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Feasibility of nutrient recovery from industrial sludge by vermicomposting technology

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ABSTRACT

Transformation of industrial sludges into vermicompost is of double interest: on the one hand, a waste is converted into value added product, and, on the other, it controls a pollutant that is a consequence of increasing industrialization. This paper reports the feasibility of utilization of vermicomposting technology for nutrient recovery from industrial sludge in laboratory scale experiment employing *Eisenia fetida* earthworm. A total of nine vermireactors, having different percentage of wastewater treatment plant sludge of a food industry and cow dung, were established and monitored for fertilizer quality of vermicompost and growth and fecundity of the earthworms for 3 months. The earthworms were unable to survive in 100% FIS. There was a decrease in pH, organic carbon content, organic matter, C:N ratio, and increase in ash content, EC, nitrogen, potassium and phosphorus content in all the vermireactors. Total Kjeldhal nitrogen (TKN) content increased in the range of 12.2–28.7 g kg^{-1} in different vermireactors after vermicomposting. C:N ratio was 1.59–5.24 folds lesser in final vermicomposts than initial raw substrate. The heavy metals' content in final vermicomposts was higher than initial feed mixtures. Maximum worm biomass was observed in control, i.e., 100% CD (836 mg earthworm^{-1}) and the lowest in 30% CD + 70% FIS feed mixture (280 mg earthworm^{-1}). Cocoon production was started during 6–7th week in all feed mixture except in feed mixture no. 9. After 12 weeks maximum cocoons (57) were counted in 100% CD and minimum (2) in 30% CD + 70% FIS feed. The results indicated that food industry sludge could be converted into good quality manure by vermicomposting if mixed up to 30% with cow dung.

1. Introduction

Food processing has emerged as one among the most important industrial activities in recent years. To accommodate the food processing industries, the concept of Industrial Food Parks has been emerging in India. These parks have a large number of food industries operating at different scales large to small. Food processing industries produce huge quantities of liquid and solid wastes and their treatment results into the generation of sludges. But economical and ecologically acceptable disposal of industrial sludges is becoming a great challenge to industries as well as scientists due to high cost of sludge stabilization reactors, dehydration systems and transportation of sludge to disposal sites. The authors have observed that industrial sludge are generally disposed off in open dumps or poorly designed landfills causing public health and environmental hazards by surface and ground water pollution. These improper and indiscriminate disposal methods of sludges also lead to the loss of nutrient resources and also cause economic loss [1]. The damaging long-term environmental impacts and resource depletion indicate un-sustainability of the current methods.

Industrial wastes that are rich in organic matter and free from toxic substances or ions could be suitable substrates vermicomposting [2]. In yesteryears several researches have been conducted on the potential use of earthworms in nutrient recovery from industrial sludges. It has been well established that epigeic forms of earthworms can hasten the waste stabilization process to a significant extent with production of a better quality of vermicompost as compared with those prepared through traditional composting methods [2]. Various industrial sludges tested for vermicomposting include solid paper mill sludge, textile mill sludge, winery waste, guar gum industrial waste, etc. [3–9].

From the bibliographic survey, it is evident that there is paucity of data on vermicomposting of food industry wastewater treatment plant sludges which is available in huge quantities. Authors have observed that farmers are reluctant to apply it directly due to its odour, transportation cost and fear that its application may lead to crust formation, pH variation and pollution problem. The vermicomposting of food industrial sludges is of double interest: on the one hand, a waste is converted into value added product, and, on the other, it controls a pollutant that is a consequence of increasing industrialization. This paper reports the feasibility of

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Table 1
Initial physico-chemical characteristics of CD and FIS.

S. no.	Parameter	CD	FIS
1	pH	7.9 ± 0.45	6.5 ± 0.2
2	EC (ds m^{-1})	1.2 ± 0.1	1.6 ± 0.2
3	Ash content (g/kg)	260.5 ± 5.2	371.2 ± 3.8
4	TOC(g/kg)	427 ± 3.0	360 ± 2.6
5	TKN (g/kg)	8.5 ± 0.2	10.3 ± 0.2
6	TP (g/kg)	5.06 ± 0.3	6.16 ± 0.3
7	TK (g/kg)	8.8 ± 0.2	1.3 ± 0.1
8	C:N ratio	50.23 ± 2.6	34.9 ± 1.5
9	TNa (g/kg)	5.8 ± 0.2	8.6 ± 0.4
10	TCa (g/kg)	2.0 ± 0.2	4.2 ± 0.4
11	Fe (mg/kg)	1859 ± 18.5	1685 ± 19.3
12	Cu (mg/kg)	234 ± 14.6	214 ± 12.0
13	Mn (mg/kg)	561 ± 13.6	1120 ± 21.9
14	Zn (mg/kg)	110 ± 13.0	113 ± 16.1

vermicomposting of food industry sludge employing the composting worm, *Eisenia fetida*.

2. Materials and methods

2.1. Food industry sludge (FIS), cow dung (CD) and E. fetida

Food industry sludge (FIS) was procured from wastewater treatment plant of a food industry located at Bahadurgarh, Haryana, India. The sludge used in this study was obtained from the sand beds which contained a mixture or primary as well as activated sludge. FIS was dried in direct sunlight for a week with periodic turnings. Then it was mixed with CD in different proportions. Fresh CD was procured from an intensively live stocked farm at Hisar, India. The physico-chemical characteristics of FIS and CD are given in Table 1. All the organic wastes were used on dry weight basis. *E. fetida* a composting worm, was used in the experiment because of its wide spread use in vermicomposting of relatively moist organic material [10]. Healthy unclitellated hatchlings weighing 100–150 mg live weight were randomly picked up for the experiment from stock culture maintained by authors in the laboratory with CD as culture medium. The worms were adapted to laboratory conditions before inoculating into reactors.

2.2. Experimental setup

To achieve the objectives, the vermicomposting experiments were carried out in laboratory using circular plastic containers of 1 l capacity as vermireactors (diameter 16 cm and depth 10 cm). We prepared nine waste mixtures of CD and increasing contents of FIS over a total amount of 150 g (100, 90, 80, 70, 60, 50, 40, 30 and 20% CD). The physico-chemical characteristics of waste mixtures in different vermireactors were calculated on the basis of their composition in the mixture (Table 2). Each vermireactor was established in triplicate. All the FIS and CD quantities were used on dry weight basis. The mixtures were turned manually every day for 21 days in order to semi-compost the feed so that it becomes palatable to worms. After 21 days, 10 unclitellated *E. fetida* hatchlings were introduced in each vermireactor unit. All the vermireactors were kept in dark at a laboratory temperature of 25 ± 3 °C. The moisture content was maintained at 70 ± 10% by periodic sprinkling of distilled water throughout the study period and pests were kept away by covering the vermireactors with moist jute clothes. During the study period no extra feed was added at any stage. Biomass gain and cocoon production were recorded weekly for 12 weeks. The feed in each vermireactor was turned out, earthworms and cocoons were separated from the feed by hand sorting, after which earthworms were counted and weighed after washing with water and drying them by paper towels. The worms were weighed without voiding their gut content. Corrections for gut content were not applied to any data in this study. Then all earthworms, cocoons and feed were returned to the respective container. Nine controls without worms were also maintained to compare the results.

Table 2
Initial physico-chemical characteristics of feed mixtures in different vermireactors.

Vermireactor	Ph	EC	TOC	TCa	TK	TP	TNa
1	7.9	1.20	427	2.0	8.80	5.06	5.8
2	7.8	1.24	420	2.2	8.05	5.17	6.08
3	7.7	1.28	413	2.4	7.30	5.28	6.36
4	7.6	1.32	407	2.7	6.55	5.39	6.64
5	7.6	1.36	400	2.9	5.80	5.50	6.92
6	7.5	1.40	393	3.1	5.05	5.58	7.20
7	6.6	1.44	385	3.2	4.32	5.72	7.48
8	6.5	1.48	377	3.5	3.55	5.83	7.76

Units of all the parameters except pH and EC are in g kg^{-1}. The EC values are in ds m^{-1}.

2.3. Physico-chemical analyses

Homogenized samples of all feed mixtures were drawn at 0 day (initial) and day 84 (at end). The 0 day refer to the day of inoculation of earthworms after pre-composting of 21 days. Homogenized samples (free from earthworms, hatchlings and cocoons) of the vermicompost were drawn at the end of vermicomposting process. The samples were air dried in the shade at room temperature, ground in a stainless steel blender and stored in plastic vials for further physico-chemical analysis. The physico-chemical analysis was done on dry weight basis. All the chemicals used were analytical reagent (AR) grade supplied by S.D. Fine Chemicals, Mumbai, India. Double distilled water was used for analytical work. All the samples were analyzed in triplicate and results were averaged. The results were reproducible with in ±4% error limits. The pH and electrical conductivity (EC) were determined using a double distilled water suspension of each vermicompost in the ratio of 1:10 (w/v) that had been agitated mechanically for 30 min and filtered through Whatman No. 1 filter paper. Ash content and total organic carbon (TOC) was measured using the method of Nelson and Sommers [11]. Total Kjeldhal Nitrogen (TKN) was determined by using the method provided by Bremner and Mulvaney [12] procedure. Total potassium (TK) and total sodium (TNa) were determined by flame photometer (Elico, CL 22 D, Hyderabad, India) [7]. Total phosphorus (TP) was analyzed by using the spectrophotometric method with molybdenum in sulphuric acid. Total heavy metals were determined by atomic absorption spectrophotometer (AAS) [AAS 414, Electronic Corporation of India, BDL 0.001 ppm] after digesting the samples with conc. HNO_3 and conc. $HClO_4$ (4:1, v/v).

Biodegradability a parameter relates initial and final content of vermicompost organic matter during composting [13–15] was also calculated for each vermireactor. Initial organic matter and final organic matter were calculated from ash content (%):

$$\mathrm{OM}\,(\%) = (100 - \text{Ash content}\,\%)$$

Biodegradability coefficient (K_b) was calculated using the equation [16]:

$$K_b = \frac{(\mathrm{OM}_i - \mathrm{OM}_f)100}{\mathrm{OM}_i(100 - \mathrm{OM}_f)}$$

where OM_f is the organic matter content at the end of process and OM_i is the organic matter content at the beginning of the process.

2.4. Statistical analysis

One-way ANOVA was used to analyze the significant differences among different vermireactors for studied parameters. Tukey's *t*-test was also performed to identify the homogeneous type of vermireactors for the various parameters. The probability levels used for statistical significance were $p < 0.05$ for the tests.

3. Results and discussion

3.1. Nutrient quality of vermicompost

The earthworms were unable to survive in 100% FIS. Addition of some other organic waste to FIS was necessary for the survival of earthworms. So CD was added to FIS as an additional organic matter source [6]. In vermireactor no. 9 (20% CD + 80% FIS) most of the worms died in 5 days only three worms survived and they also died after 42 days. Hence results are not given for vermireactor no. 9.

The final vermicompost were pleasantly earthy in odour, granular, much darker in color and homogeneous than initial feed after 84 days of earthworms' activity. Physico-chemical characteristics of the initial feed mixtures and vermicompost have been encapsulated in Table 3. There were slight changes in the pH of vermicompost as compared to initial values (Table 3). The pH decreased from alkaline (6.5–7.9) to slightly acidic (5.8 ± 0.02–6.7 ± 0.01) in all the vermireactors. Whereas in controls, final pH was in the range of 6.2 ± 0.13–7.4 ± 0.06. The pH shift towards acidic conditions has been attributed to mineralization of the nitrogen and phosphorus into nitrites/nitrates and orthophosphates and bioconversion of the organic material into intermediate species of organic acids [17–19]. The electrical conductivity (EC) was increased in the different feed mixtures after vermicomposting. This increase in EC might have been due to loss of organic matter and release of different mineral salts, such as phosphate, ammonium, potassium etc [20,21]. EC was increased in controls also but to a lesser extent. Increase in ash content is an indication of stabilization and mineralization of composted material [22]. In our experiments ash content of vermicomposts was higher than the initial feed mixtures as well as controls. Maximum ash content was recorded in vermireactor no. 1 (526 g kg^{-1}) and minimum was reported in vermireactor no. 8 (446 g kg^{-1}) after vermicomposting. The ash content in final vermicompost decreased substantially as FIS concentrations increased in the vermireactors. The increase in ash content was 27.4–50.3% in final vermicompost as compared to initial feed mixtures. Final ash content in controls was in the range of 344–378 g kg^{-1}. Higher ash content may be due to the enhanced mineralization in the presence of earthworms [23].

Total organic carbon (TOC) decreased in all vermireactors, remarkably in those which contained lower concentrations of FIS. It may be due to the mineralization of organic matter [6]. As the FIS concentration increased in the feed mixtures, the TOC content decreased as compared to initial feed mixtures during vermicomposting process (Table 3). Minimum TOC was recorded in vermireactor no. 1 (275 g kg^{-1}) after vermicomposting. Where as final TOC in control was in the range of 395–360 g kg^{-1}. Inoculation

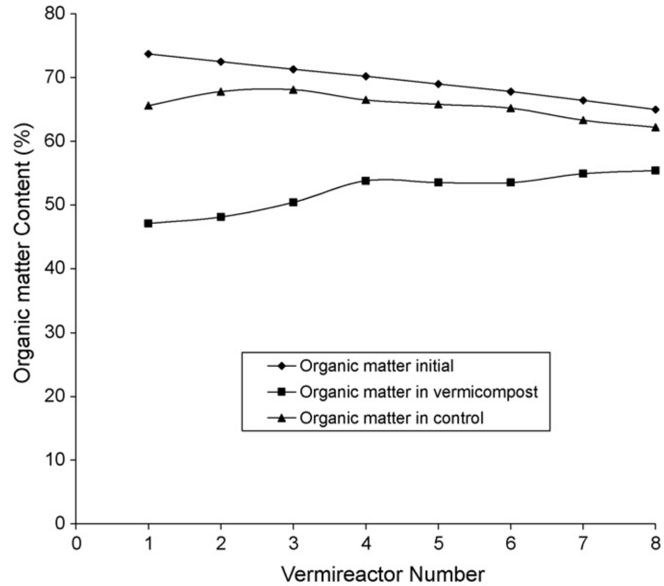

Fig. 1. Organic matter content of initial feed, control (without worms) and vermicompost in different vermireactors.

of earthworms in decomposing organic waste material promotes biochemical degradation, and their activity also promoted the colonization of decomposer communities of waste system, this is due to suitable biological and chemical environmental conditions [9]. Earthworms break and homogenize the ingested material through muscular action of their foregut and, also add mucus and enzymes in ingested material, this increase the surface area for microbial action. Thus combined action of earthworms and microorganisms bring TOC loss from the substrates in the form of CO_2 [24]. Earthworms and microorganisms use large portion of carbon as a energy source and nitrogen for building cell structure which causes decomposition of organic matter [25].

The final organic matter content (OM_f) of final product was lesser than initial organic matter content (OM_i). Maximum OM loss was noticed in vermireactor no. 1 (100% CD) and lowest in vermireactor no. 8 (30% CD + 70% FIS) (Fig. 1). Losses of OM were to the extent of 36.1, 33.7, 29.3, 23.4, 22.5, 21.1, 17.3 and 15.2% for vermireactor nos. 1–8, respectively. Loss in organic matter is directly related to earthworm activity and mineralization of organic matter. Biodegradability during composting is directly proportional to loss in organic matter during the process. Highest OM losses and highest values of biodegradability constants (K_b) were observed in vermireactor no. 1 (Fig. 2).

A significant increase in the TKN content was observed in all the vermireactors. The initial TKN content of the vermireactors was in the range of 8.50–9.56 g kg^{-1} (Fig. 3). Final TKN in vermicomposts was in the range of 15.2 ± 0.36–28.7 ± 0.17 g kg^{-1} in different

Table 3
Physico-chemical characteristics of vermicompost obtained from different CD + FIS feed mixtures (mean ± S.D., n = 3).

Vermireactor	pH	EC	TOC	TCa	TK	TP	TNa
1	6.7 ± 0.01d	1.6 ± 0.36a	275 ± 2.0a	3.10 ± 0.17ab	9.7 ± 0.26f	10.25 ± 0.02d	5.5 ± 0.10a
2	6.2 ± 0.04c	1.5 ± 0.17a	279 ± 3.0a	2.90 ± 0.06a	7.9 ± 0.01de	9.50 ± 0.02c	5.9 ± 0.26ab
3	6.5 ± 0.04d	1.6 ± 0.40a	292 ± 6.2b	3.35 ± 0.07b	8.0 ± 0.20e	9.28 ± 0.02c	5.8 ± 0.26a
4	6.1 ± 0.03bc	1.6 ± 0.43a	312 ± 4.3c	3.88 ± 0.07c	7.4 ± 0.26d	9.11 ± 0.34c	5.9 ± 0.30ab
5	6.1 ± 0.06bc	1.5 ± 0.26a	310 ± 4.6c	4.17 ± 0.10cd	6.5 ± 0.26c	9.07 ± 0.26c	6.0 ± 0.26ab
6	6.0 ± 0.02b	1.7 ± 0.26a	310 ± 3.5c	4.28 ± 0.07de	6.0 ± 0.46bc	8.04 ± 0.15b	6.4 ± 0.20b
7	6.0 ± 0.05b	1.6 ± 0.60a	318 ± 4.0c	4.91 ± 0.09f	5.4 ± 0.26ab	8.19 ± 0.03b	6.5 ± 0.17b
8	5.8 ± 0.02a	1.6 ± 0.36a	321 ± 5.2c	4.58 ± 0.10e	5.0 ± 0.46a	7.33 ± 0.02a	7.2 ± 0.26c

Mean value followed by different letters is statistically different (ANOVA; Tukey's test, $P < 0.05$); units of all the parameters except pH and EC are in g kg^{-1}. The EC values are in ds m^{-1}.

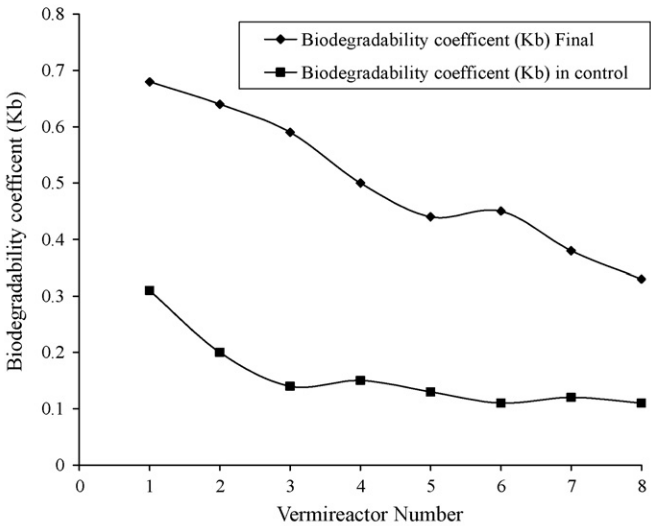

Fig. 2. Biodegradability coefficient (K_b) in different vermireactors.

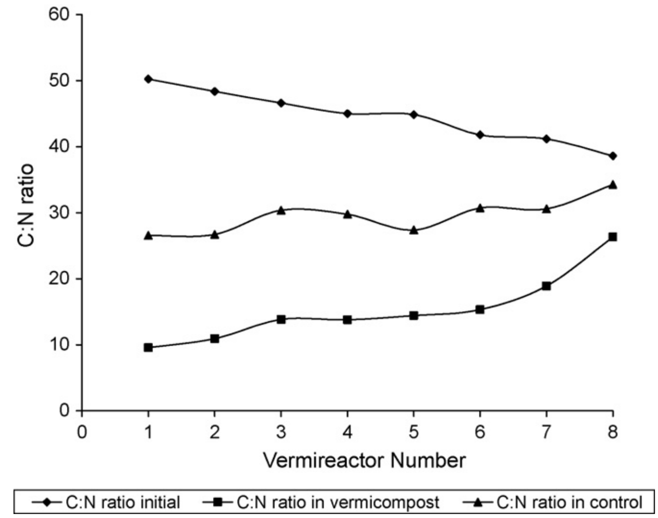

Fig. 4. C:N ratio of initial feed, control (without worms) and vermicompost in different vermireactors.

vermireactors after vermicomposting. On the other hand, final TKN content in controls was in the range of 10.5 ± 0.15–14.7 ± 0.21 g kg^{-1} which is significantly lesser than final TKN in vermicomposts. There was 1.25–3.37 fold increase in TKN at the end of vermicomposting period in different vermireactors. This confirms that the if FIS is mixed in appropriate quantities, (up to 40% on dry weight basis) with cow dung, would not have antagonistic impact on the final TKN content of the vermicompost. Similar observations have also reported by other workers [26,27]. Kaushik and Garg [7] have observed 2.0–3.2-fold increase in TKN in textile mill sludge vermicomposting. It is suggested that in addition to releasing N from compost material, earthworms also increase N level by adding their excretory products, mucus, body fluids, enzymes growth stimulating hormones etc to the substrate [28]. According to Viel et al. [29] losses in organic carbon due to substrate utilization by microbes and earthworms and their metabolic activities as well as water lose by evaporation during mineralization of organic matter might be responsible for nitrogen addition. Decreases in pH may be another important factor in nitrogen retention as nitrogen is lost as volatile ammonia at higher pH values. It has also been suggested that the final nitrogen content of vermicompost is dependent on the initial

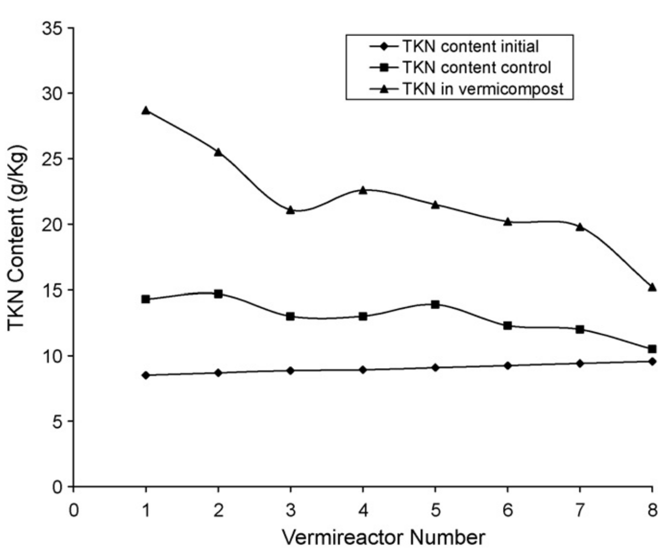

Fig. 3. TKN of initial feed, control (without worms) and vermicompost in different vermireactors.

nitrogen content present in the waste and the extent of decomposition [30].

The C:N ratio of a substrate material reflects the organic waste mineralization and stabilization during the process of vermicomposting. The loss of carbon as CO_2 through microbial respiration and simultaneously addition of nitrogen by worms in the form of mucus and nitrogenous excretory material lower the C:N ratio of the substrate [31]. It is evident from (Fig. 4) that C:N ratios decreased with time in all worm worked vermireactors and controls. Initial C:N ratio was in the range of 38.6–50.2 before the inoculation of earthworm in the feed mixture (at 0 day). Finial C:N ratios were in the range of 9.6–26.3 in vermicomposts. Final C:N ratio in controls was the range of 26.6–34.3. Decline of C:N ratio was 2.19–5.24 folds in final vermicomposts. The C:N ratio was higher in those feed mixtures which had higher percentage of FIS in final vermicompost. The relevance of the C:N ratio relies on the fact that a decrease in the ratio implies an increase in the degree of humification of organic matter. Decline of C:N ratio to less than 20 indicates an advanced degree of organic matter stabilization and reflects a satisfactory degree of maturity of organic wastes [32]. So, in the present study, a high degree of organic matter stabilization was achieved in all the vermireactors. This demonstrates the role of earthworms in much more rapid decomposition and rates of mineralization of organic matter.

Calcium (Ca) concentration in the final vermicompost was slightly higher then initial mixtures in all the vermireactors. The Ca increments were in the range of 22.7–33.8%. Maximum increment was observed in vermireactor no. 1 (3.10 g kg^{-1}) and minimum increment in vermireactor no. 8 (5.08 g kg^{-1}) (Table 3). Spiers et al. [33] have reported that earthworms convert calcium oxalate crystals in ingested fungal hyphae to calcium bicarbonate which then is egested in cast material, this increase calcium availability in the final vermicompost. The total potassium (TK) content was also higher in all the vermireactors then initial substrate and controls. Maximum TK content was recorded in vermireactor no. 1 (100% CD) and minimum in vermireactor no. 8 (30% CD + 70% FIS). The initial TK content in the feed mixture was in the range of 3.55–8.80 g kg^{-1}. But vermicomposts' TK content was in the range of 5.0 ± 0.46–9.7 ± 0.26 g kg^{-1} (Table 3). Suthar [34] has suggested that earthworm processed waste material contains higher concentration of exchangeable K due to enhanced microbial activity during the vermicomposting process, which consequently enhances the rate of mineralization. There are contradictive reports regarding the K content in vermicompost obtained from different feedstocks. Delgado et al. [35] have reported higher potassium content in sewage sludge compost where as Orozco et al. [36] have reported lower K content in coffee pulp waste after vermicomposting. These differences in the observation can be attributed differences in the chemical nature of the initial feed mixture.

There was about 1.5–2-fold increase in total phosphorus (TP) of the final vermicompost in all the vermireactors as compared with TP content in initial feed mixtures. The overall increase in the TP content was maximum in the vermireactor no. 1 ($10.25 \pm 0.02\,g\,kg^{-1}$), and minimum increase was in the vermireactor no. 8 ($7.33 \pm 0.02\,g\,kg^{-1}$) (Table 3). Satchell and Martin [37] found an increase of 25% in total P of paper-waste sludge, after worm activity. According to Lee [38], if the organic materials pass through the gut of earthworms then some of phosphorus being converted to such forms that are available to plants. Moreover, it was concluded that availability of P to plants is mediated by phosphatase produced within the earthworms and further release of P may be introduced by microorganisms in their casts, after their excretion. Ghosh et al. [39] have reported that vermicomposting efficiently transform unavailable forms of phosphorus to easily available forms for plants. Similarly, the C:P ratio was also significantly lesser in the after 84 days' worms activity. The initial C:P ratio was in range of 64.7–84.4 in different vermireactors at day zero. After 12 weeks C:P ratio was in range of 26.8–47.0 in final vermicomposts (Fig. 5). The final C:P ratio in controls was in the range of 57.6–64.8 which is much higher than vermicomposts. It is mainly due to lesser TOC loss in controls than vermireactors.

In small amounts, some of the heavy metals may be essential for plant growth, however, in higher concentrations they are likely to have detrimental effects upon plant growth [40]. So, prior to vermicompost application to the soils, there is a need to determine the heavy metal concentrations in the final vermicomposts. In the present study, initially Cu and Fe concentrations of FIS were lower than CD; while, Mn and Zn concentrations were higher in FIS than CD. A comparison of the results showed that Fe concentrations in the final vermicompost in the vermireactor nos. 1–8 were higher than in the initial feed mixtures. Where as, Cu, Zn and Mn concentration in final vermicomposts in relation to initial concentration did not follow any regular pattern and Cd concentration was below detection limit (Table 4). Our results are supported by Gupta and Garg [41] who reported an increase in heavy metals concentration in vermicompost of sewage sludge. The weight and volume reduction due to breakdown of organic matter during vermicomposting may be the reason of increase in heavy metal concentrations in vermicompost [42].

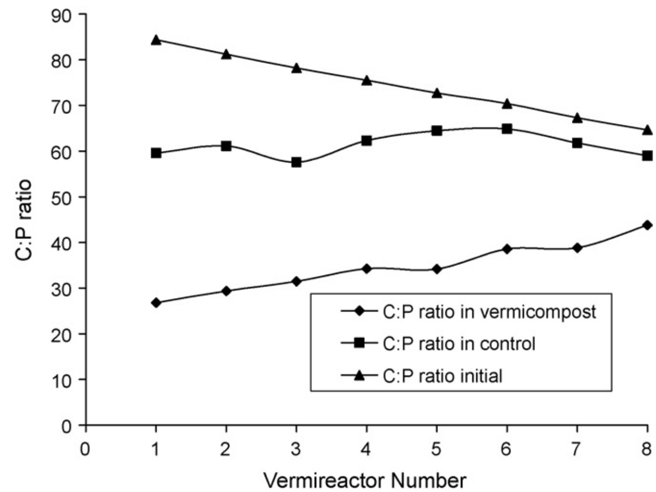

Fig. 5. C:P ratio of initial feed, control (without worms) and vermicompost in different vermireactor.

3.2. Growth and reproduction of *E. fetida* in different vermireactors

The biomass production by *E. fetida* in different vermireactors has been given in Table 5. In this study maximum worm biomass was observed in 100% CD ($836\,mg\,earthworm^{-1}$) and lowest in 30% CD + 70% FIS feed mixture ($280\,mg\,earthworm^{-1}$). Increasing percentage of FIS in the feed mixtures resulted in a decrease in biomass of *E. fetida*. The maximum worm biomass was

Table 4
Heavy metal content ($mg\,kg^{-1}$) in vermicompost obtained from CD + FIS vermireactors (mean ± S.D., $n = 3$).

Vermireactors	Total			
	Fe	Cu	Zn	Mn
1	1902 ± 48.49a	267 ± 29.46a	111.4 ± 3.41a	589.6 ± 38.35a
2	2087 ± 151.0a	247 ± 48.87a	111.5 ± 6.87a	651.5 ± 21.67a
3	2464 ± 102.5bc	244.3 ± 27.98a	114.7 ± 5.98a	759.1 ± 12.80b
4	2403 ± 50.26b	262.3 ± 37.58a	112.3 ± 7.69a	870.5 ± 27.30cd
5	2525 ± 56.78bc	280.3 ± 19.50a	112.3 ± 2.85a	838 ± 11.26c
6	2628 ± 86.62bc	247 ± 33.0a	112.3 ± 0.57a	933.4 ± 12.59d
7	2518 ± 77.01bc	231 ± 18.30a	114.2 ± 12.51a	1030 ± 26.45e
8	2671 ± 122.3c	226 ± 11.57a	116.6 ± 18.35a	1009.6 ± 20.66e

Mean value followed by different letters is statistically different (ANOVA; Tukey's test, $P < 0.05$).

Table 5
Biomass production by *Eisenia fetida* in different vermireactors (mean ± S.D., $n = 3$).

Vermireactor	Mean initial biomass $worm^{-1}$ (mg)	Final biomass $worm^{-1}$ (mg)	Net biomass gained $worm^{-1}$ (mg)	Maximum biomass achieved in (week)	Worm biomass gained per unit waste ($mg\,g^{-1}$)
1	150 ± 4.3b	836 ± 12.1f	686 ± 12.1e	6th	4.57 ± 0.63d
2	100 ± 1.7a	780 ± 32.7ef	680 ± 21.0e	6th	4.53 ± 0.53d
3	100 ± 2.0a	767 ± 16.6e	667 ± 12.0e	6th	4.44 ± 0.51d
4	100 ± 3.6a	750 ± 32.7e	650 ± 26.5e	6th	4.30 ± 0.65d
5	100 ± 4.5a	654 ± 15.0d	554 ± 16.0d	6th	3.70 ± 0.95cd
6	110 ± 4.5a	669 ± 16.5d	559 ± 16.8d	7th	3.73 ± 0.81cd
7	110 ± 1.0a	408 ± 15.8c	298 ± 12.5c	7th	1.98 ± 0.92bc
8	100 ± 5.2a	280 ± 17.3b	180 ± 10.5b	7th	1.20 ± 0.36ab
9	100 ± 2.0a	0 ± 0.0a	0 ± 0.0a	–	0 ± 0.0a

Mean value followed by different letters is statistically different (ANOVA; Tukey's test, $P < 0.05$).

Table 6
The industrial wastes used as substrate in vermicomposting.

S. no.	Industrial waste	Organic amendment	Earthworm species	Reference
1	Filter cake, trash, bagasse	Cow dung	*Eudrilus eugeniae*	[44]
2	Distillery sludge	Cow dung	*Perionyx excavatus*	[45]
3	Lignocellulosic waste from olive oil industry	Municipal biosolids	*Eisenia andrei*	[46]
4	Solid textile mill sludge	(a) Cow dung and (b) poultry droppings (c) Biogas plant slurry (d) Agricultural wastes	*E. fetida*	[19,47,48]
5	Guar gum industry waste		*P. excavatus*	[9]
6	Paper-pulp mill sludge	a) *Mangifera indica* and (b) cow dung, (c) Saw dust	(a) *E. eugeniae* (b) *E. fetida* (c) *Lampito mauritii*	[49]
7	Winery waste		*E. andrei*	[8]
8	Wood chips (from platinum ore extraction process)	Sewage sludge	*E. fetida*	[50]
9	Filter cake	Horse dung	*E. fetida*	[51]
10	Sewage sludge	Cow dung	*E. fetida*	[41]
11	Pig waste		*E. fetida*	[52]

attained in 6th week in the feed mixtures containing 10–40% FIS. While in vermireactor nos. 6–8 the maximum worm biomass was attained in 7th week. The net weight gain by *E. fetida* in 100% CD was higher than FIS containing feed mixtures. The growth rate (mg weight gained day^{-1} $earthworm^{-1}$) has been considered a good comparative index to compare the growth of earthworms in different feeds [10]. The fastest growth rate was observed in 100% CD (19.6 mg $worm^{-1}$ day^{-1}) where as 30% CD + 70% FIS feed mixture supported the least growth (3.7 mg $earthworm^{-1}$ day^{-1}) (Fig. 6). The net weight gain by *E. fetida* (wet weight) per unit food source (dry weight basis) was highest in 100% CD (4.6 mg g^{-1}) and minimum (1.2 mg g^{-1}) in 30% CD + 70% FIS feed mixture (Table 5). 100% mortality was observed in feed mixture no. 9 (20% CD + 80% FIS) during the study period after 42 days of experimentation. After the initial biomass gain, a stabilization and, later, weight loss by earthworms was observed in all the feed mixtures. The worm biomass loss can be attributed to the exhaustion of food. When *E. fetida* received food below a maintenance level, it lost weight at a rate which depended upon the quantity and nature of its ingestible substrates [43].

The cocoon production by *E. fetida* in different feed mixtures is given in Fig. 7. Cocoon production was started during 6–7th week in all vermireactors. After 12 weeks maximum cocoons (57) were counted in 100% CD and minimum (2) in 30% CD + 70% FIS feed mixture. Mean number of cocoon production was between 5.7 (in 100% CD) and 0.2 (in 30% CD + 70% FIS) cocoon per worm for different feed mixtures. Cocoons production fluctuated with time. Initially cocoon production rate was higher and with time the cocoons production was declined. The maximum number of hatchling was produced in vermireactor no. 4 and minimum in vermireactor no. 8 (Fig. 7). The difference between rates of cocoon production in different feed mixtures could be related to the biochemical quality of the feed mixtures, which is one of the important factors in determining onset of cocoon production [23]. The feeds which provides earthworms with sufficient amount of easily metabolisable organic matter and non-assimilated carbohydrates, favor the growth and reproduction of the earthworms [24]. The vermireactor no. 9 (20% CD + 80% FIS) was unable to support growth and reproductive success of *E. fetida*. It was inferred that the higher percentage of FIS in the feed mixture significantly affected cocoon production. Several other worm species have been used in different studies for the management of industrial wastes. The details of the industrial waste and worm species used are given in Table 6.

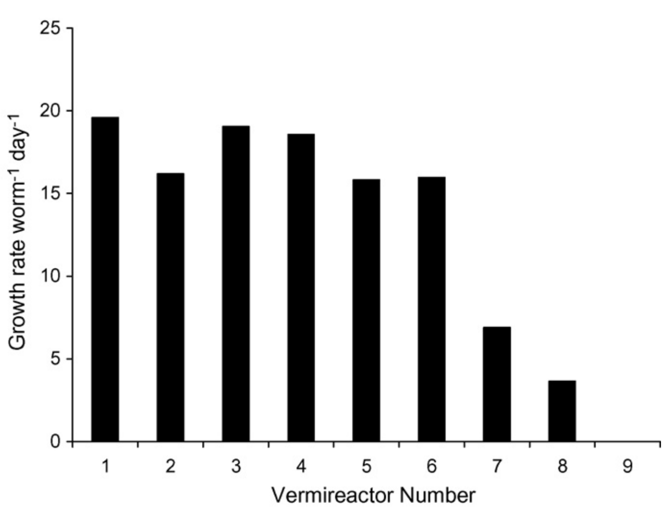

Fig. 6. Growth rate per worm per day (mg) in different vermireactors.

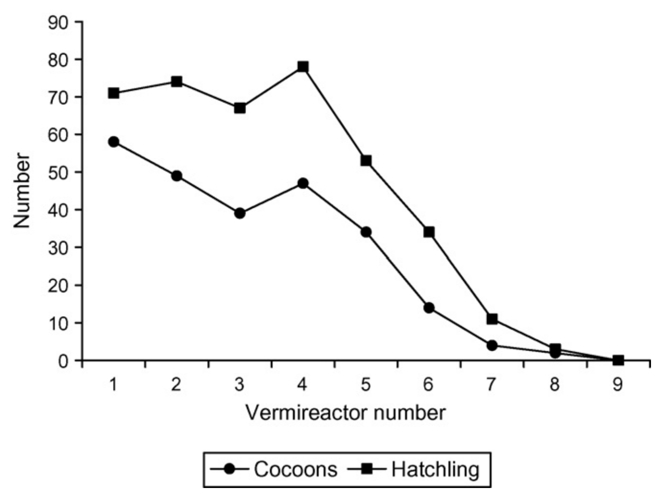

Fig. 7. Number of residual cocoons and hatchling during vermicomposting in different reactors.

4. Conclusion

The information presented in this paper provides a basis for the vermicomposting of food industry sludge spiked with cow dung. Disposal of food industry sludge by environmentally acceptable means is a serious problem. In the present study, a high degree of FIS stabilization was achieved after worm activity. The results indicate that after the addition of food industry sludge in appropriate quantities (30%) to the cow dung, it can be used as a raw material in the vermicomposting. For the processing of FIS, it is necessary to process other waste materials such as CD. The vermicompost showed higher NPK content. The end product had relatively lower C:N and C:P ratios. The growth rate and cocoon production by the earthworms was having an inverse relationship with the percentage of FIS in the feed mixture. The net weight gain by the earthworms was significantly lower in feed mixtures having higher FIS content. Our results established that if FIS is mixed 30% with CD then vermicomposting can be an alternate technology for FIS management.

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