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Nutrient Recycling from Industrial Solid Wastes and Weeds by Vermiprocessing Using Earthworms*[1]

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ABSTRACT

Vermicomposting is a biotechnological process that enables the recycling of organic waste materials into manure through the combined action of earthworms and mesophilic microorganisms. In this study, a 13-week experiment was carried to vermiprocess food industry sludge mixed with different bedding materials including two weeds, water hyacinth and parthenium, as well as cow dung, in different combinations employing earthworms of the species *Eisenia fetida*. Eight vermibins containing one kilogram of the waste mixtures (dry weight basis) were established for vermicomposting. Vermiprocessing significantly increased nitrogen, phosphorous, and potassium contents of the mixtures. However, a decrease in pH, organic carbon, and C:N ratio was observed after vermiprocessing. The heavy metal contents in the vermicomposts were higher than the initial values but within permissible limits. These results indicated that the studied wastes can be converted into good quality manure by vermiprocessing, which indicated their agricultural values as a soil conditioner if mixed with weeds in appropriate ratios.

Key Words: *Eisenia fetida*, food industry sludge, heavy metals, manure, vermicompost

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INTRODUCTION

Industries generate large quantity of liquid, gaseous, and solid wastes which cause environmental problems if disposed without proper treatment. In recent years, sustainable treatment and disposal of food industrial wastes has become an essential element of environmental management. The conventional waste disposal practices, such as open dumping, land filling, and open burning, are impractical, due to leaching and production of certain toxic substances and gases from the wastes which may cause soil, water, and air pollution. Although food industry wastewater treatment plant sludge is rich in organic matter, organic carbon, sugar, protein, enzymes, micro and macronutrients, but farmers are apprehensive to apply it directly due to its foul odour and fear that its use may lead to crust formation, pH variation, secondary salinization, *etc.* (Yadav and Garg, 2009). Fresh organic waste materials can not be applied to soil until they have been sufficiently biostabilized, because application of immature organic materials to soil may affect plant growth due to nitrogen starvation and production of toxic metabolites (Zucconi *et al.*, 1981).

Water hyacinth (WH) (*Eichhornia crassipes*) is one of the most troublesome aquatic weeds in India, spreading rapidly in most of the water bodies. It interferes with navigation, recreation, irrigation, power generation, *etc.* Several large hydropower projects had to devote significant time and money in clearing the water hyacinth to prevent its entry in the turbine because it may cause damage and power interruptions. The blockage of canals and rivers can even cause dangerous flooding (Malik, 2007). Several attempts have been made for its prevention, eradication and control, but to date without success. It has successfully resisted all attempts of eradicating it by chemical, biological, mechanical, or integrated means (Gajalakshmi *et al.*, 2001). Furthermore, the quantities of the weed that can be utilized in this manner are very low.

Parthenium (PH) (*Parthenium hysterophorus*) is another exotic weed species. Parthenin is the toxic substance present in this weed and is the causative factor for many problems (Yadav and Garg, 2011a). Due to the invasive capacity and allelopathic effects of *P. hysterophorus* (Mersie and Singh, 1987), natural ecosystems are disrupted (Evans, 1997). *P. hysterophorus* is a weed of global significance; it causes severe economic,

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environmental, human, and animal health problems in Asia, Africa, Australia, and the Pacific. The ability of parthenium to grow in a wide range of areas and habitats, its persistent seed bank, and its allelopathic potential make its management more difficult. So, a sustainable technology which is ecological sound and economically viable is needed to solve this problem.

Vermicomposting is a biotechnological process that enables the recycling of organic waste materials into manure through the combined action of earthworms and mesophilic microorganisms. In vermicomposting, earthworms play a significant role in concentrating nutrients in their casts and also a major role in mixing feed substrates. During vermicomposting, earthworms turn, ingest, grind, and digest organic wastes with the assistance of microflora present in their guts and convert them into a fine, homogenized, microbiologically active manure (Hait and Tare, 2011). Vermicomposting has dual benefits, management of organic wastes on one hand and, on the other, production of vermicomposts. The nutritional quality of the vermicomposts produced is determined by several factors, including earthworm species used and the characteristics of the raw waste such as C:N ratio, aeration, moisture content, pH, and temperature. Various attempts have been made on vermicomposting of organic materials such as poultry wastes (Garg and Kaushik, 2005), sewage sludge (Gupta and Garg, 2008), plant wastes (Deka *et al.*, 2011), winery wastes (Nogales *et al.*, 2005), biogas digester slurry (Suthar, 2010), green guar gum industrial wastes (Suthar, 2006), sugar industry wastes (Sangwan *et al.*, 2008), textile industry wastes (Kaushik and Garg, 2004), olive oil industry wastes (Vivas *et al.*, 2009), sago industry solid wastes (Subramanian *et al.*, 2010), paper pulp industry sludge (Kaur *et al.*, 2010), and food industry wastes (Yadv and Garg, 2011b). However, there is a paucity of data on the vermicomposting of food industry wastewater treatment plant sludge mixed with different bedding materials. The aim of the present study is to assess the feasibility of vermiprocessing of food industry sludge mixed with cow dung (CD) and two weeds, *viz.*, water hyacinth and parthenium, employing an epigeic earthworm species *Eisenia fetida.* It was hypothesized that different percentages of sludge and cow dung and weeds in feed mixtures would affect the vermicompost quality and the growth and fecundity of the earthworms.

MATERIALS AND METHODS

Raw materials

Eisenia fetida is a most widely used worm species for the purpose of vermiprocessing of solid wastes. So young unclitellated *Eisenia fetida* hatchlings were randomly picked from stock cultures maintained in the laboratory using cow dung as the culturing material. Food industry sludge (FIS) was procured from the wastewater treatment plant of a food industry located at Bahadurgarh, Haryana, India. The major products of this industry are biscuits and candies. The sludge used in this study was a mixture of primary and activated sludge collected from the sand beds. It was dried in direct sunlight for a week with periodic turnings before use as feed stock in waste mixture for vermicomposting. Fresh urine free cow dung was collected from a livestock farm located at Hisar, India. Fresh water hyacinth plants were collected from a water hyacinth-infested pond. The mud was washed away from the roots and leaves of the plants with running water before use in the experiment. Full-grown, but without flowering, plants of *P. hysterophorus* were collected from the premises of Guru Jambheshwar University of Science & Technology, Hisar, India.

Experimental procedure

The fresh weed plants were shredded to 2–3 cm size before mixing with other raw waste substrates. Eight kinds of vermibins (Vermibins 1-8) in triplicate were established having different ratios of CD, FIS, WH, and PH (Table I). One kg of each waste mixture (dry weight basis) was taken in appropriate size circular plastic containers. The physico-chemical characteristics of CD, FIS, WH, and PH are given in Table II.

TABLE I

Eight kinds of vermibins established with different ratios of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH) for the vermicomposting experiment

Vermibin	CD	FIS	WH	PH
	%			
1	100	-	-	-
2	25	25	50	-
3	50	25	25	-
4	25	50	25	-
5	25	25	-	50
6	50	25	-	25
7	25	50	-	25
8	25	25	25	25

The mixtures in all vermibins were turned manually every day for 3 weeks in order to pre-compost the feed so that it becomes palatable to worms. After 3 weeks, 40 healthy unclitellated hatchlings were inoculated in each vermibin. All the vermibins were kept in dark at room temperature. The moisture content was maintained at 60%–80% during the experiment. The containers were covered with moist jute to prevent mo-

TABLE II

Selected physico-chemical properties of the raw cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH) for vermicomposting

Property[a)]	CD	FIS	WH	PH
pH	8.1±0.1[b)]	6.25±0.27	7.1±0.03	8.0±0.1
EC (dS m^{-1})	1.2±0.01	1.8±0.04	2.2±0.01	2.7±0.03
TOC (g kg^{-1})	505±15	380±19	312±7.8	470±31
TKN (g kg^{-1})	6.5±0.2	21±0.8	6.8±0.5	7.5±0.3
TAP (g kg^{-1})	6.60±0.2	7.90±0.3	3.86±0.2	3.69±0.3
TK (g kg^{-1})	2.8±0.1	3.5±0.25	6.6±0.3	9.0±0.5
TCa (g kg^{-1})	1.87±0.08	3.8±0.2	5.75±0.25	2.21±0.05
C:N ratio	77.7±3.3	18.1±0.9	45.9±2.3	62.7±5.1
C:P ratio	76.51±3.1	48.10±2.3	80.82±6.1	127.3±11
OM (%)	87.5±5.5	65.4±3.8	53.7±5.1	81±6.1
Fe (mg kg^{-1})	1 750±140	1 585±110	448±11	1 090±55
Cu (mg kg^{-1})	31±2.1	89±2.8	221±9.3	73±3.3
Cd (mg kg^{-1})	2.10±0.03	4.7±0.04	0.60±0.01	1.10±0.02
Zn (mg kg^{-1})	143±8.3	430±9	315±10	398±14
Pb (mg kg^{-1})	2.40±0.08	4.0±0.20	0.06±0.008	1.10±0.01

[a)]EC = electrical conductivity; TOC = total organic C; TKN = total Kjeldhal N; TAP = total available P; TK = total K; TCa = total Ca; OM = organic matter.
[b)]Values are means±standard deviations ($n = 3$).

isture loss and to keep away the pests. During the study period, no extra feed was added at any stage. Homogenized samples (free from earthworms, hatchlings, and cocoons) of all the feed materials were drawn at the end. The term “zero day” refers to the day of inoculation of earthworms after pre-composting for three weeks. The vermicompost was air dried at room temperature prior to physico-chemical and heavy metal analysis. The pH and electrical conductivity (EC) were determined using a water suspension of the vermicompost in the ratio of 1:10 (w/v) after agitating for 30 min by pH and electrical conductivity meters, respectively. Total organic carbon (TOC) was determined as reported by Nelson and Sommers (1982). Total Kjeldhal nitrogen (TKN) was determined after digesting the sample with concentrated H_2SO_4 and concentrated $HClO_4$ according to the Bremner and Mulvaney (1982) procedure. Total available phosphorus (TAP) was determined spectrophotometrically with molybdenum in sulphuric acid. Total calcium (TCa) and total potassium (TK) were determined after digesting the sample in a diacid mixture of concentrated HNO_3 and concentrated $HClO_4$ (9:1, v/v) by a flame photometer. Heavy metals were determined by an atomic absorption spectrophotometer (AAS) after digestion of the sample with a diacid mixture of concentrated HNO_3 and concentrated $HClO_4$ (9:1, v/v). C:N and C:P ratios were calculated using the values of TOC, TKN, and TAP.

Biomass gain and cocoon production by the 40 hatchlings in each vermibin were recorded weekly for 13 weeks. The earthworms were weighed with full gut. The earthworms and cocoons were separated from the bins by hand sorting, counted and weighed after washing with water. Then, all earthworms (but not cocoons) were returned to their respective bins.

Statistical analysis

The reported results are the mean of three replicates. One-way analysis of variance (ANOVA) was used to analyze the significant differences among different vermibins for studied parameters. Tukey's t test as a *post hoc* was also performed to identify the homogeneous type of vermibins for the various parameters. All statistical tests were evaluated at the 95% confidence level. All statistical analyses were done using the SPSS software.

RESULTS AND DISCUSSION

Organoleptic properties

After 13 weeks of worm activity, the vermicomposts were fine, odour free, and homogeneous than the raw waste. This indicated that the earthworms were effective in reducing the particle size of organic matter in the vermibins and reduced the overall weight and volume of the waste mixture.

pH

Initially, FIS was slightly acidic (pH = 6.2±0.27), WH neutral (pH = 7.1±0.03), CD alkaline (pH = 8.1±0.1), and parthenium alkaline (8.0±0.1) (Table

II). After vermicomposting, the pH values of different feed mixtures were 7.0±0.3 to 8.1±0.04, lower (9.8%–15.4%) than those of the raw waste mixtures (Table III). Processing by earthworms in organic wastes could result in the production of different intermediate species in vermibins, which lowered the pH of the substrates. Decreases in pH were significantly different between different vermibins ($P < 0.05$) (Table IV). The decreases in pH may be due to mineralization of nitrogen and phosphorus into nitrites/nitrates and orthophosphates and bioconversion of the organic material into intermediate species of organic acids (Ndegwa *et al*., 2000). The lowering of pH may also be due to accumulation of acids from the microorganisms or from the production of humic and fulvic acids during decomposition (Chan and Griffiths, 1988). The decline in pH could be attributed to the production of CO_2, ammonia, NO_3^-, and organic acids by microbial decomposition of feed substrates during vermicomposting (Garg and Gupta, 2011).

Electric conductivity

The EC values of vermicomposts, which were in range of 2.15–3.0 dS m^{-1}, were higher than those of the initial waste mixtures (Table III). This increase may be due to mineralization and consequent formation of ions in different waste mixtures in the presence of earthworms. The maximum increase in EC was recorded in Vermibin 3 and minimum in Vermibin 5. Deka *et al.* (2011) have reported that earthworms produce organic-mineral compounds by digesting organic materials as feed and these minerals may accumulate in the final products.

Organic matter content

The initial organic matter (OM) contents in the raw waste mixtures were 67±1.93%–87±2.44% at the onset of experiment. The OM content decreased significantly in all the vermibins after vermiprocessing (Table III). The vermicomposts obtained from Vermibin 1 had the highest OM loss (44.7%), followed by Vermibins 6 (39.1%), 3 (35.7%), 8 (34.3%), 5 (29.6%), 7 (27.6%), 2 (23.3%), and 4 (22.7%). Statistically, the OM loss in Vermibins 1, 2, 5, and 6 was not significantly different from each other ($P < 0.05$). These results indicated that vermiprocessing with *E. fetida* was an effective tool in organic matter degradation of the wastes. The decrease in organic matter content in vermiprocessing may be due to mutualistic relationships between microflora, ingested microorganisms, and intestinal mucous of earthworms (Trigo and Lavelle, 1993).

Total organic C

The TOC content in the vermicomposts was lesser

TABLE III

Selected physico-chemical properties[a)] of the initial waste mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH)

Vermibin[b)]	pH	EC	TAP	TK	TCa	OM
		dS m^{-1}	g kg^{-1}			%
			Initial mixture			
1	8.1±0.04[c)]d[d)]	1.20±0.08a	6.62±0.18c	2.80±0.08a	1.80±0.19a	87.06±2.44c
2	7.1±0.05ab	1.85±0.09bcd	5.60±0.05a	4.80±0.08c	4.30±0.25e	67.23±1.93a
3	7.4±0.12abc	1.60±0.15b	6.30±0.08ab	4.00±0.20b	3.25±0.15c	73.78±3.79ab
4	7.0±0.30a	1.75±0.05bc	6.54±0.20ab	4.15±0.15b	3.81±0.14d	68.96±3.79abc
5	7.5±0.20bc	2.10±0.22d	5.40±0.10a	6.70±0.20e	2.50±0.16b	77.92±7.7abc
6	7.6±0.20c	1.75±0.05bc	6.25±0.10b	4.30±0.10b	2.48±0.07b	79.30±4.35bc
7	7.1±0.10ab	1.80±0.06abc	6.50±0.08ab	4.70±0.01c	3.00±0.15c	73.95±2.75ab
8	7.3±0.09abc	2.00±0.12cd	5.56±0.04a	5.55±0.15d	3.40±0.1cd	71.37±2.41ab
			Vermicompost			
1	7.0±0.14e	3.00±0.18bc	9.73±0.27cd	4.14±0.14a	2.50±0.20a	48.09±2.06abc
2	6.4±0.14bcd	2.55±0.12ab	7.32±0.68a	7.12±0.12cd	6.00±0.23f	51.54±3.27abc
3	6.1±0.12ab	2.15±0.25a	8.98±0.2bcd	6.00±0.23b	5.00±0.09e	47.41±1.36ab
4	6.1±0.23ab	2.95±0.15bc	8.79±0.21bc	5.86±0.14b	4.50±0.1d	53.27±1.64bc
5	6.6±0.08d	2.61±0.31ab	8.70±0.40b	9.72±0.22e	4.00±0.20c	54.82±2.03bc
6	6.5±0.10cd	2.85±0.15bc	8.26±0.26ab	6.88±0.12c	3.10±0.14b	48.27±0.69abc
7	6.0±0.14a	2.59±0.29ab	9.78±0.22d	7.10±0.10cd	3.90±0.08c	53.44±1.90c
8	6.2±0.08abc	2.60±0.10ab	8.68±0.12b	8.38±0.12d	4.00±0.12c	46.89±2.93a

[a)]EC = electrical conductivity; TAP = total available P; TK = total K; TCa = total Ca; OM = organic matter.
[b)]See Table I for the ratios of CD, FIS, WH, and PH in each vermibin.
[c)]Values are means±standard deviations ($n = 3$).
[d)]Mean values followed by the same letter(s) in a column within the raw mixtures or the vermicomposts are not significantly different at $P < 0.05$.

TABLE IV

Summary of analysis of variance (ANOVA) results of selected physico-chemical properties of different vermicomposts obtained from different kinds of vermibins with waste mixtures of cow dung, food industry sludge, water hyacinth, and parthenium

Property[a)]	Sum of square	Degrees of freedom	F value	P value
pH	2.634	23	17.93	0.00
EC	3.303	23	8.67	0.00
TOC	9 931.9	23	5.50	0.02
TKN	44.34	23	4.36	0.007
TAP	14.91	23	16.28	0.00
TK	53.35	23	310	0.002
TCa	27.95	23	164.6	0.00

[a)]EC = electrical conductivity; TOC = total organic carbon; TKN = total Kjeldhal N; TAP = total available P; TK = total K; TCa = total Ca.

than the initial levels. The TOC loss in different vermibins ranged from 22.7% to 44.7% (Fig. 1). TOC loss was maximum in Vermibin 1 and minimum in Vermibin 4. There were several factors which governed TOC loss during the vermiprocessing of the wastes. During this process earthworms fragmented and homogenized the ingested material through muscular action of their foregut and also add mucus and enzymes to the ingested material and thereby increased the surface area for microbial action. The microbial communities of the vermicomposting sub-systems are primarily responsible for extra-cellular enzymes required for waste mineralization in vermicomposting bins (Edwards and Fletcher, 1988). Aira *et al.* (2007) reported that earthworms modified the substrate conditions, which subsequently enhanced the carbon losses from the substrates through microbial respiration in the form of CO_2.

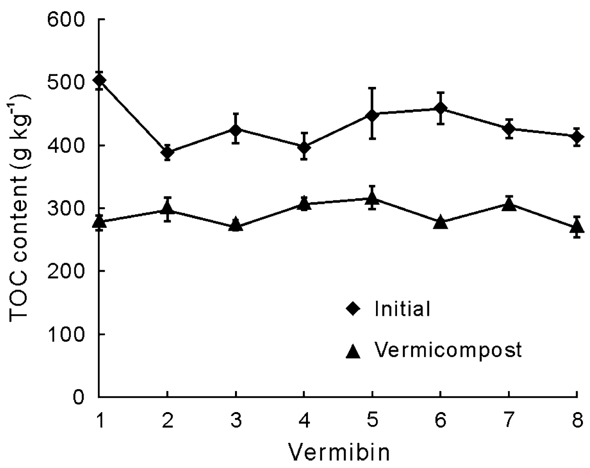

Fig. 1 Total organic carbon (TOC) contents of the initial waste mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH). See Table I for the ratios of CD, FIS, WH, and PH.

Total Kjeldhal N

The TKN contents were higher in all vermicomposts (8.15–14.4 g kg^{-1}) than the raw waste mixtures (6.5–14.0 g kg^{-1}) (Fig. 2). In the products of vermibins 1–8, the TKN content after vermiprocessing was 3.21, 2.10, 2.23, 1.58, 2.14, 2.22, 1.71, and 2.33 fold higher, respectively, than the initial value. The differences in TKN content in the end products obtained from different vermibins were insignificant ($P < 0.05$) (Table IV). Loss of organic carbon content, decrease in pH, mineralization of the organic matter containing proteins, and conversion of ammonium nitrogen into nitrate might be responsible for nitrogen addition in vermicompost (Yadav and Garg, 2011b). Earthworms also add nitrogen in the form of mucus, nitrogenous excretory substances, growth stimulating hormones, and enzymes during the fragmentation and digestion of organic matter in the vermicomposting process (Hobson *et al.*, 2005; Vig *et al.*, 2011).

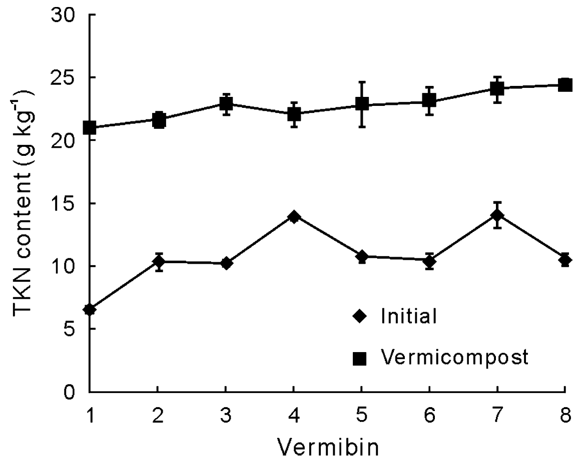

Fig. 2 Total Kjeldhal nitrogen (TKN) contents of the initial waste mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH). See Table I for the ratios of CD, FIS, WH, and PH.

Total available P

The TAP contents were from 30% to 60% higher in the vermicomposts than the raw waste mixtures, in the ranges of 7.32–9.78 and 5.40–6.62 g kg^{-1}, respectively (Table III). Vermicomposts of the parthenium-containing vermibins (Vermibins 2–4) registered comparatively more increase in TAP contents compared to those of the water hyacinth-containing vermibins (Vermibins 5–7). This increase may be due to mineralization and mobilization of phosphorus due to bacterial and fecal phosphatase activity of earthworms (Edwards and Lofty, 1972). Lee (1992) reported that if the organic materials passed through the gut of earthworms, then some P would be converted to such forms that are available to plants. The differences in P mineralization rate among vermibins could be due to different concentrations of feed substrates in the bedding materials. The release of phosphorus in available forms is performed partly by earthworm gut phosphatases, and further release of phosphorus might be attributed to the phosphorus-solubilizing microorganisms present in worm casts (Le Bayon and Binet, 2006).

Total K

The TK contents increased in the vermicomposts as compared to the raw waste mixtures, with the increases ranging from 41.2% (Vermibin 4) to 60% (Vermibin 6) (Table III). The differences in TK content after vermicomposting between the vermibins except that between Vermibins 3 and 4 and those between Vermibins 2, 6, and 7 were significantly different ($P < 0.05$). Delgado *et al.* (1995) also reported a higher content of TK in the sewage sludge vermicomposts. In contrast, Orozco *et al.* (1996) and Sangwan *et al.* (2008) found decreases in TK in coffee pulp waste and sugar mill sludge after vermicomposting.

Total Ca

An increase in TCa content of vermicomposts was observed at the end of the experiment over the initial levels (Table III). The increases were 38.8%, 39.5%, 53.2%, 18.1%, 60%, 25%, 30%, and 17.6% in Vermibins 1–8, respectively. The increased TCa contents may be attributed to the enhanced mineralization in the presence of earthworms during vermiprocessing. The TCa contents after vermicomposting were significantly different between vermibins except those between Vermibins 5, 7, and 8 ($P < 0.05$) (Tables III). Similar observations have been reported by Yadav and Garg (2009) for the vermicomposting of urban green wastes.

C:N and C:P ratios

The C:N ratio is an important parameter as plants can not assimilate mineral N if this ratio is greater than 20:1 (Gupta and Garg, 2008). The variations in C:N ratio with time in different vermibins during vermicomposting are given in Fig. 3. Initial C:N ratios in the different raw waste mixtures were in the range of 28.88–77.69. The C:N ratio decreased with time in all the waste mixtures during vermicomposting. The vermicomposts had C:N ratios ranging from 11.14 to 14.04. Gupta and Garg (2008) demonstrated an approximately 58%–85% decrease in C:N ratio of primary sewage sludge after composting through *E. fetida*. Senapati *et al.* (1980) reported that the loss of carbon as carbon dioxide in the process of respiration and production of nitrogenous excreta enhanced the level of nitrogen, which lowered the C:N ratio of the waste substrate. It is evident from the Fig. 4 that the C:P ratios decreased with time in all vermibins. The initial C:P ratio was in the range of 61.1–83.7; after vermiprocessing, the C:P ratio ranged from 28.76 to 40.8. In this experiment, a high degree of organic matter stabilization was achieved in all the vermibins. This demonstrated the role of earthworms in rapid decomposition and mineralization of waste mixtures during vermiprocessing.

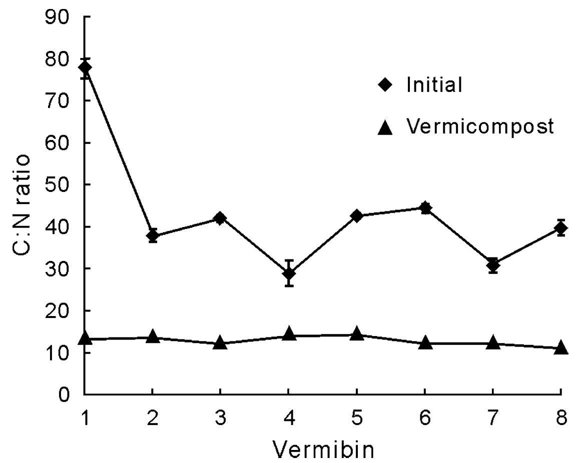

Fig. 3 C:N ratios in the initial mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH). See Table I for the ratios of CD, FIS, WH, and PH.

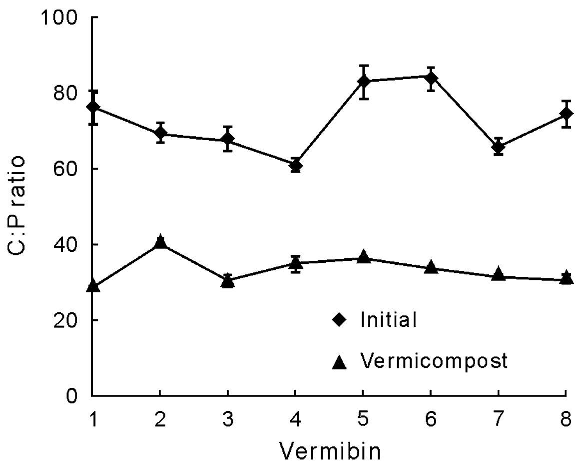

Fig. 4 C:P ratio in the initial mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH). See Table I for the ratios of CD, FIS, WH, and PH.

Heavy metal contents

The metal contents in the initial raw waste mixtures and final vermicomposts are given in Table V. The contents of the studied metals (Fe, Cu, Pb, Cd, and Zn) were higher in the vermicomposts than their initial level in the raw waste mixtures. The maximum increase in Fe content was found in Vermibin 2 and minimum in Vermibin 5 (Table V). The Fe contents in the vermicomposts increased by 23.1%–46.2% over the initial contents. The increases in total Cu content ranged from 20.4% (Vermibin 2) to 170% (Vermibin 1) in the vermicomposts over the initial content. The Cu contents in Vermibins 1, 5, 6, and 7 were not significantly different from each other ($P < 0.05$). Total Pb contents were 5.3%–16.9% higher in the vermicomposts than the initial levels. The Cd contents increased by 22.5%–82.2 % in the vermicomposts. After vermiprocessing, the Zn contents increased by 16.2%–77.7%. The carbon losses by mineralization and reduction of waste biomass due to the breakdown of organic matter during vermicomposting may be the reason for the increases in heavy metal content in the final products (Yadav and Garg, 2011a). However, the heavy metal contents in the vermicomposts obtained from different vermibins were lower than the prescribed limits for heavy metal application in agricultural soils. Elvira *et al.* (1998) have also reported the increases in Zn, Fe, Mn, and Ni contents in the vermicompost of paper-pulp mill sludge. Similarly, Nogales *et al.* (2005) have reported an increase in total micronutrients in winery waste after vermicomposting.

Growth and reproduction of E. fetida

During the vermiprocessing period, the worms grew well in all the vermibins and very little worm mortality was observed during the initial stages of vermiprocessing. The mortality ranged from 2% to 10% of the total number of the worms in different vermibins, being higher in those which had higher ratios of PH and FIS. The dead worms were replaced with an equal number of new worms of almost the same biomass from the stock culture. No mortality was observed in Vermibins 1 and 3. Fig. 5 depicts the growth pattern of *E. fetida* in different vermibins with time. Initially increases in worm biomass and later weight loss by worms were observed in all the vermibins. The increase in worm biomass in the initial stages may be due to availability of food and in the later stages, the decrease in biomass may be due to exhaustion of food with time. The biomass gain was variable in different waste mixtures. The maximum worm biomass was obtained in Vermibin 1, followed by Vermibins 8 and 6, and the minimum worm biomass was recorded in Vermibin 7. Maximum worm biomass was attained in the

TABLE V

Heavy metal contents in the initial mixtures and vermicomposts obtained from different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH)[a)]

Vermibin	Total Fe	Total Cu	Total Pb	Total Cd	Total Zn
	mg kg^{-1}				
	Initial mixture				
1	1 765±47.9[b)]d[c)]	31.5±4.6a	2.42±0.18bcd	2.14±0.14a	148±19a
2	1 087±89.1a	142.0±6.4d	2.53±0.07cd	2.08±0.08a	300±9cd
3	1 390±121.0abc	95.2±6.3c	2.68±0.12cd	2.41±0.10ab	260±11b
4	1 350±170.0abc	108.0±7.0c	3.15±0.15e	3.08±0.08c	333±10de
5	1 785±217.0d	65.5±2.1b	1.79±0.21a	2.28±0.22ab	348±8e
6	1 583±74.6d	58.9±6.0b	2.30±0.10bc	2.57±0.70b	277±3bc
7	1 520±132.0bcd	73.0±7.0b	2.72±0.08d	3.19±0.19c	351±13e
8	1 228±4.4ab	106.0±7.0c	2.10±0.10ab	2.25±0.15ab	324±16de
	Vermicompost				
1	2 383±106.2e	84.2±5.2a	2.83±0.11d	3.90±0.25a	263±16a
2	1 590±91.5a	171.0±3.5c	2.70±0.14cd	3.10±0.20a	379±11bc
3	1 934±134.0bcd	137.0±12.1b	2.90±0.15d	3.68±0.43a	347±14b
4	1 702±110.0abc	137.0±5.7b	3.32±0.03e	3.87±0.31a	399±12cd
5	2 199±189.0de	88.3±3.1a	1.94±0.06a	3.00±0.24a	409±21cd
6	2 126±74.7de	96.8±3.3a	2.42±0.08bc	3.27±0.23a	351±16b
7	1 977±23.4cd	94.5±5.1a	2.98±0.12d	3.91±0.09a	408±14cd
8	1 651±94.3ab	151.0±16.5bc	2.35±0.08b	3.64±20.66a	425±14d

[a)]See Table I for the ratios of CD, FIS, WH, and PH.
[b)]Values are means ± standard deviations ($n = 3$).
[c)]Mean values followed by the same letter(s) in a column within the raw mixtures or the vermicomposts are not significantly different at $P < 0.05$.

7th week in Vermibin 1, and in the 8th week in Vermibins 3 and 8 (Table VI). The highest mean net worm biomass gain (823±57.2 mg worm^{-1}) was recorded in Vermibin 1 and the lowest mean net worm biomass gain (555±32 mg worm^{-1}) was in Vermibin 7. The higher net biomass produced per worm in Vermibins 1 and 8 as compared to the other vermibins indicated the high palatability of these feed wastes to the earthworms. The highest growth rate of the earthworms was observed in Vermibin 1 (33.2±0.60 mg worm^{-1} d^{-1}), and the minimum growth rate was observed in Vermibin 7 (22.2±1.0 mg worm^{-1} d^{-1}). The growth rate of the earthworms in Vermibins 1 and 7 were significantly different from those of the other vermibins ($P < 0.05$).

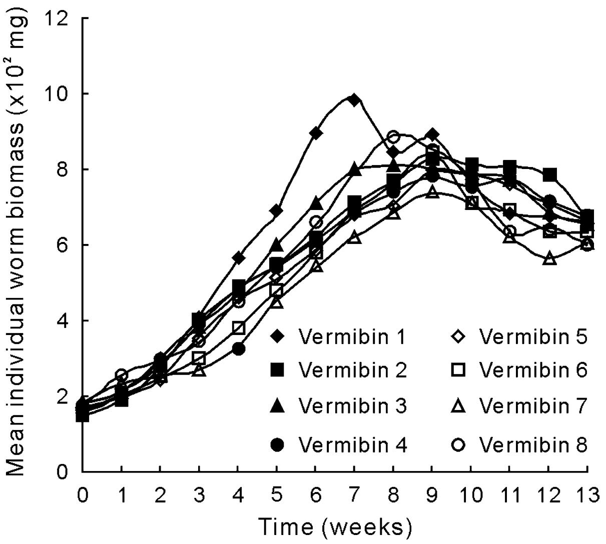

Fig. 5 Growth curves of *E. fetida* in different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH). See Table I for the ratios of CD, FIS, WH, and PH.

The reproductive potential of *E. fetida* in different vermibins was shown in Table VII. All earthworms reproduced successfully during the vermicomposting period. Clitellum development of the worms started in the 3rd week in Vermibin 1, 4th week in Vermibins 2, 3, 6, and 8, and 5th week in Vermibins 4, 5, and 7. Cocoon production started in the 4th–7th week in different vermibins. After 13 weeks, the maximum number of cocoons was recorded in Vermibin 1, followed by Vermibins 3 and 8 (Table VII). The earthworms exhibited different patterns of cocoon production with varying percentages of substrates in the feed mixtures. The number of cocoons produced per worm was also the maximum in Vermibin 1 (9.7 ± 0.3) and minimum in Vermibin 7 (3.8 ± 0.2). The numbers of cocoons produced per worm were significantly different between all the vermibins except between Vermibins 4 and 5 and Vermibins 3 and 8 ($P < 0.05$). The differences in the number of cocoons produced per worm per day were insignificant between Vermibins 1, 2, 3, 6, and 8 and between Vermibins 4, 5, and 7, but significant between the two groups ($P < 0.05$). The maximum number of hatchlings produced was in Vermibin 1 and minimum in Vermibin 7 (Table VII). The maximum hatchling biomass was recorded in Vermibin 1 and minimum in Vermibin 4.

CONCLUSIONS

Various mixtures of CD, WH, PH, and FIS were vermiprocessed using an epigeic earthworm species (*E. fetida*) and the vermicompost quality and growth and fecundity of the worms were studied in different waste mixtures. The final vermicomposts were homogenous, rich in important plant nutrients (NPK) and their C:N ratios were below 20, which indicated their agricultural

TABLE VI

Biomass production of *E. fetida* in different kinds of vermibins (Vermibins 1–8) with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH)[a)]

Vermibin	Mean initial biomass	Maximum biomass achieved	Time of maximum biomass achieved	Net biomass gain	Growth rate	Biomass gained per unit feed waste
	mg worm^{-1}		week	mg worm^{-1}	mg worm^{-1} d^{-1}	mg worm^{-1} g^{-1}
1	158±21[b)]a[c)]	990±20.6c	7th	823±57d	16.97±1.05e	33.2±0.6d
2	150±18a	830±38ab	9th	680±18bc	10.70±0.6bc	27.2±0.8c
3	180±31a	810±78ab	8th	630±19abc	11.25±0.31c	25.2±0.6b
4	180±20a	781±19ab	9th	601±20ab	9.66±0.34ab	24.0±0.8b
5	175±4a	801±22ab	9th	626±17ab	9.93±0.15abc	25.0±0.7b
6	162±26a	842±30ab	9th	680±26bc	10.70±0.24bc	27.2±0.7c
7	184±17a	739±17a	9th	555±32a	8.80±0.27a	22.2±1.0a
8	175±21a	980±69bc	8th	715±39c	12.76±0.65d	28.6±0.4c

[a)]See Table I for the ratios of CD, FIS, WH, and PH.
[b)]Values are means ± standard deviations ($n = 3$).
[c)]Mean values in a column with the same letter(s) are not significantly different at $P < 0.05$.

TABLE VII

Reproduction potential of *E. fetida* in different kinds of vermibins with waste mixtures of cow dung (CD), food industry sludge (FIS), water hyacinth (WH), and parthenium (PH)[a)]

Vermibin	Starting time of clitellum development	Starting time of cocoon production	Total No. of cocoons produced	No. of cocoons produced per per worm	No. of cocoons produced per worm day	Total No. of hatchlings produced	Biomass of hatchlings produced
	week	week					g
1	3rd	4th	388±36[b)]c[c)]	9.7±0.3f	0.14±0.06b	138.0±8.0d	25.5±1.5d
2	4th	5th	284±9b	7.1±0.3c	0.11±0.01b	116.0±9.0cd	22.1±1.8c
3	4th	5th	360±27c	9.0±0.2e	0.14±0.02b	124.0±17.0cd	25.4±1.4d
4	5th	6th	196±24a	4.9±0.3b	0.08±0.01a	67.2±10.8a	11.7±0.3a
5	5th	7th	188±22a	4.7±0.2b	0.08±0.01a	72.8±16.2ab	14.7±0.6b
6	4th	5th	312±32bc	7.8±0.1d	0.12±0.05b	96.0±5.0bc	21.1±0.9c
7	5th	7th	152±24a	3.8±0.2a	0.07±0.01a	63.6±7.4a	12.6±0.4ab
8	4th	5th	356±19c	8.9±0.3e	0.14±0.06b	121.0±10.5cd	25.2±0.8d

[a)]See Table I for the ratios of CD, FIS, WH, and PH.
[b)]Values are means ± standard deviations ($n = 3$).
[c)]Mean values in a column with the same letter(s) are not significantly different at $P < 0.05$.

values as a soil conditioner. These results also indicated the economic utilization of food industry sludge mixed with weeds which may be very important to achieve sustainable development. It should be noted that higher ratios of PH and WH resulted in higher vermiprocessing efficiency. Finally, it is concluded that vermiprocessing can be introduced as one of the technologies for management of industrial wastes and weeds into value-added products.

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