.7	32.1 ± 10.9	32.9 ± 11.6	1.1 ± 1.5	1.8 ± 1.9	1.6 ± 1.6	1.4 ± 1.5	1.7 ± 1.7	1.9 ± 1.6
Overall average ± SD		32.5 ± 11.6			1.5 ± 1.7			1.7 ± 1.6	
Average ± SD (of the last six month's data)	40.5 ± 5.2	37.3 ± 7.6	36.4 ± 8.1	0.2 ± 0.6	1.2 ± 1.2	1.3 ± 1.2	0.6 ± 0.8	1.1 ± 1.0	1.8 ± 1.4
Overall average ± SD (of the last six month's data)		38.1 ± 7.1			0.9 ± 1.1			1.2 ± 1.2	

Table 7. Vermicomposting of parthenium with 50 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	10.0	9.7	16.7	5	6	6	5	4	7
50	13.7	7.3	17.7	6	7	5	4	6	3
70	9.3	9.8	11.8	1	7	2	6	4	2
90	6.7	7.7	5.8	6	4	2	4	3	3
110	10.0	15.9	11.2	4	6	4	7	9	3
130	10.8	9.3	9.8	0	0	0	0	0	0
150	19.3	17.7	18.0	11	10	7	4	8	5
170	9.2	9.4	9.3	5	4	6	4	3	2
190	22.3	21.4	23.8	6	4	7	4	5	3
210	34.7	34.0	33.8	5	3	7	4	3	6
230	23.8	17.8	21.5	2	3	2	1	0	2
250	12.8	15.4	18.1	5	4	1	2	0	3
270	16.5	21.3	18.7	2	3	0	0	2	1
290	20.8	14.4	21.3	4	7	3	3	4	5
310	20.3	19.3	15.8	3	4	2	3	1	4
330	22.6	24.8	20.3	2	4	4	3	5	2
350	20.9	18.3	17.8	2	1	4	3	2	4
370	29.4	25.6	18.2	0	3	2	2	4	1
390	23.1	27.2	16.7	2	1	0	3	2	2
410	19.8	26.1	12.9	4	0	3	2	3	0
430	30.2	28.2	22.3	2	3	0	2	4	2
450	28.0	26.7	26.3	3	4	2	2	3	1
470	31.3	28.4	29.2	4	5	4	4	3	2
Average ± SD	19.4 ± 8.0	18.9 ± 7.8	18.1 ± 6.5	3.7 ± 2.4	4.0 ± 2.4	3.2 ± 2.3	3.1 ± 1.7	3.4 ± 2.3	2.7 ± 1.8
Overall average ± SD		18.8 ± 7.4			3.6 ± 2.4			3.1 ± 1.9	
Average ± SD (of the last six month's data)	24.6 ± 4.6	23.9 ± 4.8	20.1 ± 4.9	2.6 ± 1.3	3.2 ± 2.1	2.4 ± 1.5	2.7 ± 0.7	3.1 ± 1.2	2.3 ± 1.6
Overall average ± SD (of the last six month's data)		22.9 ± 5.0			2.7 ± 1.6			2.7 ± 1.2	

Table 8. Vermicomposting of parthenium with 80 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	13.3	11.0	11.7	11	7	8	8	14	7
50	7.8	20.4	18.7	12	11	17	4	7	6
70	9.8	6.5	8.0	7	6	8	6	4	5
90	8.2	7.8	5.0	6	4	2	2	1	4
110	11.4	11.0	10.4	3	0	2	4	2	3
130	13.5	10.1	12.8	0	0	0	0	0	0
150	13.1	14.8	15.3	14	9	16	7	8	4
170	6.7	6.5	6.9	7	6	5	4	3	5
190	20.3	20.9	20.5	8	7	6	6	5	5
210	33.5	31.7	22.5	6	4	7	7	12	11
230	17.3	14.5	20.7	3	3	4	5	2	1
260	17.7	20.7	19.1	2	6	4	3	4	7
290	22.1	23.2	25.3	6	3	5	3	0	6
320	25.6	25.5	20.2	3	6	7	2	4	3
350	18.9	18.3	17.1	3	3	2	2	1	0
380	18.0	17.5	17.3	4	5	2	3	2	6
410	22.2	17.0	19.2	2	3	0	4	3	2
440	24.8	22.8	22.8	2	1	2	2	4	3
470	25.1	25.5	26.9	2	1	3	3	2	1
510	28.4	26.7	26.5	8	6	4	5	4	6
Average ± SD	17.9 ± 7.4	17.6 ± 7.2	17.3 ± 6.4	5.5 ± 3.8	4.6 ± 2.9	5.2 ± 4.5	4.0 ± 2.1	4.1 ± 3.7	4.3 ± 2.7
Overall average ± SD		17.6 ± 6.9			5.1 ± 3.8			4.1 ± 2.9	
Average ± SD (of the last six month's data)	23.3 ± 3.8	21.9 ± 4.2	21.4 ± 4.1	3.4 ± 2.1	3.6 ± 2.1	2.9 ± 2.2	3.0 ± 1.2	2.9 ± 1.2	3.0 ± 2.3
Overall average ± SD (of the last six month's data)		22.2 ± 3.9			3.3 ± 2.1			3.0 ± 1.6	

3.2.2. Chemical Characteristics of the Vermicast Relative to the Substrate

Upon vermicomposting parthenium loses about 25% of its TOC, leading to a change in the C:N ratio from 18 to 12. There is extensive mineralization, evidenced by the increase in nitrate nitrogen, and in the levels of available phosphorous, sodium, potassium, calcium, copper, manganese, and zinc levels (Table 9). In most cases, the increase is of several orders of magnitude (as in the case of available phosphorous, copper, manganese, and zinc). These changes, together with the fall in the C:N ratio below 15, indicate that parthenium has potentially turned into a fertilizer.

Table 9. Chemical characteristics of parthenium and its vermicast.

Variables	Values in	
	Parthenium	**Vermicast**
Total organic carbon (g/kg)	312 ± 7	234 ± 13
Total nitrogen (g/kg)	17 ± 0.2	20 ± 1.5
C:N ratio	18:1	12:1
Ammoniacal nitrogen (mg/kg)	-	262.5 ± 6.9
Nitrate nitrogen (g/kg)	1.31 ± 0.082	16.2 ± 1.4
Available sodium (g/kg)	0.145 ± 0.012	0.326 ± 0.0013
Available potassium (g/kg)	1.142 ± 0.015	2.5 ± 0.1
Available calcium (g/kg)	1.15 ± 0.11	3.2 ± 0.6
Available phosphorous (mg/kg)	116.4 ± 3.1	402.7 ± 5.6
Total copper (mg/kg)	24.9 ± 1.47	35.6 ± 11.05
Available copper (mg/kg)	0.37 ± 0.152	7.8 ± 0.23
Total manganese (mg/kg)	70.33 ± 16.62	88.6 ± 26.81
Available manganese (mg/kg)	7 ± 2.2	69.9 ± 1.2
Total zinc (mg/kg)	148.27 ± 9.32	173.2 ± 6.29
Available zinc (mg/kg)	3.9 ± 0.503	44.96 ± 2.27

3.3. Vermicomposting of Ipomoea

3.3.1. Vermicast Production and Fecundity

The findings are summarized in Tables 10–12. In terms of reproducibility of average output in triplicates—even as data of individual runs fluctuated from module to module—ipomoea-fed modules behaved in the same manner as the modules fed with lantana and parthenium. However, ipomoea-fed systems significantly deferred from these of the other two weeds in that the average output during the last six months did not vary substantially from the average output of the earlier months. Thus, earthworms seem to have adapted to the ipomoea feed straightaway. Accordingly, the statistical trend lines were more or less flat (Figure 4a–c).

Ipomoea also differed from other feeds in the sense that crowding of earthworms seemed to effect the per capita vermicast generation more than it did for the other two feeds, as reflected in an almost 50% drop in 50 animals per kg reactors compared to the 20 animals per kg reactors.

Following the methodology of converting the average per capita vermicast production of the last six months of the experiment to percent utilization of feed per month, we see that in modules with 20 earthworms per kg (or 221 g dry weight equivalent) of ipomoea, the vermicast generated is 8.9% of the feed. In modules with 50 and 80 earthworms, the corresponding figures are 13.8% and 19.5%, respectively. With higher earthworm density and by retaining the juveniles and cocoons in the modules the utilization per month for vermicast production can be taken to 50% or higher, thereby attaining full utilization in about 60 days. This rate is still significantly faster than the period of 90–120 days needed by conventional vermireactors which also require liberal supplementation of cowdung (in 1:1 or higher manure-ipomoea ratios) to utilize half of the same quantity of ipomoea.

Table 10. Vermicomposting of ipomoea with 20 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	44.8	41.4	32.6	7	7	6	3	4	1
50	19.8	24.2	22.7	7	4	3	6	12	11
70	17.4	21.4	20.0	5	4	7	2	3	2
90	39.1	34.9	40.0	2	4	4	3	6	2
110	29.4	35.0	26.0	4	3	6	2	4	6
130	31.3	26.5	29.0	5	4	6	4	3	3
150	45.4	40.6	36.0	6	4	6	5	7	7
173	28.3	21.5	36.3	5	3	0	3	4	2
193	32.9	29.0	40.1	2	1	3	4	0	6
213	24.3	29.3	35.0	2	0	3	1	3	2
233	31.0	38.2	33.3	6	4	7	2	1	3
253	22.0	27.3	27.0	4	3	6	2	0	3
273	19.0	23.8	20.0	2	1	4	1	0	2
293	20.9	21.4	21.4	3	2	4	2	0	3
313	29.4	28.3	21.1	3	1	2	2	4	1
333	35.1	23.2	33.2	2	1	3	1	4	2
353	44.9	42.9	34.9	2	1	2	0	4	3
373	44.5	39.5	41.7	2	1	4	2	3	2
393	43.6	41.5	35.3	2	1	2	1	2	3
413	47.1	44.8	46.5	2	1	3	2	3	4
Average ± SD	32.5 ± 10.1	31.7 ± 8.2	31.6 ± 7.9	3.7 ± 1.8	2.5 ± 1.8	4.1 ± 1.9	2.4 ± 1.5	3.4 ± 2.8	3.4 ± 2.4
Overall average ± SD		32.0 ± 8.6			3.4 ± 1.9			3.1 ± 2.3	
Average ± SD (of the last six month's data)	33.8 ± 10.9	33.1 ± 9.1	31.4 ± 9.0	2.8 ± 1.3	1.6 ± 1.1	3.7 ± 1.7	1.5 ± 0.7	2.1 ± 1.7	2.6 ± 0.8
Overall average ± SD (of the last six month's data)		32.8 ± 9.4			2.7 ± 1.6			2.1 ± 1.2	

Table 11. Vermicomposting of ipomoea with 50 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	19.4	18.8	16.3	10	12	9	6	7	10
50	11.5	9.9	10.6	12	10	9	14	17	22
70	13.8	13.6	15.0	7	5	9	3	4	8
90	24.9	29.0	29.7	5	4	7	3	6	5
110	24.5	21.3	22.7	6	7	5	5	9	7
130	18.6	20.0	22.3	7	8	7	5	6	4
150	26.6	30.4	27.7	10	8	14	8	9	11
173	31.8	20.5	28.4	7	6	5	6	4	3
193	23.5	27.8	26.9	4	6	2	5	7	3
213	23.3	29.7	24.2	3	0	5	4	2	6
233	29.6	31.3	33.9	11	7	9	7	5	4
253	20.9	20.5	23.2	7	6	5	4	3	7
273	16.2	19.0	16.5	4	6	3	3	4	5
293	13.0	13.2	15.6	5	6	4	3	5	4
313	13.0	14.1	14.0	3	6	5	4	3	6
333	16.0	14.4	14.8	4	3	3	4	5	2
353	20.4	22.1	31.9	3	6	4	4	5	3
373	20.4	22.6	26.5	3	6	3	6	4	5
393	19.7	19.8	19.7	3	4	5	5	4	6
413	22.5	23.0	23.5	3	4	6	6	5	7
Average ± SD	20.5 ± 5.6	21.1 ± 6.2	22.2 ± 6.6	5.9 ± 2.9	6.0 ± 2.5	6.0 ± 2.9	5.3 ± 2.5	5.7 ± 3.2	6.4 ± 4.3
Overall average ± SD		21.2 ± 6.1			5.9 ± 2.7			5.8 ± 3.4	
Average ± SD (of the last six month's data)	19.2 ± 5.0	20.0 ± 5.4	22.0 ± 7.1	4.6 ± 2.6	5.4 ± 1.3	4.7 ± 1.8	4.6 ± 1.3	4.3 ± 0.8	4.9 ± 1.7
Overall average ± SD (of the last six month's data)		20.4 ± 5.8			4.9 ± 1.9			4.6 ± 1.3	

Table 12. Vermicomposting of ipomoea with 80 adults of *E. fetida* per kg of feed in pulse-fed modules.

Number of Days from the Start of the Reactor	Vermicast Generated per Worm (mg), per Day			Number of Juveniles Produced			Number of Cocoons Generated		
	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III	Reactor I	Reactor II	Reactor III
30	9.9	11.8	10.6	14	16	11	12	14	16
50	11.8	11.0	11.2	17	14	21	12	16	7
70	14.9	12.4	12.3	9	7	8	12	14	11
90	27.0	23.9	23.2	8	13	11	12	7	9
110	21.7	20.2	22.3	8	6	9	9	11	10
130	18.2	21.2	17.4	12	14	12	10	11	9
150	23.9	24.8	20.6	17	12	9	12	11	8
173	33.1	28.0	25.9	9	12	16	11	7	5
203	19.5	20.6	22.3	7	5	4	2	6	8
233	20.5	20.5	18.5	6	4	7	2	3	5
265	19.3	17.0	19.3	4	6	5	3	2	4
295	15.5	17.7	15.5	4	6	5	3	4	7
325	14.2	16.3	15.2	5	4	7	6	3	4
355	16.7	16.8	13.9	5	4	6	6	7	6
388	17.3	11.0	17.5	5	6	4	4	6	7
418	23.1	25.2	24.9	6	8	5	7	4	6
Average ± SD	19.2 ± 5.8	18.7 ± 5.3	18.2 ± 4.8	8.5 ± 4.3	8.6 ± 4.2	8.8 ± 4.7	7.7 ± 4.0	7.9 ± 4.4	7.6 ± 3.0
Overall average ± SD		18.7 ± 5.2			8.6 ± 4.3			7.7 ± 3.8	
Average ± SD (of the last six month's data)	18.1 ± 3.1	17.8 ± 4.3	17.8 ± 3.7	5.0 ± 0.8	5.4 ± 1.5	5.6 ± 1.1	4.4 ± 1.9	4.1 ± 1.8	5.6 ± 1.3
Overall average ± SD (of the last six month's data)		17.9 ± 3.5			5.3 ± 1.2			4.7 ± 1.7	

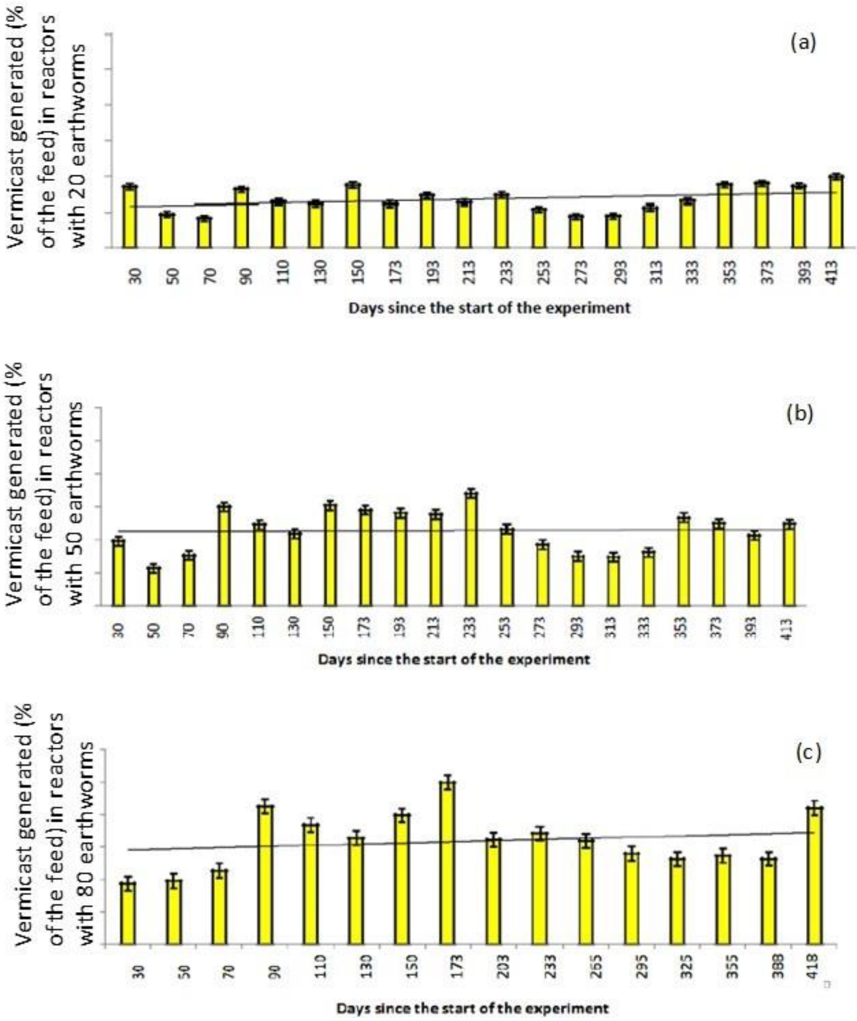

Figure 4. Trend in the generation of vermicast as a function of time in pulse-fed, semi-continuous reactors operated with (**a**) 20, (**b**) 50, and (**c**) 80 earthworms with fresh ipomoea.

3.3.2. Chemical Characteristics of Ipomoea Vermicast Relative to the Parent Substrate

Ipomoea loses 53% of its TOC in the process of getting converted to vermicast (Table 13) and its C:N ratio falls from 21 to 10,which is a level highly desirable in an organic fertilizer. It also gets extensively mineralized by having its nitrate nitrogen, available phosphorous, and available sodium, potassium, calcium, copper, manganese, and zinc increased in concentration by several orders of magnitude.

Table 13. Chemical characteristics of ipomoea and its vermicast.

Variables	Values in	
	Ipomoea	**Vermicast**
Total organic carbon (g/kg)	438 ± 15.3	233.3 ± 16.6
Total nitrogen (g/kg)	21 ± 0.7	23 ± 0.8
C:N ratio	21:1	10:1
Ammoniacal nitrogen (mg/kg)	-	237 ± 8.3
Nitrate nitrogen (g/kg)	1.8 ± 0.06	15.4 ± 1.5
Available sodium (g/kg)	0.072 ± 0.006	0.246 ± 0.0042
Available potassium (g/kg)	1.048 ± 0.012	3.6 ± 0.1
Available calcium (g/kg)	1.24 ± 0.18	4.5 ± 0.1
Available phosphorous (mg/kg)	89.9 ± 4.7	478 ± 6.2
Total copper (mg/kg)	40.2 ± 4.65	53 ± 6.08
Available copper (mg/kg)	1.33 ± 0.99	18.73 ± 0.37
Total manganese (mg/kg)	142.67 ± 7.02	183.2 ± 17.75
Available manganese (mg/kg)	17.3 ± 1.86	91.2 ± 1.7
Total zinc (mg/kg)	152.2 ± 7.53	181.1 ± 17.32
Available zinc (mg/kg)	13.8 ± 1.6	88.3 ± 1.4

3.4. Fertilizer Value of the Vermicasts

While these studies were being carried out, another group in the author's laboratory was parallelly investigating the fertilizer value of the vermicast of lantana, parthenium, ipomoea, salvinia, and prosopis (*Prosopis juliflora*). It carried out studies on germination and early growth [4,40–43] as well as full plant life up to the end of the fruit yield [44–47] of several vegetables with or without fertilization by these weed's vermicomposts. The studies showed that the vermicomposts of all the weeds were as plant friendly and soil-friendly as manure-based vermicasts are known to be [48]. The group also explored the causes behind the transformation of the toxic weeds into benign fertilizers [49–52]. It was seen that a) the chemicals responsible for the toxicity and allelopathy of these weeds were destroyed in the course of vermicomposting, and b) there was mineralization in the form of degradation of organic carbon into CO_2 (which escaped into the atmosphere) and of various nutrients (which became more bioavailable).

Another group studied the effect of vermicompost of lantana on the grain yield and greenhouse gas (GHG) emissions from rice cultivation [53–55]. It was seen that fertilization by the weed's vermicompost led to better yields of rice, with significantly lesser emission of greenhouse gases than fertilization by chemicals [56,57].

So far, vermicomposting at a commercial scale has been largely confined to the use of animal manure as the feedstock. But animal manure has several competing uses, especially in developing countries such as India [10]. Consequently, it has limited supply as a vermicomposting feedstock. In contrast, weeds such as the ones explored in the present study have no competing use. They are more widely available, in much larger quantities, than animal manure. Secondly, the use of those weeds as vermireactor feedstock opens up the possibility of large-scale harvesting of such weeds. This, in turn, is likely to help in reducing the hold of those weeds in the areas dominated by them, enabling other vegetation to come up. Thirdly, the use of the weeds as vermireactor feedstock will prevent their debris and senescenced plants from degradation in the open, thereby preventing them from generating global warming gases. Lastly, organic fertilizers have high and unlimited demand. The use of weeds as feedstock can meet the demand. All these factors indicate the much higher economic viability of the present weed-based vermicomposting process than the pre-existing manure-based processes have.

4. Summary and Conclusions

A novel process has been reported which enables rapid, inexpensive, and sustainable vermicomposting of the toxic weeds parthenium *(Parthenium hysterophorus)*, ipomoea *(Ipomoea carnea)*, and lantana *(Lantana camara)*. By invoking the concept of 'high-rate vermicomposting', developed earlier by S. A. Abbasi and coworkers, it has become possible to vermicompost the weeds directly without the need for pre-composting or providing any other form of pretreatment. The manure warm *Eisenia fetida*, which had been cultured on cowdung as feed, was slow to adapt to the weed-feed but survived and then began to thrive in all three weeds, enabling the sustained and efficient vermicomposting of the weeds throughout 480 days of uninterrupted operation of the vermireactors. In all cases, the extent of vermicast production per unit of time showed a rising trend, indicating that the rate of vermicomposting was set to rise further with time as the second and the third generations of earthworms, better adapted to the weeds than the pioneers, take over the feeding. The vermicomposting was found to accompany a $50 \pm 10\%$ loss of organic carbon of each weed. There was about an 8-fold increase in nitrate nitrogen reflecting the high degree of mineralization occurring in the course of vermicomposting. There was an equally dramatic increase in available sodium, potassium, calcium, and phosphorous. The levels of total copper, total manganese, and total zinc have also gone up mildly, while those of available copper, manganese, and zinc have gone up dramatically. There was a lowering of the carbon:nitrogen ratio to less than 15 in the vermicast of all three weeds, bringing the vermicast to the level considered highly desirable for use as fertilizer. The findings establish that sustained, direct, and rapid conversion of even toxic and allelopathic weeds to fertilizers can be accomplished with the high-rate vermicomposting paradigm. Among the three weeds, lantana was fed upon most voraciously by the earthworms, followed by parthenium and ipomoea. The juvenile and cocoon production was also the highest in lantana followed by ipomoea and parthenium.

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Abbreviations

HEVSTOW	High efficiency vertically stocked vermicomposting system for treating organic waste
PDCOP	Pseudo-discretized continuous reactor operation
SRT	Solid retention times
TOC	Total organic carbon
C:N	Carbon-to-nitrogen
SD	Standard deviation

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