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Vermiremediation and nutrient recovery of non-recyclable paper waste employing *Eisenia fetida*

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ABSTRACT

With the industrial growth, changing life style and consumeristic attitude paper consumption has increased significantly in yesteryears. The authors have observed that waste paper obtained from consumable items and used paper products are disposed in open by the consumers as these are not accepted by the salvaging industry. In the present study, an attempt has been made to vermicompost non-recyclable post-consumer paper waste (PW) amended with cow dung (CD) employing *Eisenia fetida* earthworm in order to transform it into a value added product, i.e., vermicompost. Vermicomposting of paper waste resulted in net reduction in ash content and total organic carbon (42.5–56.8%) but increment in total Kjeldhal nitrogen (2.0–2.4-fold), total potassium (2.0-fold), and total phosphorous (1.4–1.8-fold) was achieved after 91 days of worms' activity. The C:N ratio decreased with time in all the worm-worked vermireactors in the range of 71.9–82.0%, depicting advanced degree of organic matter stabilization. The FT-IR spectroscopy of the vermicomposts showed reduction in aliphatic compounds during the vermicomposting process. The results also demonstrated the worm growth and reproduction are not significantly affected if PW content is upto 30% in the vermireactor.

1. Introduction

There has been a rapid industrialization and urbanization in India in the last few decades, which has led to improvement in the living standards and change in the production and consumption patterns. Consequently, the nature and volume of the solid waste has changed considerably. According to CPCB [1], the annual solid waste generation in Indian cities has increased from 6 million tonnes in 1947 to 48 millions tonnes in 1997 with an annual growth rate of 4.25% and it is expected to increase to 300 million tonnes by 2047. The National solid waste legislation {Municipal Solid Waste (Management and Handling) Rules, 2000}endorses the responsibility of the municipal authorities to provide appropriate sites for disposal and sustainable treatment of solid waste in a city. But, in most of the Indian cities, municipal authorities lack appropriate strategies, infrastructure and financial resources for organized and sustainable solid waste management [2]. As a result, more than 90% of solid waste is directly disposed off on land in an indiscriminate manner, mainly in open dumps and poorly managed landfills in the low-lying areas outside the cities, posing significant hazards to the environment [3].

According to Indian Paper Manufacturers Association, with rapid urbanization, increasing literacy, changing life style, consumeristic attitude and industrial growth, paper consumption in India is set to double from the current seven million tonnes per annum in the next eight years. Presently, the paper consumption is about 6.5 kg per capita, and is projected to grow to 8.5 kg per capita by 2010. The use of wrapping paper for consumable items and disposable paper molded products has increased significantly in yesteryears. There is well established market for the recycling of waste paper products such as old newspapers, magazines, books, etc. But, due to the poor collection and segregation practices, the waste paper recovery rate is only 19% of the total paper consumption in India [4]. Moreover, the authors have observed that waste paper obtained from consumable items and used paper products are disposed in open by the consumers as these are not accepted by the junk-dealers for recycling. A study conducted by Tata Energy Research Institute, India showed that about 6–10% of the household waste consists of paper, which due to absence of proper waste segregation practices, goes to the waste bins. As a result, a sizeable portion of the used and soiled paper is dumped along with other kind of the solid waste and ultimately, finds its way to the landfill sites. The situation of solid waste disposal and management in other developing countries is no different and may perhaps exist elsewhere too. The solid waste, if remains unattended in the landfills, undergo anaerobic decomposition,

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eventually releasing a significant amount of methane into atmosphere. According to an estimate, landfills contribute about 3–19% emissions of the total anthropogenic methane emission globally. In this view, there is a pressing need of such innovative technologies which have the potential to minimize the organic burden on the landfills as well as to reduce the wide environmental impacts of improper solid waste management. From environmental and economical point of view, vermicomposting technology can prove as an efficient and sustainable method to dispose the organic solid waste.

The non-recyclable paper waste can be a good feed for earthworms in the vermicomposting process due to its non-toxic and biodegradable nature. The transformation of non-recyclable paper waste 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 economic development. During vermicomposting, earthworms ingest, grind and digest organic waste with the help of aerobic and anaerobic microflora in their gut, leading to rapid mineralization and humification process, converting the unstable organic matter into a relatively stable and microbially active material [5]. The generated product, vermicompost, resembles native soil humic substances [6,7] and is a valuable, marketable plant growth medium [8]. Different wastes including primary sewage sludge [9]; dairy processing plant sludge [10]; sugar industry waste [11,12]; textile mill sludge [13,14]; pig waste [15,16]; water hyacinth [17,18]; crop residue [19,20]; livestock excreta [21], etc., have been tested for their suitability in vermicomposting process. Recently, the performance of four species of earthworms––*Eudrilus eugeniae*, *Drawida willsi*, *Lampito mauritii* and *Perionyx excavatus* was studied in cowdung-spiked paper waste in terms of vermicast output per unit feed and production of offsprings, but, the vermicompost quality was not assessed at the end of vermicomposting period [22]. The aim of present work is to assess the feasibility of using non-recyclable paper waste in vermicomposting employing the composting worm, *Eisenia fetida*. It was hypothesized that different percentages of paper waste in feed mixtures would affect the vermicompost quality and growth and reproduction of *E. fetida*.

2. Materials and methods

2.1. Materials

The non-recyclable post-consumer paper waste (PW) was salvaged from municipal solid waste stream of Gurgaon city, India. It contained office paper trimmings, food-soiled paper, napkins, brown paper, cardboards, torn-off corrugated boxes, paperboard packaging material and other paper scraps. The paper waste was shredded and mixed with cow dung. Fresh cow dung (CD) was procured from an intensively live stocked farm at Hisar, India. The physico-chemical characteristics of PW and CD are given in Table 1. *E. fetida* hatchlings and clitellated adults were randomly picked for use in the experiments from several stock cultures containing 500–2000 earthworms in each, maintained in the laboratory by authors with CD as culturing material.

2.2. Vermicomposting experiments

In the present study, two different experiments were conducted. The first experiment was to determine the effect of PW on the fertilizer value of vermicompost. To accomplish this, seven bench-scale vermireactors (vol. 10 L, diameter 40 cm, depth 12 cm) were filled with one kg of feed mixture, containing PW mixed with CD in different ratios (Table 2). A control vermireactor having CD only as feed mixture was also set. All the PW and CD quantities were used on dry weight basis. These mixtures were turned manually every day for 21 days in order to eliminate volatile gases potentially toxic to earthworms. After 21 days, 20 adult individuals of *E. fetida* (weighing between 400 and 600 mg each) were introduced into each vermireactor. The moisture content was maintained at 70 ± 10% of water holding capacity by periodic sprinkling of an adequate quantity of distilled water throughout the vermicomposting period. All the containers were kept in the dark under identical ambient conditions (room temperature 25 ± 3 °C, relative humidity 60–80%). The experiments were conducted in triplicate. Homogenized samples (free from earthworms, hatchlings and cocoons) of the feed material were drawn at 0, 21, 42, 63, 77 and 91 days from each vermireactor. The zero day refers to the time of initial mixing of the PW and CD before preliminary decomposition. Prior to chemical analysis, the samples were air dried in the shade at room temperature, ground in a stainless steel blender and stored in plastic vials.

Table 1
Initial physico-chemical characteristics of CD and PW

Serial number	Parameter	CD	PW
1.	pH	8.2	7.6
2.	EC (dS m^{-1})	1.60	0.5
3.	Ash content (g/kg)	245	120
4.	TOC (g/kg)	430.2	510.4
5.	TKN (g/kg)	6.8	2.02
6.	TK (g/kg)	6.7	3.7
7.	TP (g/kg)	7.5	4.6
8.	C:N ratio	63.3	253.2

The second experiment was undertaken to study the growth and fecundity of *E. fetida* at different PW concentrations in the feed mixture. In this, seven circular plastic containers (diameter 14 cm, depth 12 cm) were filled with CD and PW feed mixtures having percentage composition similar to first experiment, but the total feed quantity was reduced to 250 g in each vermireactor. After 21 days, 10 non-clitellated hatchlings of *E. fetida*, each weighing 50–150 mg were introduced in each vermireactor. All other experimental conditions were similar to first experiment. To determine the worm growth response, worm biomass as a function of time was monitored at weekly intervals. The feed in each vermireactor was turned out, and earthworms and cocoons were separated from the feed by hand sorting. After this, they were counted and weighed after washing with water and drying them by paper towels. The worms were weighed without purging 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. No additional feed was added at any stage during the study period.

Table 2
The composition of CD and PW in different vermireactors

Vermireactor number	CD (g)	PW (g)
1	1000 (100)[a]	0 (0)
2	900 (90)	100 (10)
3	800 (80)	200 (20)
4	700 (70)	300 (30)
5	600 (60)	400 (40)
6	500 (50)	500 (50)
7	400 (40)	600 (60)

[a] Figure in parentheses indicate the percentage of the waste material in the feed mixture.

2.3. Physico-chemical quality analysis and Fourier-transform infrared spectroscopy

All the chemicals used were analytically reagent (AR) grade supplied by S.D. Fine Chemicals, Mumbai, India. Alkali resistant borosilicate glass apparatus and double glass distilled water was used throughout the study for analytical work. The samples were used on dry weight basis for chemical analysis. All the samples were analyzed in triplicate and results were averaged. The results were reproducible with in 3–7% 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 [23]. Total Kjeldhal nitrogen (TKN) was determined after digesting the sample with concentrated H_2SO_4 and concentrated $HClO_4$ (9:1, v/v) by Bremner and Mulvaney procedure [24]. Total phosphorus (TP) was analyzed using the colorimetric method with molybdenum in sulphuric acid. Total potassium (TK) was determined after digesting the sample in diacid mixture (concentrated HNO_3:concentrated $HClO_4$, 4:1, v/v), by flame photometer [Elico, CL 22 D, Hyderabad, India].

The Fourier-transform infrared (FT-IR) spectra of vermicompost were carried out on a Shimadzu, FT-IR-8400S spectrometer. Vermicompost was oven dried and finely ground prior to analysis. Five mg sample were mixed with 400 mg KBr, homogenized in an agate mortar and pressed into a pellet. Infrared spectra were recorded in mid infrared area (wave number ranged 4000–400 cm^{-1}).

2.4. Statistical analysis

One-way ANOVA was used to analyze the significant difference between different reactors for observed parameters. Tukey's *t*-test also performed to identify the homogeneous type of the reactors for their different chemical properties and earthworm growth parameters, i.e., individual weight, earthworm weight gain, individual growth rate, cocoon production, etc. The probability levels used for statistical significance were $P < 0.05$ for the tests.

3. Results and discussion

3.1. Vermicompost quality obtained from PW mixed with CD

In vermicomposting process, earthworms mineralize the organic matter, converting a part of it in worm biomass and respiratory products, and, the rest is egested as nutrient rich vermicompost. The appropriate feed composition for the earthworms could optimize the manurial value of the vermicompost. To establish this, physico-chemical analysis of the initial feed mixtures (after mixing different compositions of CD and PW) and vermicompost was performed and the results have been encapsulated in Table 3. The vermicompost obtained after 91 days of earthworm's activity was much fine, odor-free, dark in color and homogeneous. The pH and EC values are the most frequent parameters used to characterize the vermicompost quality. Hogg et al. [25] have suggested the pH range 6.0–8.5 for vermicompost application to the soils to ensure compatibility with most plants. As evident from Table 3, there were slight changes in the pH of vermicompost as compared to initial values in all the vemireactors. The pH was in the range of 7.7 ± 0.1–8.0 ± 0.1 in final vermicompost. The pH shift has been reported due to mineralization of the nitrogen and phosphorus into nitrites/nitrates and orthophosphates; bioconversion of the organic material into intermediate species of organic acids [26]. Moreover, Gupta and Garg [9] pointed out that the shift in pH during vermicomposting is substrate-specific, as different substrates could result in the production of different intermediate species. The EC values were in the range of 0.94–1.60 dS m^{-1} in the initial feed mixtures. It was increased significantly in final vermicompost and was in the range of 1.17 ± 0.07–1.84 ± 0.06 dS m^{-1} (Table 3). The EC values in vermireactor no. 2 (10% PW + 90% CD) and 3 (20% PW + 80% CD) were not significantly different from the EC values in control (100% CD) ($P < 0.05$). The increase in EC is due to loss of organic matter and release of different mineral salts in available forms such as phosphate, ammonium, potassium, etc. [27]. With respect to the vermicompost application to the land, Lasaridi et al. [28] suggested that the maximum tolerance limit of plants for EC is 4.0 dS m^{-1}. Our results corroborates with these findings, depicting the suitability of paper waste vermicompost to the plants for pH and EC values. Ash content of vermicompost from all the vermireactors was significantly higher than the initial feed mixtures (Table 3). The increase in ash content was maximum in vermireactor no. 1 (100% CD; control), thereafter, it reduced significantly with the increasing composition of PW in the vermireactors. The results are in consistent with previous studies [9,18] which reported that increase in ash content may be due to enhanced mineralization in the presence of earthworms. As compared to the initial feed mixtures, total organic carbon (TOC) of the final vermicompost was remarkably reduced at the end of the experiment (Fig. 1a). Data revealed that TOC loss was highest in control, i.e., vermireactor no. 1 (100% CD; 185.6 ± 18.7 g kg^{-1}). The TOC reduction was inversely related to the PW content in the vermireactors, i.e., the reduction was maximum for vermireactor no. 1 (56.8%) and minimum for vermireactor no. 7 (42.5%). The decrease in TOC after vermicomposting indicates net organic matter stabilization in the substrate due to combined action of earthworms and microorganisms. It has been reported that earthworms modify the substrate conditions, which subsequently enhance the carbon losses from the substrates through microbial respiration in the form of CO_2 [10]. These results were supported by Tripathi and Bhardwaj [29] who observed a significant decline in organic carbon in worm inoculated mixed bedding material at the end of vermicomposting period. Similarly, Aira et al. [30] investigated the rate of carbon loss almost twice in the presence of earthworms in pig manure, revealing faster decomposition of organic matter.

The TKN content in all vermireactors was significantly enhanced at the end of vermicomposting period (Fig. 1b). The initial TKN content of the feed mixtures was in the range of 3.9–6.8 g kg^{-1} and in the final vermicompost, it increased to 7.72 ± 0.14–16.43 ± 0.45 g kg^{-1} in different vermireactors, depicting 2.0–2.4-fold increment in the final values. It is suggested that the final TKN content in vermicompost is dependent on the initial nitrogen present in the feed material and the degree of decomposition [31]. In our experiment, the increase in TKN content was significant in control, i.e., 100% CD, but the difference in the TKN content of the vermicomposts obtained from vermireactors 2–6 was not significant ($P < 0.05$). This shows that the percentage of PW up to 50% addition in the initial feed mixture have no impact on the final TKN content of the vermicompost. During the process of vermicomposting, the earthworms enhanced the nitrogen mineralization in the substrate, so that the mineral nitrogen is retained in the nitrate form [32]. Plaza et al. [33] during vermicomposting of cattle manure and olive pomace, demonstrated that the nitrogen increased significantly due to mineralization of C-rich materials and, possibly, to the action of N-fixing bacteria. Simultaneously, it has been reported that the earthworms add nitrogen in the form of mucus, nitrogenous excretory substances, growth stimulating hormones and enzymes during the fragmentation and digestion of organic matter, thereby, enhancing the final nitrogen levels in the vermicompost [29].

Table 3
Physico-chemical characteristics of initial feeds and vermicompost obtained from different CD + PW vermireactors

Vermireactor number	pH	EC (dS m^{-1})	Ash content[a]
Initial physico-chemical characteristics of initial feed mixtures			
1.	8.2	1.60	245.0
2.	8.1	1.49	232.5
3.	8.1	1.38	220.0
4.	8.0	1.27	207.5
5.	8.0	1.16	195.0
6.	7.9	1.05	182.5
7.	7.8	0.94	170.0
Physico-chemical characteristics of final vermicompost obtained from different vermireactors (mean + S.E., n = 3)[b]			
1.	8.0 ± 0.1a	1.84 ± 0.06bc	680 ± 18.4c
2.	7.9 ± 0.2a	1.52 ± 0.07ab	640 ± 10.5c
3.	8.0 ± 0.1a	1.54 ± 0.07ab	620 ± 7.5b
4.	7.9 ± 0.1a	1.32 ± 0.06a	612 ± 9.2b
5.	7.8 ± 0.2a	1.28 ± 0.08a	586 ± 6.7ab
6.	7.7 ± 0.1a	1.22 ± 0.06a	540 ± 10.4a
7.	7.7 ± 0.1a	1.17 ± 0.07a	526 ± 4.2a

[a] The unit of ash content is in g/kg.

[b] Mean value followed by different letters (a–c) is statistically different (ANOVA; Tukey's test, $P < 0.05$).

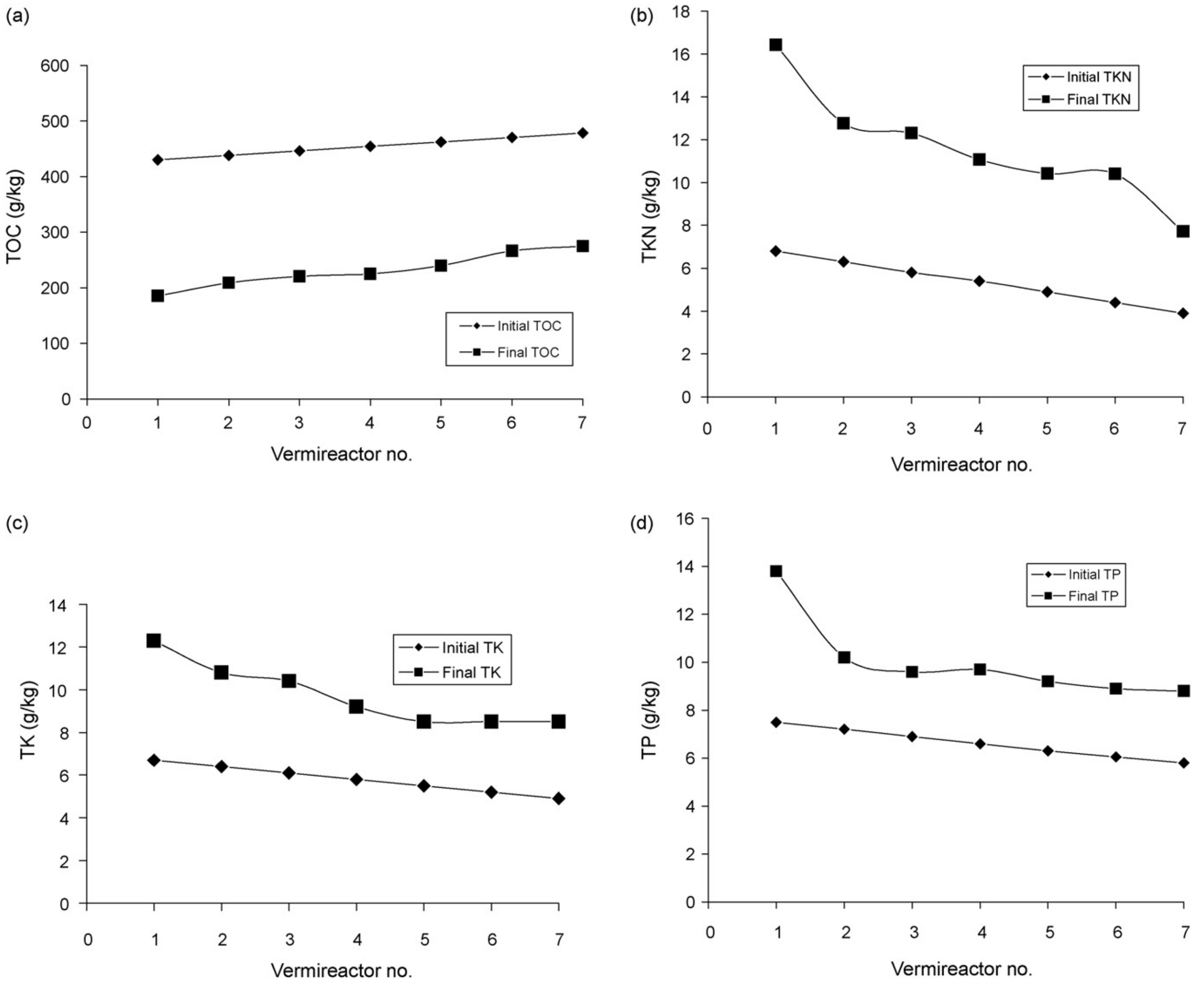

Fig. 1. (a) Comparison of TOC change in different vermireactors. (b) Comparison of TKN change in different vermireactors. (c) Comparison of TK change in different vermireactors. (d) Comparison of TP change in different vermireactors.

The initial TK content in the feed mixture was in the range of 4.9–6.74 g kg^{-1} (Fig. 1c). Final TK content in all the vermireactors was about 2-fold higher than initials and was in the range of 8.5 ± 0.18–12.28 ± 0.83 g kg^{-1} (Fig. 1c). When organic matter passes through the gut of earthworms, various plant nutrients are transformed from unavailable forms to more soluble and available forms to the plants, hence, increasing the concentration in vermicomposts. Data revealed that the TK content in the final vermicompost for vermireactor no. 1–3 was not significantly different from each other ($P < 0.05$), inferring that upto addition of 20% PW did not affected the TK content in vermicompost as compared to control. Similar results on potassium increment have been reported by other workers also [34,35].

The worm-worked vermireactors after 91 days exhibited about 1.4–1.8-fold increase in total phosphorus (TP) in the final vermicompost compared with TP content in initial feed mixtures. The initial TP content of the feed mixtures was in the range of 5.8–7.5 g kg^{-1}, while, final TP in vermicompost was in the range of 8.8 ± 0.23–13.8 ± 0.42 g kg^{-1} (Fig. 1d). The increase in TP ranged between 2.68 and 6.3 g kg^{-1} in different worms worked vermireactors. Lee [36] reported that the release of phosphorous in available form is partly by earthworm gut phosphatases and further release of P may be by P-solubilizing microorganisms in casts. Le Bayon and Binet [37] have stated that earthworms mediate the phosphatase enhancement in the soils, produced in worm gut and excreted through cast deposition.

3.2. C:N ratio-index of vermicompost maturity

The drift in C:N ratio as a function of time is an important index widely used for the assessment of efficiency of the vermicomposting process and vermicompost maturity. According to Senesi [38], a decline in 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. Initial C:N ratio was in the range of 63.3–122.6 at zero day in different vermireactors (Fig. 2). The initial C:N ratio was more in those feed mixtures which had higher percentage of PW. This was attributed to the fact that the initial C:N ratio of raw paper waste was high (253.2), owing to the high TOC content (510.4 g/kg) (Table 1). As evident from Fig. 2, the C:N ratio decreased with time in all the worm-worked vermireactors. Final C:N ratios of vermicompost were in the range of 11.3–35.6, depicting the overall decrease of 71.9–82.0% after 91 days of worms' activity from the initial values at 0 day. However, C:N ratio in vermireactor nos. 5, 6 and 7 was still higher at the end of the vermicomposting period. This clearly indicates that the earthworm's waste conversion efficiency is highly related to the organic carbon and nitrogen content in the initial feed mixtures. Moreover, the decline in C:N ratio was observed faster up to 63 days, thereafter, it showed a more or less stabilized pattern upto 91 days at the end of the vemicomposting period. This may be owed to the faster decomposition rates during early phase of vermicomposting due to availability of the feed for the earthworms. Our findings corroborate with the reports of other researchers [19,21,39–41]. The drift in C:N ratio reflects TOC decrease due to loss of carbon as CO$_2$ through microbial respiration and a higher proportion of total nitrogen content in the final vermicompost added by the combined action of earthworms and microflora. Also, it was found that there was a rapid decrease in C:N ratios after inoculation of earthworms (i.e., at 42nd day) as compared to the values of C:N ratios during the period of without earthworms (at 21st day). This concluded the role of earthworms in much more rapid decomposition and rates of mineralization of organic matter.

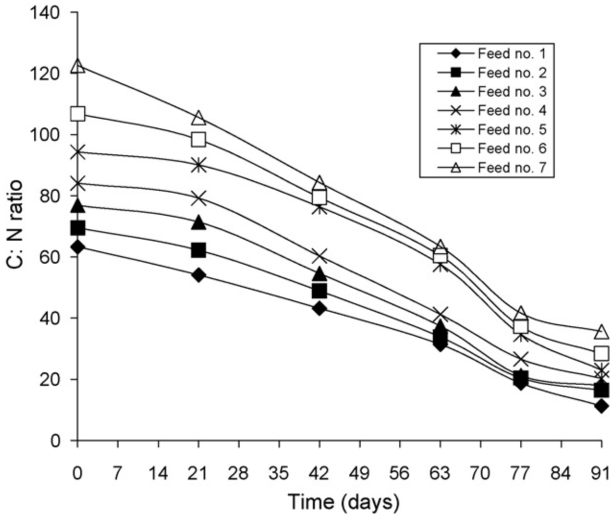

Fig. 2. Comparison of C:N ratio in different feed mixtures.

3.3. Evaluation of vermicomposting process by FT-IR spectroscopy

The FT-IR spectroscopy provides information about the chemical structure of the material. Analysis of the composting process by Fourier-transform infrared spectroscopy is considered a reliable technique for compost maturity determination in addition to C:N ratio [42]. Several indicator bands in the spectra that are referred to functional groups represent the components or metabolite products, the presence or absence of which indicate the degradation or stabilization process. The FT-IR spectra of raw cow dung, vermicomposts obtained from 100% CD, 10% PW + 90% CD; 20% PW + 80% CD and 30% PW + 70% CD vermireactors are given in Figs. 3–7, respectively. The spectra are interpreted based on Hsu and Lo [42]; Wang et al. [43] and Sen and Chandra [11]. The common series of bands observed were: a very broad band at around 3100–3600 cm^{-1} (hydrogen bonded O—H stretch), two distinct peaks at 2783 and 2879 cm^{-1} (aliphatic C–H asymmetric stretching), a prominent peak at 2349 cm^{-1} attributed to C≡N stretch, small peaks at 1600–1720 cm^{-1} (C═O stretch of esters, amides and aldehydes), a peak at 1558 cm^{-1} (skeleton vibration of aromatic rings relative to lignin and lignocellulose), a peak at 1460–1420 cm^{-1} (C—H deformation of CH$_2$ or CH$_3$ groups, COOH); a distinct peak at 1260–1240 cm^{-1} (C—O and C—N vibration of carboxylic acids and amides) and a peak at around 1045 cm^{-1} (C—O stretch of polysaccharides).

Distinct changes in the spectra resulting from the vermicomposting process are reduction in band height at 3100–3600 cm^{-1} region in Fig. 4 (100% CD) and 5 (10% PW + 90% CD) as compared to Fig. 3 (raw cow dung). The decomposition of carbohydrates as a result of decrease of atomic groups and structure of OH and CH$_2$ may be responsible for this reduction [43]. A comparison of the spectra of vermicomposts showed that there is gradual decrease in the peak intensities in the aliphatic region at 2783 and 2879 cm^{-1} in the vermicomposts as compared to raw substrate. Smidt and Meissl [44] showed that the reduction in the methylene bands at ~2783 and 2879 cm^{-1} was due to decrease in CH$_2$ and CH$_3$ groups, suggesting the decomposition of aliphatic compounds. Furthermore, C—O and C—N vibration of carboxylic acids and amides (1260–1240 cm^{-1}) reduced to weak shoulders in vermicomposts. The peak at around 1045 cm^{-1}

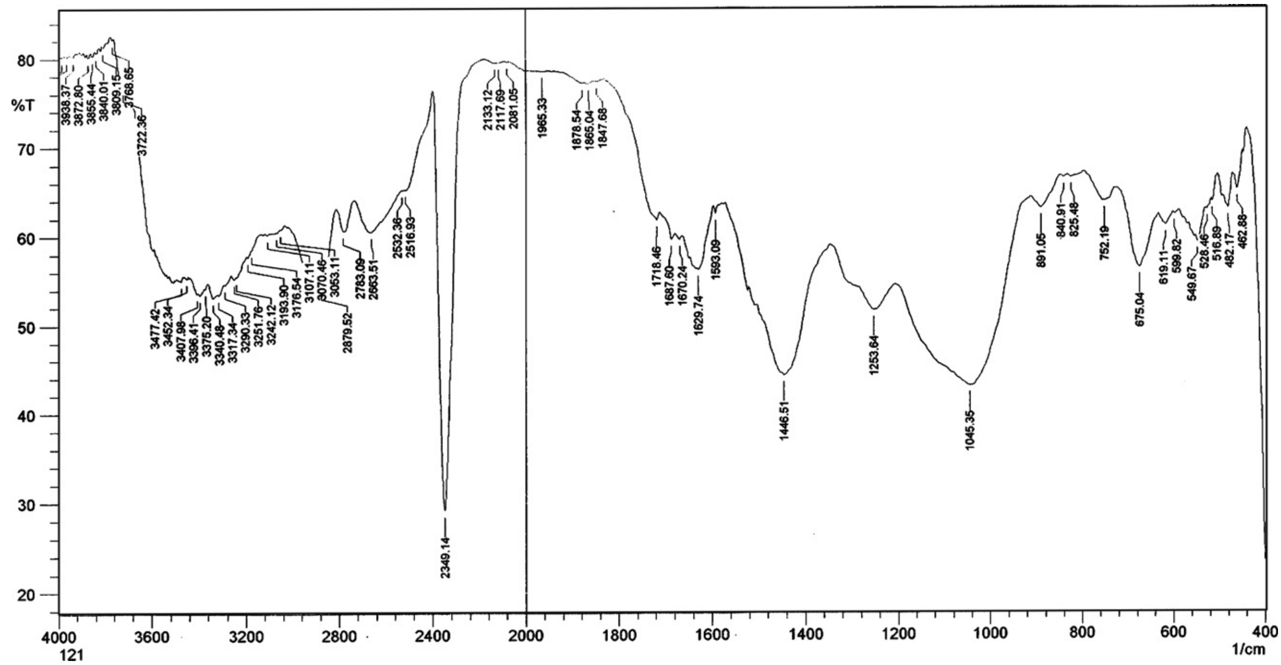

Fig. 3. FT-IR spectra of raw cow dung.

due to C—O stretch of polysaccharides decreased in due course of vermicomposting process. Sen and Chandra [11] attributed this decrease to progressive transformation of the polysaccharides in other oxygenated compounds, particularly carboxylic and ester group. Thus, during the vermicomposting of paper waste mixed with cow dung, the relative decrease in OH, CH_3 and CH_2 groups and the appearance of COO groups in the form of carboxylic salts indicate the reduction in aliphatic compounds and organic matter decomposition during the vermicomposting process.

3.4. Growth analysis and cocoon production of *E. fetida* (second experiment)

In the present study, the increase in biomass showed variation with different proportions of paper waste in the vermireactors. The biomass production by *E. fetida* in different vermireactors at the offset of second experiment has been given in Table 4. The highest worm biomass was observed in vermireactor no. 1 (100% CD; 878.5 ± 16.25 mg earthworm^{-1}) and the lowest in the 60% PW + 40% CD feed mixture (595.4 ± 13.06 mg worm^{-1}). The biomass

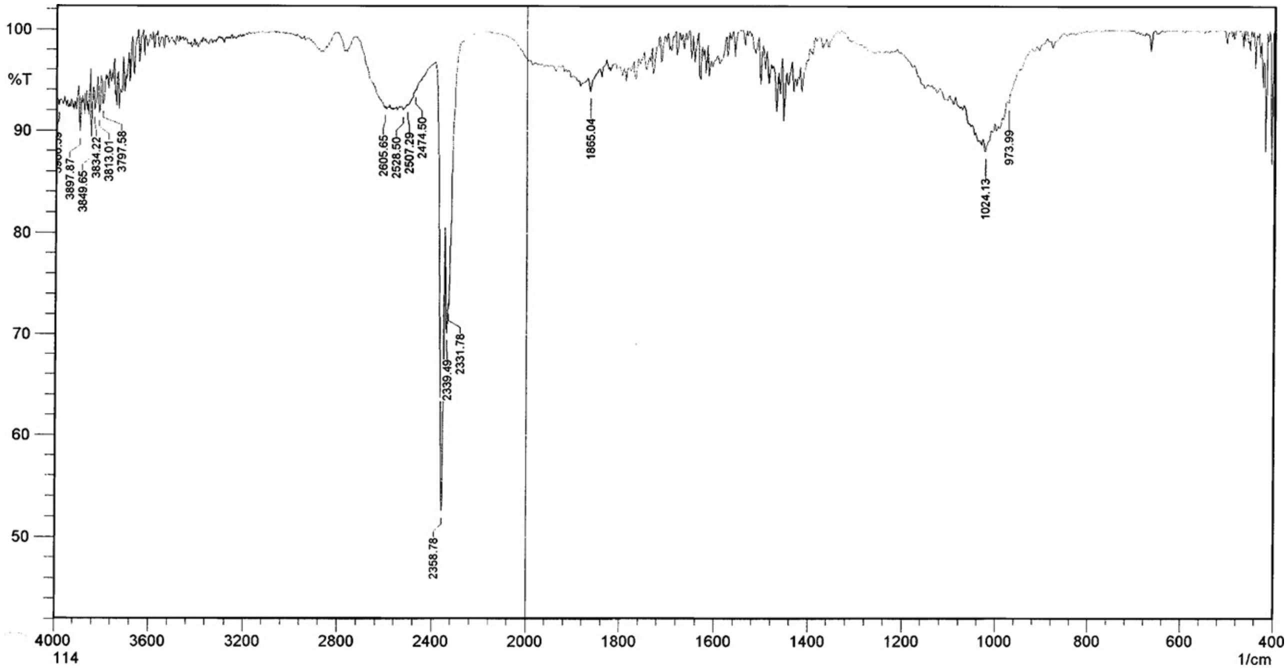

Fig. 4. FT-IR spectra of vermicompost obtained from cow dung.

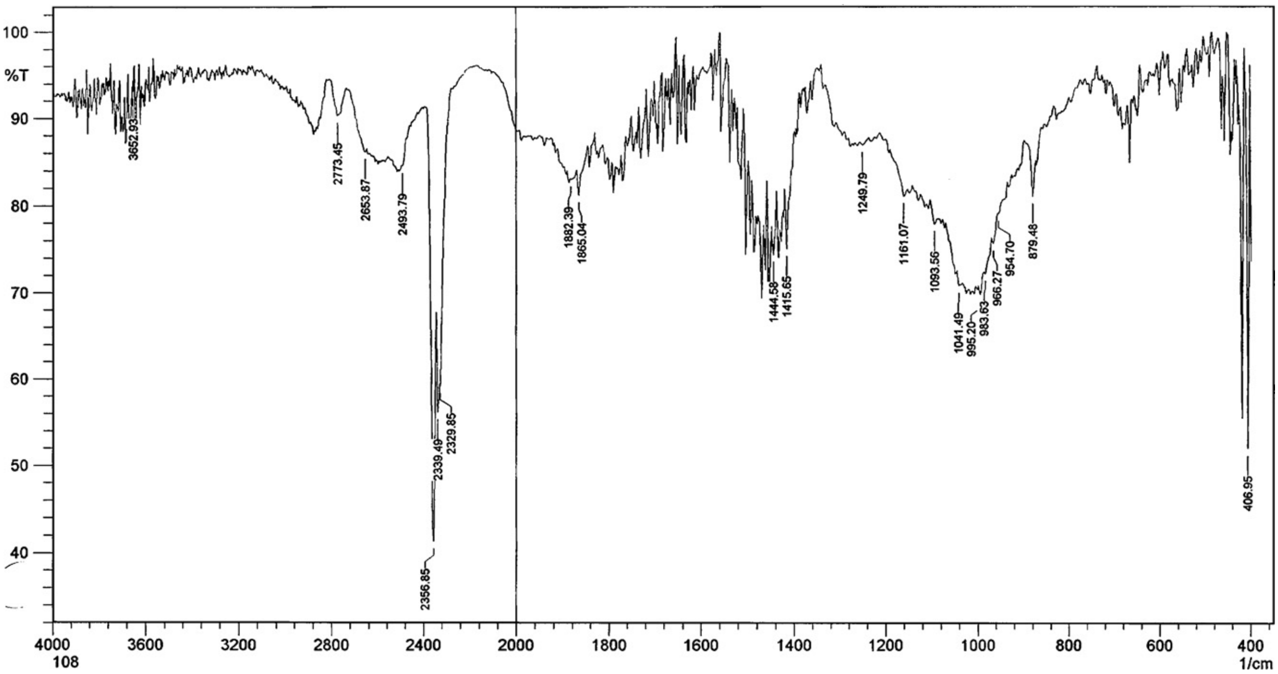

Fig. 5. FT-IR spectra of vermicompost obtained from 90% cow dung + 10% paper waste.

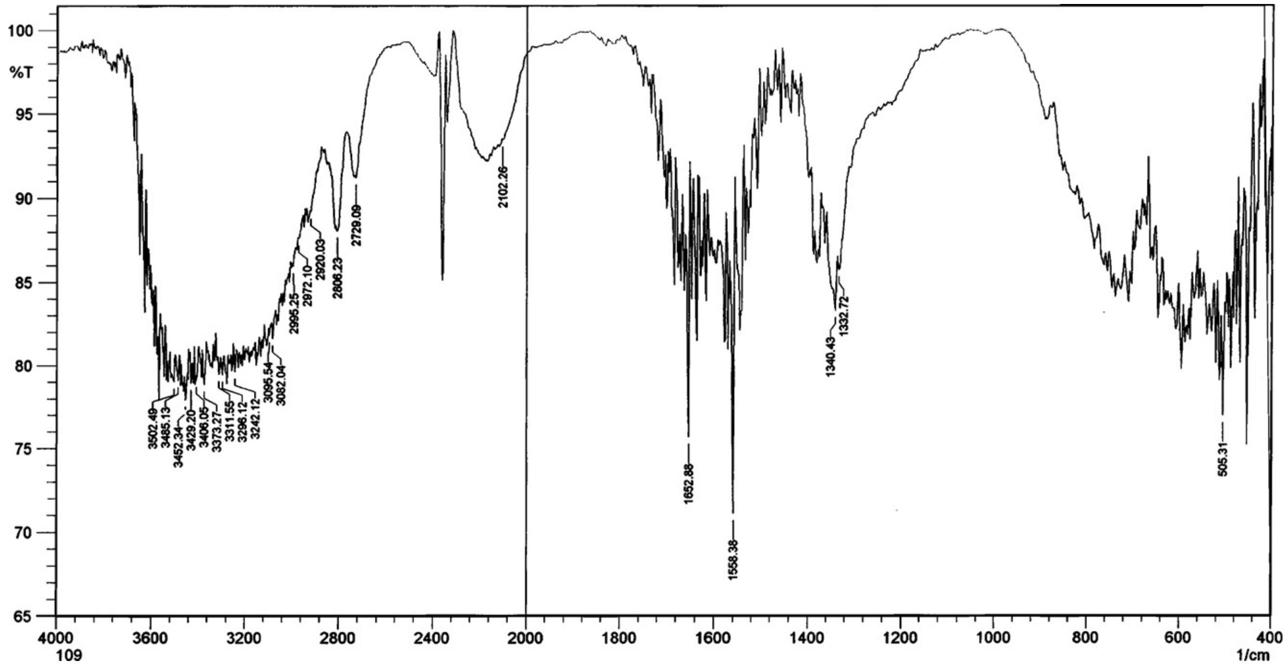

Fig. 6. FT-IR spectra of vermicompost obtained from 80% cow dung + 20% paper waste.

Table 4
Biomass production by *Eisenia fetida* in different vermireactors (mean ± S.E., $n = 3$)

Vermi-reactor number	Mean initial biomass worm^{-1} (mg)	Maximum biomass worm^{-1} (mg)	Maximum biomass achieved in (week)	Net biomass gained worm^{-1} (mg)	Growth rate worm^{-1} day^{-1} (mg)	Cocoon produced
1.	146.2 ± 3.95b	878.5 ± 16.25e	4th	732.3 ± 14.01e	26.1 ± 0.50d	38.3 ± 3.5d
2.	142.0 ± 3.24b	808.0 ± 18.31d	4th	666.0 ± 15.12d	23.8 ± 0.52c	21.7 ± 3.3c
3.	125.1 ± 3.27a	765.4 ± 11.43cd	4th	640.3 ± 9.43cd	22.9 ± 0.35c	18.3 ± 2.4bc
4.	127.1 ± 3.84a	701.6 ± 13.91bc	5th	574.5 ± 10.57bc	16.4 ± 0.30b	7.7 ± 2.2ab
5.	134.2 ± 4.41ab	672.3 ± 10.95b	5th	538.1 ± 7.11b	15.4 ± 0.22b	7.0 ± 2.3a
6.	120.3 ± 3.70a	643.7 ± 15.86ab	5th	523.4 ± 12.59ab	14.9 ± 0.37ab	1.0 ± 0.0a
7.	127.3 ± 3.45a	595.4 ± 13.06a	5th	468.1 ± 9.88a	13.4 ± 0.28a	0.0 ± 0.0a

Mean value followed by different letters (a–e) is statistically different (ANOVA; Tukey's test, $P < 0.05$). The experiment was terminated on 70th day.

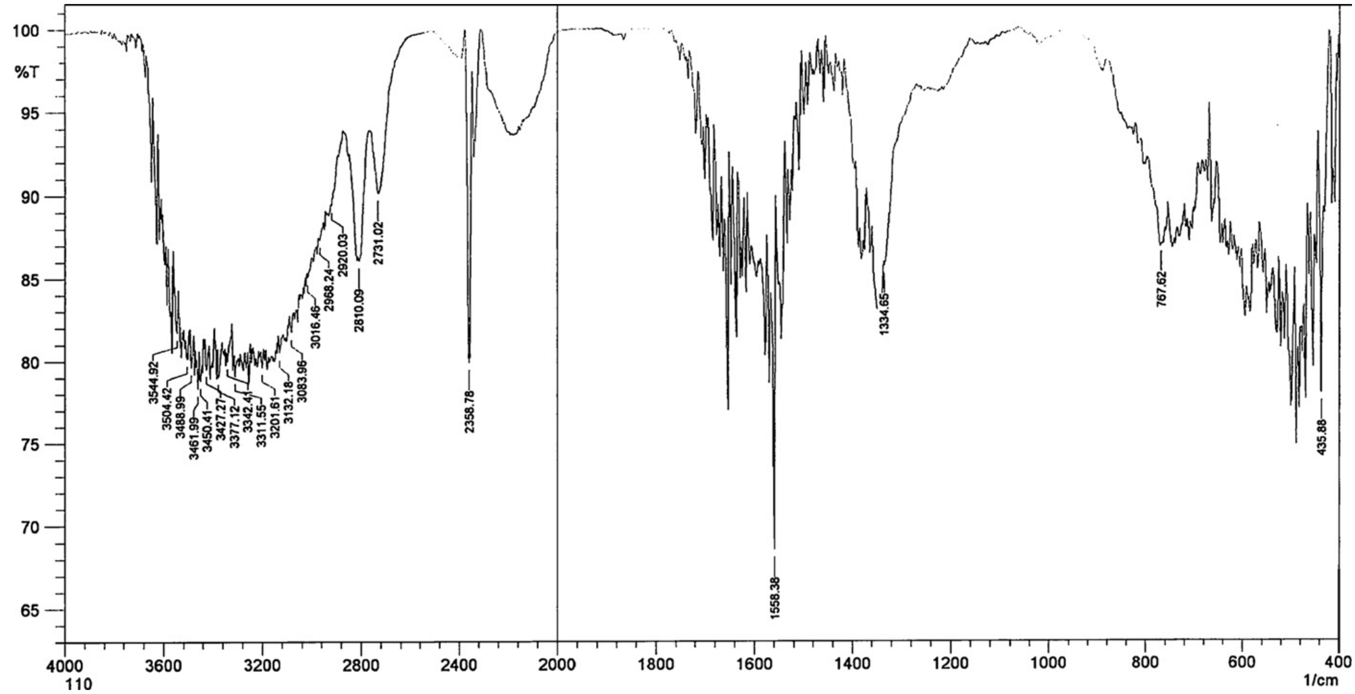

Fig. 7. FT-IR spectra of vermicompost obtained from 70% cow dung + 30% paper waste.

production was significantly ($P < 0.05$) decreased with increasing percentage of paper waste in the vermireactors. The maximum worm biomass was attained in the 4th or 5th week in all the vermireactors (Table 4). Initial increase in biomass was followed by stabilization, and, later weight loss was observed in all the vermireactors. This loss in worm biomass can be attributed to the exhaustion of food. When *E. fetida* received the food below a maintenance level, it lost weight at a rate which depends upon the quantity and nature of ingestible substrate [45]. The net biomass produced worm^{-1} was 1.09, 1.14, 1.27, and 1.36, 1.40 and 1.56 times lesser in vermireactors 2, 3, 4, 5, 6 and 7 than vermireactor 1. The C:N ratio of substrate material seems to be an important factor for determining the worm's assimilation capacity, contributing to their growth and reproductive success. As evident from Table 4, the growth rate showed tapering off with increase in C:N ratio (ranging from 63.3 to 122.6) in initial blends of raw materials. The fastest growth rate was observed in vermireactor no. 1 (100% CD) (26.1 ± 0.50 mg worm^{-1} day^{-1}) with initial C:N ratio 63.3. Where as, the growth rate in 10% PW + 90% CD and 20% PW + CD (with initial C:N ratios 69.5 and 76.9, respectively) was relatively comparable to the C:N values in 100% CD. Thereafter, the growth rate decreased significantly with the increase in initial C:N ratio in the remaining vermireactors, which supports the above hypothesis. These results confirm the inversely relationship between growth rate of the earthworms and initial C:N ratio of the feeds. Butt [46] obtained a better growth rate on a food composed of paper pulp and yeast extract with a C:N ratio of 40. Although Neuhauser et al. [45] showed that *E. fetida* gain weight at lesser C:N ratio (in the range 15–35), but the microorganisms, such as bacteria, fungi and protozoa, play an important role in the nutrition of earthworms. The total number of cocoons after 70 days in different vermireactors has been given in Table 4. The earthworms exhibited different patterns of cocoon production depending on the percentage of substrate in the feed mixtures. The maximum no. of cocoons was observed in vermireactor no. 1 (100% CD; 38.3 ± 3.5). The addition of 20% PW in CD, the cocoon production was found significant, but concentration above this level was not able to support the cocoon production efficiently. *E. fetida* could not reproduce in vermireactor 7, declaring the feed is not suitable for reproductive success. Fayolle et al. [47] have also pointed out that food source play an important role on cocoon production rates by worms. Recently, Suthar [20] emphasized that in addition to the biochemical properties of waste, the microbial biomass and decomposition activities during vermicomposting are also important in determining the worm biomass and cocoon production. The ratio of conversion of organic waste into worm biomass is an important parameter in growth studies and is expressed as biomass gained per unit of the feed. Worm biomass gained per unit of the waste was highest in vermireactor no. 1 (35.12 ± 3.24 mg g^{-1}), then, it decreased significantly in the subsequent vermireactors (Fig. 8). But, the values in vermireactor nos. 2, 3 and 4 were not significantly different from each other, depicting the acceptability of up to 30% PW in the feed mixtures. It is concluded from the results that addition of 30% paper waste to the cow dung is acceptable during the vermicomposting of PW in terms of growth and reproductive success of the earthworms. But, if the prime concern is vermiculture (production of

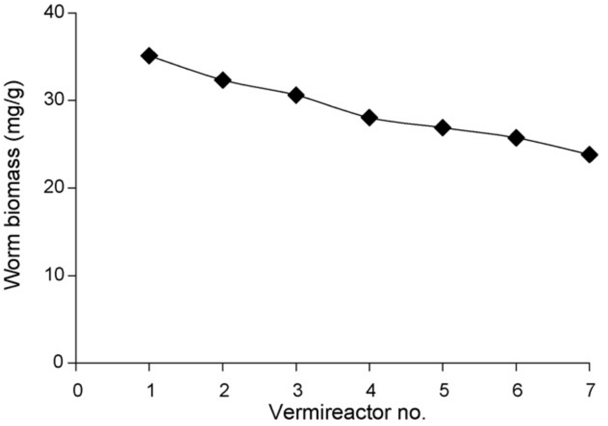

Fig. 8. Worm biomass gained per unit waste (mg/g) in different vermireactors.

earthworms), then addition of PW in the CD is not suggested, as it was not found effective to support a sustainable harvest of earthworms.

4. Conclusions

The present study substantiated the feasibility of utilization of non-recyclable paper waste in vermicomposting process. It was concluded that vermicomposting of paper waste can prove an effective technology for nutrient recovery from the paper waste material as evident from the high nutrient levels, viz., nitrogen (TKN), phosphorus (TP) and potassium (TK) at the end of the vermicomposting period. Our results demonstrated that after the addition of paper waste in appropriate quantities (30%) to the cow dung, it can be used as a raw material in the vermicomposting. The decomposition of the waste materials was enhanced, as indicated by reduction in C:N ratios, in the presence of earthworms. The FT-IR spectroscopy of the vermicomposts showed reduction in aliphatic compounds during the vermicomposting process. Addition of more than 30% PW in the CD was not efficient to support various earthworms' growth parameters, i.e., biomass production, growth rate, biomass produced per unit waste and cocoon production. Finally it was concluded that if non-recyclable paper waste and cow dung are blended in appropriate quantities, it would be converted into a good quality vermicompost as well the quantity of solid waste dumped in the landfills would be appreciably reduced.

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