FEASIBILITY OF VERMICOMPOSTING DEWATERED SLUDGE FROM PAPER MILLS USING *PERIONYX EXCAVATUS*

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ABSTRACT

India has a large network of pulp and paper mills of varying capacity. On an industrial scale the sludge from paper and pulp mills is disposed of either as landfill or incinerated. Both methods result in the loss of a valuable resource and have obvious environmental and economic disadvantages. The solid waste from pulp and paper mills is a source of organic matter and its proper disposal and management is the responsibility of the industry. As composting/vermicomposting could be used to transform this waste trials were carried out to determine the feasibility of converting dewatered sludge (DS) into a value added end product using an earthworm, *Perionyx excavatus*. The vermicomposting of the waste resulted in an increase in its electrical conductivity (EC), ash content, total nitrogen (TN), total phosphorous (TP) and available phosphorous (AP), respectively, and a decrease in total organic carbon (TOC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), oxygen uptake rate (OUR) and evolution of carbon dioxide (CO_2). Overall, the best treatment was T5 in which there was a 76.1% increase in TP, 58.7% in TN, 74.5% decrease in TOC, and a reduction of 6.7 fold in the production of CO_2 and 10.7 fold in BOD, respectively. Our trials demonstrate that vermicomposting using an epigeic earthworm, *Perionyx excavatus*, is an alternate and environmentally safe way of recycling paper mill sludge if it is mixed with an appropriate amount of cow dung and food processing waste. Overall T5 was the best combination of paper mill sludge and waste for vermicomposting followed by T3, T2, T4 and T1, respectively.

Keywords: C/N, vermicompost, food processing waste, cow dung

Introduction

Disposal of industrial sludge using environmentally acceptable means poses a very great challenge worldwide. It has been suggested that earthworms be used for this purpose (Elvira et al. 1998) and the process has been termed vermistabilization (Neuhauser et al. 1988). A considerable amount of work has been done on the composting of various organic materials using earthworms, which has revealed that epigeic earthworms can hasten the composting process to a significant extent and produce a better quality of compost than that produced by traditional composting methods (Ghosh et al. 1999). *Perionyx excavatus* is an epigeic species of earthworm, which lives in organic waste and could be potentially used to convert organic waste into a valuable end product. *P. excavatus* is known to be good at converting organic waste into high-value vermicompost, which can be used as a medium for growing plants (Kale et al. 1982; Suthar 2006). Nevertheless, most of the vermiculture experiments using *P. excavatus* were done using animal dung e.g. cow dung (Kale et al. 1982; Reinecke et al. 1992; Edwards et al. 1998), sheep dung (Kale et al. 1982), biogas sludge (Kale et al. 1982; Edwards et al. 1998), poultry manure (Kale et al. 1982), pig solids (Edwards et al. 1998), horse solids (Edwards et al. 1998) and turkey waste (Edwards et al. 1998). The potential of *P. excavatus* for processing other wastes, namely vegetable waste (Singh et al. 2005) and water hyacinth (*Eichhornia crassipes*) (Gajalakshmi et al. 2001), however, has also been tested. Vermicomposting is not only rapid, easily controllable, cost effective, energy saving and a zero discharge process, but also efficiently accomplishes the recycling of organic substances and nutrients. Transformation of organic industrial waste by vermicomposting can be the cheapest and safest way of disposing of it without polluting the environment (Elvira et al. 1996; Kaushik and Garg 2003) and recovering vermi fertilizer and animal protein (Chaudhuri 2005). Moreover, vermicompost is fragmented and microbially active due to humification (Edwards and Bohlen 1996; Maboeta and Rensburg 2003) and contains important plant nutrients in forms that are soluble and more easily available to plants than those in ordinary compost (Ndegwa and Thompson 2001). Therefore, the objective of this study was to test the feasibility of using the earthworm *P. excavatus* to stabilize dewatered sludge (DS) from pulp and paper mills mixed with cow dung (CD) and food processing waste (FPW) in different ratios.

Materials and methods

Earthworm cultures

The species of earthworm chosen for the compositing experiment was *Perionyx excavatus*. This earthworm was obtained from Central Plantation Crops Research Institute (CPCRI), Indian Council of Agricultural Research, Guwahati, India. For rearing the earthworm cultures, hopper bottom Perspex bins, 450 mm × 300 mm × 450 mm in size, were fabricated in the laboratory. For aeration and drainage purposes 16 holes of 10 mm diameter were drilled along the longer sides and 16 in the bottom, respectively. Hoppers were used to collect leachate (if any). Before the addition of the culture medium and earthworms, bedding was prepared from partially degraded chopped hay (about 50 mm), cow dung, banana pulp (chopped about 50 mm) and tree leaves. This bedding was watered to keep it moist to enable the worms to breathe. Then the earthworms were added along with partially degraded cow dung as a source of food for the earthworms.

Compost material

Dewatered sludge (DS), cow dung (CD) and food processing waste (FPW) were mixed in different proportions. DS was collected from the *effluent treatment plant* (ETP) of Nagaon Paper Mill, Kagajnagar, Assam (India). The dewatered sludge, as the name suggests, was collected from the ETP plant after the waste had passed through the sedimentation process and then partially dewatered by pumping. CD was obtained from a livestock farm near IIT, Guwahati campus, Assam (India) and FPW from Bhogali Jalpan (a traditional breakfast item maker), Guwahati, Assam (India). The percentages and physico-chemical properties of DS, CD and FPW in the different mixtures are reported in Table 1.

Experiment

Locally made round bamboo containers, each with a radius of 120 mm and depth of 90 mm enclosing a volume of 90.47×10^4 mm^3, were filled with mixtures containing different percentages of DS, CD and FPW. There were three replicas of each treatment (Table 1). The containers were kept in the laboratory at room temperature and the total weight of substrate in each container was kept at 1.5 kg. There was 10 cm of bedding in each container consisting of a mixture of hay (155 g), CD (375 g), banana leaves and tree leaves (280 g), which had been previously partially degraded over a period of two weeks. Approximately 50 g or ~100–120 earthworms (*P. excavatus*), consisting of both mature and juvenile individuals, were placed on the bedding and left to acclimatize to the new environment and then the next day the substrate was placed on top of the bedding.

1.5 kg of five different mixtures of DS, CD and FPW was added to each of the containers and they are referred to as T1, T2, T3, T4 and T5, respectively. In addition there was a control for each mixture CT1, CT2, CT3, CT4 and CT5, respectively. The quantity of the substrate provided was based on the fact that the earthworms can consume half their body weight per day of substrate under favourable conditions (Haimi and Huhta 1987). The moisture level was maintained throughout the study period by periodically sprinkling tap water over the substrate. To pre-

Table 1 The weights and the initial characteristics of the different wastes in the compost.

Reactors/Parameters	Waste materials		
	Dewatered sludge (DS)	Cow dung (CD)	Food processing waste (FPW)
T1 (kg)	1.5	–	–
T2 (kg)	1.0	0.24	0.26
T3 (kg)	1.0	0.34	0.16
T4 (kg)	1.0	0.41	0.09
T5 (kg)	1.0	0.46	0.04
Moisture content (MC) (%)	71.2±1.2	83.1±3.2	9.2±2.6
pH	6.82±0.01	7.20±0.03	6.61±0.02
Electrical conductivity (mmohs/cm)	0.73±0.02	1.21±0.02	1.22±0.04
Ash content (%)	43.1±1.4	27.5±1.2	6.6±0.4
Total organic carbon (TOC) (%)	31.6±1.7	40.3±2.1	51.8±1.5
Total nitrogen (TN) (g/kg)	6.4±0.8	15.1±1.1	16.4±0.9
Ammonical Nitrogen (NH4-N) (mg/kg)	3.21±1.02	4.62±1.21	3.12±1.34
Total phosphorous (TP) (g/kg)	3.91±0.41	0.62±0.12	1.21±0.32
Available phosphorus (AP) (g/kg)	0.37±0.11	0.22±0.09	0.01±0.01
Chemical oxygen demand (COD) (mg/kg)	591±27	145±16	22736±341
Biochemical oxygen demand (BOD) (mg/kg)	370±41	110±17	16±8
CO2 evolution (mg/g VS/day)	8.72±0.84	22.41±1.20	10.74±0.59
Oxygen uptake rate (OUR) (mg/g VS/day)	18.9±0.5	40.1±1.1	1.0±0.1

vent moisture loss, the bamboo containers were covered with gunny bags.

Parameters measured

About 110 g of wet substrate (free of earthworms, hatchlings and cocoons) were collected from the containers on day zero and on the 15th, 30th and 45th day of the composting period. Day zero is the day before earthworm inoculation. 10 g of the sample was used to measure soluble biochemical oxygen demand (BOD), chemical oxygen demand (COD), oxygen uptake rate (OUR) and CO_2 production as described in Khwairakpam and Bhargava (2009a). Sub-samples were oven dried, ground to pass through a 0.2-mm sieve and stored in plastic vials for further analysis: pH and conductivity were measured in 1 : 10 (w/v) water suspensions using digital pH (μ pH system 361) and conductivity meters (VSI-04 Deluxe), ash content (550 °C for 2 h) (loss on ignition), total nitrogen (TN) using the Kjeldahl method, ammonical nitrogen (NH_4-N) and nitrate nitrogen (NO_3-N) using KCL extraction (Tiquia and Tam 2000), total organic carbon (TOC) determined by Shimadzu (TOC-V_{CSN}) Solid Sample Module (SSM-5000A) and total and available phosphorus (TP and AP) using acid digestion and the stannous chloride method (APHA 2001). The C/N value was calculated from the measured values of total organic carbon and nitrogen. In addition earthworm growth in terms of biomass and total mortality were measured at the end of every 15th day of the experiment.

Statistical analysis

All the results are the means of three replicates. The results were statistically analyzed at 0.05 probability level using one way analysis of variance (ANOVA) and Tukey's HSD test as a post-hoc analysis to compare the means using Statistica software.

Results and discussion

Moisture content

In most treatments the moisture content increased during decomposition. The exceptions were T1, CT1 and T5. It is important that the moisture content is suitable for the earthworms and micro-organisms in the vermicomposting system and in this experiment it was 64–67% in most of the treatments. Lower moisture contents were recorded in T1 (8%) and CT1 (4%), which might be due to the nature of the raw waste material (100% DS). The greatest changes in water content were recorded in T2 (15.7%) and CT2 (17%) at the end of 45 days (Table 1). The ideal moisture range for vermicomposting or vermiculture is 60–80% (Neuhauser et al. 1988; Edwards 1998), which was achieved in this experiment. The variations in moisture content during the vermicomposting were significant ($P < 0.05$).

pH

The value of pH increased in all the treatments. The greatest increase in pH was recorded in T3, where it increased from an initial value of 5.7 to 7.7, followed by CT3 (5.7 to 7.1) and the lowest increase was recorded in CT1 (6.8 to 6.9) followed by CT2 (6.7 to 7.2) (Table 1). That is, the change in pH in all treatments indicated the compost became more alkaline and suitable for application to soil. Compost has a liming effect due to its richness in alkaline cations such as Ca, Mg and K, which were liberated from OM due to mineralization. Consequently, regular applications of compost maintain or enhance soil pH (Ouedraogo et al. 2001). Only in a few cases is a decrease in pH recorded after applying compost (Zinati et al. 2001). The change in pH during vermicomposting depends upon substrate, as different substrates may produce different intermediate organic acids (Gupta and Garg 2008). Similar observations are also recorded for vermicomposting by earlier workers (Hait and Tare 2010; Kaur et al. 2010). Earthworms selectively increase populations of catabolically more active microbes (Aira et al. 2007) therefore the degradation of short chain fatty acids and precipitation of calcium carbonate may be the cause of the increase in pH recorded in vermicomposting (Tognetti et al. 2005). Variations in pH were statistically significant ($P < 0.05$).

Electrical conductivity (EC)

The release of different mineral salts in available forms may account for the increase in EC recorded in all the treatments. Greatest percentage change was recorded in T1 (59.2%) and T2 (45.8%) followed by CT1 (32.4%) and the least in CT5 (4.5%), CT4 (6.2%) and CT3 (7.1%), respectively (Table 1). A similar increase in EC is also reported by other authors (Suthar 2007; Gupta and Garg 2008; Yadav and Garg 2009). In a closed system there is an increase in mineral salts associated with the loss in terms of weight of organic matter, which may account for the increase in EC (Khwairakpam and Bhargava 2009a). Variations in EC were statistically significant ($P < 0.05$).

Ash content (%)

The high increase in ash content indicates that the organic material is being degraded during by the vermicomposting process. The highest increase in ash content was recorded after 30 days of vermicomposting. This shows that earthworms consumed the waste material and microbes were active during the decomposition process. The ash content is an important indicator of decomposition and mineralization of the substrate (Gupta et al. 2007; Gupta and Garg 2008; Khwairakpam and Bhargava

Table 2 Moisture content, pH and EC recorded at 15 day intervals during vermicomposting.

Reactors	Moisture content (%)				pH				EC (mmhos/cm)			
	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day
R1	70.6±1.6ad	68.6±2.4a	65.5±2.8a	65.3±1.4a	6.82±0.02a	6.70±0.30ab	7.07±0.15a	7.47±0.30ab	0.73±0.01a	1.00±0.04a	1.33±0.04a	1.79±0.02a
CR1	70.0±2.2d	68.4±2.4a	68.2±3.1a	67.2±1.2a	6.82±0.02a	7.00±0.25b	7.47±0.06a	6.94±0.02b	0.73±0.01a	0.97±0.05a	0.88±0.03g	1.08±0.01e
R2	56.0±3.1b	65.0±2.1ab	67.0±2.2a	66.5±1.5a	6.71±0.01a	6.55±0.42ab	7.32±0.05a	7.50±0.08ab	1.37±0.01b	2.17±0.02c	2.11±0.02c	2.53±0.04c
CR2	56.0±2.2b	65.2±2.2ab	67.6±1.5a	67.6±2.5a	6.70±0.01a	6.74±0.05ab	7.53±0.03a	7.25±0.30ab	1.37±0.02b	2.08±0.02f	1.89±0.02ed	1.98±0.04f
R3	62.0±2.2bc	60.0±1.5b	63.5±1.6a	64.2±2.1a	5.75 ±0.03a	6.37±0.06a	7.53±0.07a	7.70±0.40ab	1.90±0.01c	1.91±0.02be	1.76±0.02b	2.19±0.06d
CR3	62.6±2.2bc	61.0±1.5bc	64.2±2.4a	65.0±2.0a	5.70±0.01a	6.46±0.08ab	7.00±0.07a	7.14±0.40b	1.83±0.01cd	1.87±0.03b	1.67±0.02h	1.97±0.02f
R4	63.1±2.3bcd	60.0±1.8b	62.3±1.5a	64.5±3.0a	6.50±0.02a	6.57±0.20ab	7.14±0.50a	7.56±0.04ab	1.80±0.01d	1.96±0.04e	1.82±0.02be	2.51±0.03c
CR4	63.5±1.5acd	61.0±2.1bc	66.1±2.5a	66.0±1.5a	6.50±0.02a	6.51±0.05ab	7.56±0.32a	7.09±0.45b	1.81±0.01d	1.87±0.02b	1.90±0.01d	1.93±0.03f
R5	65.1±2.1acd	65.0±2.3ab	65.3±3.6a	65.0±2.0a	6.68±0.02a	6.64±0.06ab	7.37±0.40a	7.99±0.25a	2.26±0.01e	2.31±0.03d	2.40±0.03f	2.65±0.02b
CR5	65.4±4.1acd	66.0±1.7ac	67.0±2.2a	66.6±3.0a	6.56±0.03a	6.76±0.05ab	7.52±0.50a	7.41±0.30ab	2.29±0.01e	2.29±0.02d	2.32±0.02i	2.40±0.01g

Mean values followed by different letters in columns are statistically different (ANOVA; Tukey's test, $P < 0.05$)

Table 3 Ash content, TOC and TN content recorded at 15 day intervals during vermicomposting.

Reactors	Ash content (%)				TOC (%)				TN (g/kg)			
	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day
R1	43.1±0.1a	44.2±0.8a	48.2±1.2ac	54.1±1.0ac	31.6±0.8a	31.0±0.1a	28.8±1.1a	25.5±1.0a	6.44±1.20a	7.00±0.50ac	8.50±1.00a	10.90±0.60ae
CR1	43.1±0.1a	44.0±0.5a	46.3±0.5c	53.0±0.6c	31.6±0.1a	31.1±0.1a	29.9±1.2a	26.1±1.1a	6.44±0.83a	6.80±0.50cd	7.00±1.00a	7.70±0.20d
R2	42.8±0.2a	45.3±1.2a	50.5±1.5a	56.5±1.0a	31.8±0.2a	30.4±1.1a	27.5±0.6a	24.2±0.6ac	10.64±0.65b	11.50±1.00b	13.50±1.20b	17.00±1.10b
CR2	42.6±0.2a	43.6±0.3a	48.1±1.1ac	53.8±1.0ac	31.9±0.2a	31.4±0.1a	28.8±1.0a	25.7±0.2a	10.64±0.80b	10.60±0.08be	11.00±0.60cd	11.60±0.10ae
R3	49.8±0.2b	51.3±0.5b	56.3±1.2b	62.9±1.2bf	27.9±0.2c	27.1±0.1c	24.3±0.6b	20.6±1.0bf	9.52±0.43b	11.20±1.00b	13.30±0.80bc	16.50±0.82b
CR3	49.7±1.2b	51.0±0.2b	55.2±1.1b	60.3±0.6b	27.9±1.2c	27.2±0.1c	24.9±1.1b	22.0±1.0bc	9.52±0.50b	10.80±1.00b	11.00±0.20cd	11.60±0.15ae
R4	56.6±1.1c	59.5±1.0c	62.3±1.0de	68.9±0.5d	24.1±1.1b	22.5±1.0b	21.0±0.3cd	17.3±1.1df	7.14±1.10a	9.50±1.10ab	11.20±1.10bcd	14.20±1.12c
CR4	56.9±1.0c	58.2±1.0c	60.5±1.0e	63.7±1.0f	24.0±1.0b	23.2±0.2b	21.9±1.0bc	20.2±0.5bg	7.14±1.00a	8.20±0.80acde	9.00±0.50ad	9.60±0.20ed
R5	58.7±1.7c	60.2±1.2c	65.2±0.5d	76.3±1.5e	23.0±1.7b	22.1±0.5b	19.3±1.0d	13.2±1.0e	5.32±0.40a	9.40±1.20ab	10.90±0.50d	12.90±1.30ac
CR5	58.8±2.0c	59.6±1.0c	61.5±0.2e	65.6±0.3f	22.9±2.0b	22.5±0.1b	21.4±0.3cd	19.1±0.4fg	5.32±0.33a	6.80±1.00c	7.70±0.50a	8.50±0.40d

Mean values followed by different letters in columns are statistically different (ANOVA; Tukey's test, $P < 0.05$)

Table 4 NH_4-N, NO_3-N and TP recorded at 15 day intervals during vermicomposting.

Reactors	NH_4-N (mg/kg)				NO_3-N (mg/kg)				TP (g/kg)			
	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day
R1	32.00±2.40a	0.68±0.05a	ND	ND	ND	ND	15.28±1.10a	114.20±3.50a	3.92±0.30a	5.20±1.30abcd	6.45±1.00acdf	7.15±0.60ad
CR1	32.00±3.50a	0.72±0.02ac	ND	ND	ND	ND	3.00±0.50b	70.00±1.50b	3.92±0.45a	4.00±0.04bc	4.35±0.20f	4.75±0.30d
R2	5.02±1.80b	0.70±0.01ac	ND	ND	ND	ND	54.58±1.60c	186.20±4.60c	4.29±0.16c	5.45±0.08ac	11.32±1.20bc	16.85±1.00b
CR2	5.02±2.20b	0.79±0.02bc	ND	ND	ND	ND	1.70±0.30b	85.40±1.20g	4.29±0.30c	3.25±0.08b	6.45±0.60afg	10.5±2.00ae
R3	5.18±3.20b	0.67±0.04a	ND	ND	ND	ND	74.40±4.00d	154.00±2.50d	4.12±0.25bf	6.55±0.50a	10.28±1.00be	14.42±1.20bc
CR3	5.18±2.10b	0.75±0.02ac	ND	ND	ND	ND	15.24±1.80a	64.00±1.80b	4.12±0.41f	5.26±1.20abcd	8.12±0.05deg	12.22±1.10cef
R4	4.58±3.20b	0.86±0.01bd	ND	ND	ND	ND	138.23±3.10e	252.00±5.00e	4.02±0.80de	6.82±0.60a	10.22±1.50be	15.00±1.20bc
CR4	4.58±2.20b	0.92±0.06d	ND	ND	ND	ND	14.93±1.00a	71.50±3.00b	4.02±0.32bde	5.24±0.45abcd	8.60±1.10bcg	12.45±1.00cef
R5	4.35±1.20b	0.76±0.02ac	ND	ND	ND	ND	148.12±5.00f	442.20±5.00f	3.85±0.45de	5.44±1.10acd	10.24±1.30be	16.15±1.50b
CR5	4.35±2.00b	0.86±0.04bd	ND	ND	ND	ND	54.36±2.30c	162.49±2.10d	3.85±0.18d	4.23±0.50bcd	8.25±0.40aeg	14.50±1.00bf

Mean values followed by different letters in columns are statistically different (ANOVA; Tukey's test, $P < 0.05$) ND-Not detected

Table 5 AP, C/N ratio and OUR recorded at 15 day intervals during vermicomposting.

Rea-ctors	AP (mg/kg)				C/N ratio				OUR (mg/g VS/day)			
	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day	0 day	15 day	30 day	45 day
R1	0.40±0.05a	0.82±0.20a	1.80±0.50acde	2.20±0.20ade	49.1±0.4a	44.3±1.0a	33.9±2.1a	23.4±2.1a	18.9±2.3ab	12.5±1.3ac	8.3±1.3ae	3.4±1.1acd
CR1	0.40±0.07a	0.70±0.10a	0.82±0.05b	1.20±0.10c	49.1±0.1a	45.8±1.0a	42.6±1.0c	33.9±2.0d	18.8±1.5ab	14.5±1.0ce	12.5±1.0bcd	8.2±2.0b
R2	0.40±0.05a	1.40±0.20a	1.90±0.20acde	2.80±0.30b	29.9±3.2bd	26.4±1.1bd	20.4±2.0bde	14.2±1.5b	11.2±6.2a	8.2±2.0a	5.2±1.4a	2.4±1.0ad
CR2	0.40±0.02a	1.10±0.40a	1.70±0.30acde	1.80±0.05de	30.0±2.1bd	29.6±0.5de	26.2±0.6fg	22.1±1.2ac	11.2±5.5a	9.0±1.8a	8.6±0.6ac	7.2±0.6cb
R3	0.60±0.03ab	1.50±0.60a	2.00±0.20ade	2.50±0.20abe	29.3±0.6b	24.2±1.2bc	18.3±1.5be	12.5±0.6b	24.6±4.3b	20.9±2.1b	11.3±2.1cde	2.1±1.5a
CR3	0.60±0.02ab	1.00±0.20a	1.30±0.20abd	1.40±0.05cd	29.3±0.5b	25.2±1.5bd	22.6±1.2ef	19.0±1.5c	24.6±4.6b	21.0±3.0b	12.4±1.6bcd	6.8±1.6cb
R4	0.80±0.02b	1.18±1.00a	2.00±0.40ae	2.80±0.26b	33.8±1.2d	23.7±2.0b	18.7±2.1be	12.2±1.6b	21.4±2.5ab	15.7±1.8cb	8.7±1.5ac	2.1±1.3a
CR4	0.80±0.03b	1.08±0.20a	1.20±0.15cb	1.70±0.18acde	33.6±1.5d	28.3±2.0cd	24.4±1.3dfh	21.0±1.0ac	21.1±3.8ab	18.5±2.0be	14.0±1.4d	6.3±2.1bd
R5	0.70±0.02b	1.70±0.80a	2.20±0.22e	2.80±0.30b	43.2±0.8c	23.5±1.2b	17.7±1.5b	10.2±1.7b	10.7±3.7a	7.6±1.8a	5.4±1.0a	1.8±1.2a
CR5	0.70±0.24b	1.00±0.30a	1.70±0.20ace	2.20±0.20e	43.0±0.9c	33.0±2.0e	27.8±1.5gh	22.5±0.8ac	9.6±5.0a	8.2±0.6a	6.9±1.0a	5.2±1.0ab

Mean values followed by different letters in columns are statistically different (ANOVA; Tukey's test, $P < 0.05$)

2009b). The greatest increase in ash content was recorded in T2 (24.2%), T5 (23.1%) and T3 (20.8%) and least in CT5 (10.4%), CT4 (10.7%) and CT3 (17.6%), respectively (Table 2). Earlier workers also report an increase in ash content (Yadav and Garg 2009; Deka et al. 2011a). The variation in ash content was statistically significant ($P < 0.05$).

Total organic carbon (TOC)

There was a decrease in organic carbon in all the treatments probably due to substrate mineralization, brought about by the metabolic activity of the earthworms and associated micro flora (Orozco et al. 1996). Final TOC was lower in vermicompost and compost as compared to the initial value. At the end of bioconversion period, a significant fraction of the TOC contained in the initial mixture was lost as CO_2 (Elvira et al. 1996) possibly the result of the available carbon being used as a source of energy by the earthworms and microbes (Khwairakpam and Bhargava 2009b). The physical, biological and chemical environment of the waste is modified by the earthworms, which make the waste more suitable for colonization by microbial communities, which in turn results in loss of carbon (Suthar and Singh 2008). The greatest decrease in TOC was recorded in T5 (42.7%) and CT3 (21.1%) and least in T1 (19.4%) and CT4 (15.8%) (Table 2). These results are similar to those reported previously of between 20–43% (Elvira et al. 1997) and up to 45% (Kaviraj and Sharma 2003). Variation in TOC in the different treatments was statistically significant ($P < 0.05$).

Nitrogen content

TN increased in all the treatments, possibly a result of the activity of earthworms, as reported by other authors (Suthar and Singh 2008). Earthworms also have a great effect on the transformation of nitrogen in manure, by enhancing nitrogen mineralization, which results in nitrogen being retained in the form of nitrates (Atiyeh et al. 2000). However, in general the final nitrogen content of compost is dependent on the initial nitrogen content in the waste. TN consists of the inorganic forms of nitrogen ammonium (NH_4-N) and nitrate (NO_3-N). The greatest TN was recorded in T5 (58.7%) followed by T4 (49.7%), T3 (43.2%) and least in CT2 (8.2%) followed by CT1 (16.3%) and CT (17.9%), respectively (Table 2). Also using the same species of earthworm, earlier workers also report many fold increases in TN (Suthar and Singh 2008; Khwairakpam and Bhargava 2009a; Deka et al. 2011b). A decrease in NH_4-N and corresponding increase in NO_3-N was recorded during the final stages of the vermicomposting process (Table 3). Over the first 15 days there was a decrease in the amount of NH_4-N (98.8%). The greatest change of 98% was recorded in T1. This might be due to the loss of NH_4-N as volatile ammonia at high pH values. There was a 1.8–7.4 fold increase in NO_3-N during the later stages of the composting process. Greatest change was recorded in T1 (7.4 fold). The difference in the various forms of nitrogen is due to immobilization/denitrification or both (Khwairakpam and Bhargava 2009a). ANOVA revealed that the differences are statistically significant ($P < 0.05$).

Phosphorus turnover

Total phosphorus (TP) content was greater at the end of the composting process, probably because of mineralization of organic matter (Elvira et al. 1997). The greatest TP was recorded in T5 (76.1%) followed by T2 (74.5%) and CT5 (73.4%), and the least in CT1 (17.4%) followed by T1 (45.1%) and CT2 (59.1%), respectively (Table 4). Similar results are reported by other workers who record the stimulating effect of earthworms on the availability of phosphorous in soil (Krishnamoorthy 1990; Kaviraj and Sharma 2003; Tognetti et al. 2005). Enzymes in the guts of earthworms have a stimulating effect on phosphate solubilizing bacteria (Satchell and Martin 1984). Available phosphorus (AP) is more important for plant maturation than plant growth (Yadav and Garg 2009). Addition of phosphorus to vermicompost also prevents the loss of nitrogen by the volatilization of ammonia (Yadav and Garg 2011). Vermicomposting is an efficient way of transforming unavailable forms of phosphorous into forms easily available to plants (Ghosh et al. 1999). Similar increases in AP were recorded in the vermicompost, with greatest increase recorded in T2 (85.7%) (Table 5). The variation in TP was significant ($P < 0.05$).

C/N ratio

The C/N ratio is the most reliable indicator of the degree of decomposition and whether the compost is ready for field application. In general, the carbon content decreased and that of nitrogen increased during the decomposition process in all treatments. However, the C/N ratio varies widely depending on the rate of decomposition (Subramanian et al. 2010). The final values of the C/N ratio in all the containers were in the range of 10-23, which indicates an advanced degree of organic matter stabilization and a satisfactory degree of maturity of the organic waste (Senesi 1989) (Table 5). The greatest change was recorded in T5 (4.2 fold) followed by T4 (2.7 fold) and T3 (2.3 fold) and least in CT2 (1.3 fold) followed by CT1 (1.4 fold) and CT3 (1.5 fold), respectively. Earthworms digest long chain polysaccharides and enhance the colonization of the compost by microbes (Aira et al. 2007), which further accelerates the rate of organic matter degradation and nitrogen fixation (Garg and Kaushik 2005). This results in a greater decline in C/N ratio in the vermicompost than in the compost. Some nitrogen is also added by the worms during vermicomposting in the form of mucus, nitrogenous excretory substances, hormones and enzymes (Hobson et al. 2005; Neuhauser et al. 1986). The decrease in the C/N ratio recorded over time might also be attributed to the increase in the earthworm population (Ndegwa and Thompson 2000). Earthworms decompose the carbonaceous wastes efficiently and lower the C/N ratio, which might account for lower C/N ratio recorded in vermicompost than in compost. C/N ratio varied significantly in all vermicompost and compost treatments ($P < 0.05$).

Rate of oxygen uptake (OUR)

Initially the OUR recorded in all the treatments was high possibly due to the rapid growth of microbes. OUR is the most frequently used method for determining the biological activity of waste material (Gomez 2006). It measures compost stability by evaluating the amount of readily biodegradable organic matter still present in a sample based on the oxygen demand (Khwairakpam and Bhargava 2009b). The OUR was greatest during the active stage of composting, as microbes grow rapidly because there is an abundance of readily biodegradable substrate (Kalamdhad and Kazmi 2009). At the onset of the composting process large organic molecules are broken down into smaller, soluble ones and temporarily more substrate may become available. The decrease in OUR was greatest in T3 (11.3 fold) followed by T4 (10.1 fold) and T1 (5.5 fold) and least in CT2 (1.5 fold) followed by CT5 (1.8 fold) and CT1 (2.2 fold) (Table 5). Earlier researchers also record a decrease in OUR during the vermicomposting process (Khwairakpam and Bhargava 2009b). The changes in OUR were statistically significant ($P < 0.05$).

Rate of production of CO_2

The rate of production of CO_2 was greatest during the initial stages of the composting process possibly due to a high level of microbial activity. The production of CO_2 is the most direct way of determining the stability of the compost because it measures carbon that originates directly from the compost. Thus, the production of CO_2 directly correlates with aerobic respiration, which is the best measure of aerobic biological activity (Khwairakpam and Bhargava 2009b). The greatest decrease in respiratory activity was recorded during the initial stages of composting. The greatest production of CO_2 was recorded in T5 (6.7 fold) followed by T3 (5.6 fold) and T2 (4.8 fold), and least in CT1 (1.9 folds) followed by CT2 (2.7 fold) and CT4 (2.4 fold) (Table 6). Waste in the early stages of composting has a strong demand for O_2 and produces large quantities of CO_2 due to a great increase in the numbers of micro-organisms that develop on the abundance of easily biodegradable compounds in the raw material. For this reason, O_2 consumption or CO_2 production can be used as an indicator of the stability and maturity of the compost (Kalamdhad et al. 2008). All the variations in CO_2 production were significant ($P < 0.05$).

Table 6 CO_2 evolution, soluble BOD and COD recorded at 15 day intervals during vermicomposting.

Reactors	CO_2 evolution (mg/g VS/day)				Soluble BOD (mg/kg)				Soluble COD (mg/kg)			
	0 day	**15 day**	**30 day**	**45 day**	**0 day**	**15 day**	**30 day**	**45 day**	**0 day**	**15 day**	**30 day**	**45 day**
R1	8.75±1.20abc	5.75±1.10ab	3.24±1.00a	2.88±0.60abc	30.8±2.0a	24.3±2.2a	12.4±2.4abc	5.5±1.5a	591±30a	455±12a	250±50a	150±20a
CR1	8.75±1.20abc	7.44±0.50ab	5.45±1.20a	4.55±0.20b	30.8±1.1a	25.3±1.4a	20.2±1.6b	17.2±1.5b	591±45a	512±30a	368±20a	260±40a
R2	12.24±1.10a	8.56±1.50ab	4.92±2.10a	2.50±1.18abc	32.8±4.0a	23.0±4.0a	10.5±2.0ac	4.7±3.2a	16631±250c	11254±120c	645±150ab	307±35a
CR2	12.28±1.20ac	9.36±2.00b	6.52±1.60a	4.50±1.25cb	32.6±3.0a	24.6±4.2a	18.6±3.0cb	15.5±1.6b	16675±100c	12756±220e	7486±180d	3004±150c
R3	12.18±1.50a	8.32±2.40ab	3.24±1.50a	2.17±0.30abc	32.1±2.5a	22.4±2.5a	10.0±2.6a	3.4±1.5a	15800±200d	5621±300b	480±105ab	142±32a
CR3	12.22±1.30ac	9.26±2.30ab	5.44±2.00a	3.48±1.00abc	28.4±6.5a	23.5±2.0a	17.1±2.3abc	14.3±1.0b	15196±255f	7745±310d	5007±300c	984±261b
R4	8.62±1.50abc	5.32±0.60ab	3.54±1.00a	2.15±0.60ac	34.0±5.0a	22.0±5.0a	10.0±5.0a	4.5±2.3a	14620±321e	5442±210b	814±215b	217±125a
CR4	8.57±1.00abc	6.67±0.20ab	4.56±1.20a	3.44±0.25abc	33.7±3.3a	25.5±4.3a	17.1±3.0abc	12.6±1.5b	14901±100e	7214±300d	4897±240c	995±130b
R5	8.15±2.00b	5.01±1.10a	3.52±1.10a	1.20±1.00a	34.4±1.8a	21.5±2.6a	9.6±2.6a	3.2±1.0a	13512±246b	5289±250b	725±120a	140±41a
CR5	8.19±1.00b	5.22±1.20ab	3.80±1.00a	2.84±1.00abc	36.7±2.1a	25.0±3.1a	16.4±2.4abc	12.3±1.1b	13822±233b	7077±300d	4352±213e	885±124b

Mean values followed by different letters in columns are statistically different (ANOVA; Tukey's test, $P < 0.05$)

Soluble BOD and COD

It is generally recognized that the percentage of readily biodegradable organic matter is an important determinant of compost quality. Only the C/N ratio gives a clear indication of the stability of the compost because O_2 consumption continues, which indicates the compost is still immature. In order to determine the O_2 consumption it is necessary to measure soluble BOD and COD. When applying compost to soil for crop use, care should be taken because the biological processes will continue and can strip nutrients from soil even if the compost is stable (Wang et al. 2004). Hence it is important to monitor BOD. The decrease in BOD was greatest in T5 (10.7 fold) followed by T3 (9.3 fold) and T4 (7.5 fold), and least in CT1 (1.7 fold), CT3 (1.9 fold) and CT2 (2.1 fold) (Table 6). The greatest reduction in COD was recorded in T3 (111.2 fold), T5 (96.5 fold) and T4 (67.3 fold), and the least in CT1 (2.2 fold), T1 (3.9 fold) and CT2 (5.5 fold), respectively. The variations in BOD and COD at the end of the composting process were significant ($P < 0.05$) in all the treatments.

Growth and reproduction of earthworms

After 45 days of earthworm activity the vermicompost was a dark brown colour and had an homogenous texture. The earthworm biomass increased in all the vermicomposts. Earthworm biomass increased in all the treatments except for T1, where there was a 5.5% reduction in biomass (Table 7). This may be due to the nature of substrate, which consisted of 100% dewatered sludge. The greatest increase in earthworm biomass was recorded in T5 (19.3%) followed by T4 (16.6%) and T3 (10.7%), respectively. Cocoon production was greatest in T3 with 0.017 cocoons/worm/day followed by T2 (0.015 cocoons/worm/day) and T4 (0.014 cocoons/worm/day). Other researchers working with *P. excavatus* also report an increase in cocoons/worm/day (Knieriemen 1985; Reinecke et al. 1992; Suthar 2006; Khwairakpam and Bhargava 2009b; Deka et al. 2011b). The number of juveniles that hatched per 100 gm of end product was quite high, with the greatest number of 90 recorded in T5 and least in T2 (28).

Conclusions

The end product after 45 days of vermicomposting was a dark brown colour and smelt of humus. *P. excavatus* effectively processed the organic wastes and produced an end product rich in TN and TP. The higher nutrient content, lower C/N ratio and EC, plus higher pH of the vermicompost indicates that vermicomposting is the better option for disposing of dewatered sludge from pulp and paper mills. Overall T5 proved to be the best combination for vermicomposting followed by T3, T2, T4 and T1, respectively. The low biomass of earthworms recorded in T1 may be due to the nature of the substrate, which consisted of 100% DS. However, the growth of earthworms was good in all the other treatments and best in T5. The results indicate that there is an inverse relationship between the growth rate and cocoon production by earthworms and the percentage of DS in the waste material.

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Table 7 Live biomass production of earthworms in different treatments.

Vermireactor	Mean weight of Earthworms (g)		Live biomass (% change)	Coocons/worm/day	No. of Juveniles hatched/100 g
	Initial	Final			
T1	50	47±1.6a	–5.6±3.6ab	0.004±0.001ae	30±1a
T2	50	55±1bc	10±1.7ab	0.015±0.005bc	28±2b
T3	50	56±3cd	12±6bc	0.017±0.002c	50±1cd
T4	50	60±2de	20±4cd	0.014±0.003db	55±3d
T5	50	62±1.5e	24±3d	0.009±0.001ebd	90±4e

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