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Recycling of agro-industrial sludge through vermitechnology

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ABSTRACT

This work illustrates the feasibility of vermitechnology to stabilize sludge from an agro-industry. To achieve the goal, industrial sludge (IS) was mixed with three different bulky agents, i.e. cow dung (CD), biogas plant slurry (BGS) and wheat straw (WS), in different ratios to produce nine different feed mixtures for earthworm *Eisenia fetida*. Vermicomposting bedding material was analyzed for its different physic-chemical parameters after 15 weeks of experimentations. In all waste mixtures, a decrease in pH, organic C and C:N ratio, but increase in total N, available P, exchangeable K, exchangeable Ca and trace elements (Mg, Fe and Zn) was recorded. IS (40%) + CD (60%) and IS (40%) + BGS (60%) vermibeds showed the highest mineralization rate and earthworm growth patterns during vermicomposting process. Vermicompost contains (dry weight basis) a considerable range of plant available forms of P (17.5–28.9 g kg^{-1}), K (13.8–21.4 g kg^{-1}), Ca (41.1–63.4 g kg^{-1}), Mg (262.4–348.3 mg kg^{-1}), Fe (559.8–513.0 mg kg^{-1}) and Zn (363.1–253.6 mg kg^{-1}). Earthworm growth parameters, i.e. biomass gain, total cocoon production, individual growth rate (mg wt. $worm^{-1}$ day^{-1}), natality rate, total fecundity were optimum in bedding containing 20–40% industrial sludge. C:N ratio of worm-processed material was within the agronomic acceptable or favorable limit (<15–20). The results clearly suggested that vermitechnology can be a potential technology to convert industrial sludges into vermifertilizer for sustainable land restoration practices.

1. Introduction

Several food products are prepared in industrial units using agriculture goods/byproducts as raw materials. The raw materials are processed through several industrial mechanisms to convert it into the final consumer items. During this process a considerable amount of liquid as well as solid waste is generated. Such agro-industrial sludge/wastes not only spoil the aesthetic sense of local habitats but at the same time also create issues of all types of environmental pollution, if proper disposal and management policy is not adopted. The majority of such wastes are disposed openly at nearby locations of industrial areas. Nowadays the concept of "using waste as resource not to be discarded" is getting much attention among industrial policy makers and modern waste managers. The safe disposal and/or meaningful utilizations of agro-industrial sludge/solid wastes have been considered at top priority in this era of green economy. To achieve the goal of sustainable industrial development, with minimum pollution load, several novel techniques have been introduced in recent years. Recovery of nutrients and energy from industrials solid/liquid wastes with low-inputs is now recognized potentially in several sectors of industrial production.

Sugar processing is one of the largest polluting industries in India. India accounts for 10% of the world's total sugar production and for this about 134 million tons of sugarcane is crushed annually. From sugarcane juice extraction unit to furnishing unit, a considerable amount of sludge is produced. However, sugar industry has considered this voluminous quantity of pressmud as a waste, and society as hazards pollutant. According to Kale (1998) an average pressmud (a byproduct of sugar processing industry containing the elements added to clarify juice and sediments, solids like bagacillo, the smaller fibers of cane sugar, and particulates and mud) production per ton of sugar is 35 kg. Such sludge contains fibrous substance with high BOD and COD load. Pressmud has major water and air pollutant near the sugar industrial area. Similarly, distillery is an important sub-unit of sugar production industry. Estimates show that organic waste produced from the distillery industry includes effluent of molasses 350,000 L/day; yeast sludge 20,000 L/day and spent malt grain wash 120,000 L/day. This huge quantity of effluent enters into lagoons where it is aerated to reduce the BOD and, afterward the effluent is used for land irrigation. But the majority of such waste is deposited openly in industrial areas which creates bad smell and acts as active breeding site for many disease vectors. On the other hand the traditional disposal methods, such

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Table 1
Vermicomposting of some industrial wastes.

Industrial wastes	Amendment or bulking material	Earthworm species	Reference
Guargum industrial waste	Cow dung and saw dust	*P. excavatus* and *P. sansibaricus*	Suthar (2006), Suthar (2007a)
Textile mill sludge	Biogas plant slurry	*E. foetida*	Garg et al. (2006)
Distillery sludge	Cow dung	*P. excavatus*	Suthar and Singh (2008a)
Paper mill sludge	Sewage sludge	*Eisenia andrei*	Elvira et al. (1997)
Dairy industry sludge	Cattle manure	*Eisenia andrei*	Elvira et al. (1998)
Beverage Industry sludge	Cattle dung and saw dust	*E. fetida*	Singh et al. (2009)
Sugar industry waste	Cattle dung	*E. fetida*, *P. excavatus*, *Eudrilus eugeniae*	Khwairakpam and Bhargava (2009)
Food processing industry waste	Cattle dung	*E. fetida*	Yadav and Garg (2009)
Olive oil mill sludge	Cattle dung	*E. andrei*	Moreno et al. (2000)
Winery waste	–	*E. andrei*	Nogales et al. (2005)
Leather processing sludge	Cow dung and agriculture residues	*E. fetida*	Ravindran et al. (2008)

as open dumping and/or land filling practices of these materials are not only increasingly expensive, but impractical as open space becomes limited. Contamination of ground water, soils, as well as food resources are some of the problems which have resulted from land filling practices of dumped waste materials (Suthar, 2009a; Suthar and Singh, 2008a). It is realized that there is an instant need of safe technology to manage such noxious industrial waste; the technologies must be ecologically sound, economically viable and socially acceptable (Suthar, 2008a).

Application of sugar and associated industry byproduct has the potential to be used as soil conditioners. But C:N ratio of sugarcane industrial waste normally ranged from 28–33 (bagasse) to 99–102 (cane trash) which makes it non-suitable for direct application as manure in the field. Similarly, the sludge from distillery unit can be used as biofertilizer because of its nutritive value. But prior to its application sludge need to be processed properly using appropriate composting technology to remove putrescible substances and biotoxic compounds, formed under anaerobiosis. Earlier, studies have revealed that vermicomposting could be an appropriate technology to transfer energy rich organic wastes to value-added products, i.e. vermicompost (Kale, 1998). Few earthworms have been known as potential candidates for waste recycling operation, popularly known as vermicomposting. It is an eco-biotechnological process in which earthworm and associated microflora converts the organic garbage into a product with relatively high level of easy available forms of soil nutrients (Suthar, 2010a). In vermicomposting the earthworm acts as mechanical blenders, and by comminuting the organic matter, they modify its biological, physical and chemical status, gradually reducing its C:N ratio, increasing the surface area exposed to microorganisms. Compared to conventional composting systems (as commonly used in India to recycle organic wastes), the vermicomposting often results in mass reduction, shorter time for processing and high levels of humus with reduced phytotoxicity in ready material (vermicompost).

Earlier studies indicate the feasibility of vermitechnology for industrial solid waste/sludges stabilization. Table 1 describes some successful trails of industrial waste in vermicomposting operations.

However, industrial sludge cannot be used without dilutions for earthworm feed because it contains several hazardous chemicals, which directly harms to inoculated earthworms in vermibed. A suitable amendment substance is needed for successful vermicomposting operation. Suthar (2006) used the saw dust and cow dung as bulky agents for vermicomposting trials of guargum industrial wastes. He suggested that 60:20:20 ratio of industrial waste, cow dung and saw dust was an ideal combination to achieve the maximum biopotential of earthworms. Garg et al. (2006) suggested that substrate containing 40% textile mill sludge + 60% biogas plant slurry is a suitable combination for better mineralization and earthworm production during process. Elvira et al. (1997) studied the vermicomposting of waste water sludge form paper mill. They recorded an excellent earthworm growth in vermibed containing paper mill sludge and sewage sludge (3:1). Recently, Singh et al. (2009) demonstrated the vermicomposting of sludge from a beverage industry and suggested 50:50 as ideal waste combination of industrial sludge and cow dung in terms of nutrient quality of end material and earthworm growth performances. It is clear that industrial sludge can be vermicomposted potentially, if mixed with a bulky material in a suitable ratio.

The aim of this study to test the feasibility vermicomposting to stabilize the waste from sugar industry (pressmud + distillery sludge) mixed with bulky agents, i.e. cow dung, biogas plant slurry and wheat straw, in different ratios using earthworm *Eisenia fetida*. The different combinations of industrial waste were evaluated in terms of quality of end material (vermicompost: worm-processed material) and earthworm production.

2. Materials and methods

2.1. Earthworm, industrial waste and bulky material collection

Composting earthworms *E. fetida* (Savigny) were obtained from stock culture maintained in the laboratory. Stock earthworms were cultured on partially decomposed cow dung.

Fresh agro-industrial sludge (IS) was procured from different units of a local sugar mill. The waste was composed of filter mud and sludge from distillery unit. Agro-industrial sludge was homogenized and shade-dried in large containers at lab for 2 weeks. IS was turned daily to reduce the characteristics smell of putrescible substances and biotoxic compounds, formed under anaerobiosis. Three bulky materials, i.e. cow dung, biogas slurry and wheat straw were used to prepared different bedding mixture for earthworms. The chopped straw of wheat (WS), fresh sugarcane trash and dried and chopped guar bran were procured from a local agriculture farm, Sri Ganganagar, India. The bio-digested effluent (BGS) was obtained from a domestic cattle dung-based biogas production unit situated in Sri Ganganagar, India. Fresh BGS was collected in large-sized plastic containers and brought to the laboratory. BGS was slightly shade dried. Fresh urine-free cow dung (CD) was procured from a local cowshed. The main chemical characteristics of IS, WS, BGS and CD are given in Table 2.

2.2. Preparation of vermibeds and composting trial

IS and bulky materials were mixed in different ratios to produce nine feed mixtures (Table 3) for experimentations.

For experimentation, 500 g waste mixture (dry weight basis) was filled in plastic circular containers of 2 L capacity (one for each mixture). The waste mixtures moistened with tap water to maintain appropriate moisture level for initial decomposition of waste mixtures. These bedding were kept for 3 weeks for initial com-

Table 2
Description of different vermibeds used for vermicomposting experiment.

Treatment	Treatment description	IS (g)	CD (g)	BGS (g)	WS (g)
T_1	IS[a] (20%)[b] + CD[c] (80%)	100	400	–	–
T_2	IS (40%) + CD (60%)	200	300	–	–
T_3	IS (20%) + BGS[d] (80%)	100		400	–
T_4	IS (40%) + BGS (60%)	200	–	300	–
T_5	IS (40%) + WS[e] (30%) + CD (30%)	200	150	–	150
T_6	IS (40%) + WS (30%) + BGS (30%)	200	150	–	150
T_7	IS (60%) + CD (40%)	300	200	–	–
T_8	IS (60%) + BGS (40%)	300	–	200	–
T_9	IS (60%) + CD (20%) + BGS (20%)	300	–	–	200

[a] Industrial sludge (IS).
[b] The figures in parenthesis indicates the percent content in the initial substrate material.
[c] Cow dung (CD).
[d] Biogas plant slurry.
[e] Wheat straw.

posting (thermal stabilization, initiation of microbial degradation and softening of waste mixture). The waste mixture in different bedding was turned out periodically (after 3 days) for aeration and to remove odor from decomposing wastes. After 3-week composting, twenty five earthworms (4-week old) having individual live weight of ≈254–267 mg were released into each experimental container. The experimental beddings were kept in triplicate for each treatment. The moisture content was maintained at 65–70%, throughout the study period by periodic sprinkling of adequate quantity of water. The containers were placed in a humid and dark room at a temperature 26.8 °C (SD = 0.3). The earthworm mortality was observed for initial critical periods (initial 15 days of experimental starting) and data of mortality were recorded for different experimental vermibeds. Homogenized samples of waste mixtures were drawn at 0, 15, 30, 45, 60, 75, 90 and 105 days from each experimental container. The samples were oven dried (48 h at 60 °C), ground in stainless steel blender and stored in sterilized plastic airtight containers for further physico-chemical analysis.

The biological productivity (biomass change, cocoon production etc.) of *E. fetida* was also monitored during the same interval for whole experiment duration by following method as described by Suthar (2008a, 2009a).

2.3. Chemical analysis

The pH was measured using a digital pH meter (Systronics made) in 1:10 (w/v) aqueous solution (deionized water). Organic carbon was determined by the partial-oxidation method (Walkley and Black, 1934). Total Kjeldahl nitrogen (TKN) was measured using the method described by Jackson (Jackson, 1975). Available phosphorous was measured using the method described by Anderson and Ingram (Olsen et al., 1954). Exchangeable cations (K^+, Ca^{2+} and Mg^{2+}) were determined after extracting the sample using ammonium acetate (Simard, 1993). Extractable trace elements (Fe and Zn) were determined by following diethylene-triaminepentaacetic acid (DTPA) extraction method; analyzed by atom absorption spectrophotometer (APHA–AWWA–WPCF, 1994).

2.4. Statistical analysis

One-way ANOVA was used to analyze the differences between treatments. A Tukey's *t*-test was also performed to identify the homogeneous type of the data sets. SPSS® statistical package (Window Version 13.0) was used for data analysis. All statements reported in this study are at the $P < 0.05$ levels.

3. Results and discussion

3.1. Physico-chemical changes in waste mixture during vermicomposting

The earthworm-processed waste mixture was more stabilized, odor-free, dark brown and nutrient rich material i.e. vermicompost. During the process the physico-chemical properties of waste mixtures changed drastically and end material was rich in soil nutrients. The pH of waste mixtures was lower in all treatments than their initial values (Table 4).

The range of pH in vermicomposted material was 7.0–7.6 (Table 4). The shifting in pH could be attributed to the production of CO_2, ammonia, NO_3^- and organic acids by microbial decomposition during vermicomposting process, which lowers the pH of substrate. Moreover, production of intermediate species of organic acids can lower the pH of substrate. The difference among vermibeds for mineralization rate or quality of initial feed stock may influence the pH level of vermibeds, and observed difference in this study supports it. pH level within acidic or neutral ranges seems beneficial for microbial enhancement of bedding materials, as it accommodates

Table 3
Chemical characteristics (g kg^{-1}) of organic wastes used as amendment material (mean ± SD, *n* = 3).

Parameters	Cow dung	Biogas slurry	Wheat straw	Industrial sludge
pH	8.5 ± 0.1	7.3 ± 0.5	ND	7.4 ± 0.02
Organic C (g kg^{-1})	392.8 ± 0.3	359.5 ± 1.9	495.8 ± 2.9	364.5 ± 0.05
Total N (g kg^{-1})	7.96 ± 0.2	18.7 ± 0.2	5.7 ± 0.2	14.3 ± 0.04
Available P (g kg^{-1})	2.32 ± 0.1	2.96 ± 0.1	2.89 ± 0.2	19.7 ± 0.06
Exchangeable K (g kg^{-1})	5.67 ± 0.2	13.2 ± 0.3	14.8 ± 0.4	5.78 ± 0.06
Exchangeable Ca (g kg^{-1})	12.7 ± 0.8	15.0 ± 1.9	67.4 ± 1.4	62.7 ± 1.5
Exchangeable Mg (mg kg^{-1})	264.2 ± 2.1	289.3 ± 2.2	ND	360.5 ± 3.6
DTPA-Fe (mg kg^{-1})	389.7 ± 3.1	401.3 ± 2.0	ND	612.6 ± 4.2
DTPA-Zn (mg kg^{-1})	118.5 ± 1.0	127.8 ± 1.1	ND	456.4 ± 2.1
C:N ratio	49.35 ± 1.3	19.2 ± 0.9	87.0 ± 3.1	25.4 ± 0.7

ND: not determined.

Table 4
Chemical characteristics of initial (at start) and vermicomposted material (at end) (mean ± SD, $n = 3$).

	T_1		T_2		T_3		T_4	
	At start	At end	At start	At end	At start	At end	At start	At end
pH	8.2 ± 0.01	7.5 ± 0.2	8.6 ± 0.01	7.4 ± 0.04	8.3 ± 0.01	7.6 ± 0.03	8.4 ± 0.01	7.2 ± 0.05
${}_{\mathrm{org}}$C (g kg^{-1})	377.5 ± 0.46	296.9 ± 3.8	362.7 ± 0 .63	262.9 ± 3.2	358.6 ± o.33	290.0 ± 3.4	342.5 ± 0.33	254.2 ± 3.9
${}_{\mathrm{tot}}$N (g kg^{-1})	9.32 ± 0.07	24.5 ± 0.45	10.68 ± 0.08	33.67 ± 0.39	17.84 ± 0.09	29.66 ± 0.58	16.74 ± 0.07	35.67 ± 0.43
${}_{\mathrm{avail}}$P (g kg^{-1})	5.88 ± 0.05	19.43 ± 0.22	9.28 ± 0.07	28.85 ± 0.28	6.48 ± 0.05	18.95 ± 0.16	9.73 ± 0.07	25.42 ± 0.45
${}_{\mathrm{exch}}$K (g kg^{-1})	5.67 ± 0.05	17.58 ± 0.46	5.79 ± 0.07	20.47 ± 0.21	11.79 ± 0.08	21.43 ± 0.29	10.30 ± 0.07	19.38 ± 0.36
${}_{\mathrm{exch}}$Ca (g kg^{-1})	23.06 ± 0.11	36.42 ± 0.60	32.68 ± 0.09	51.03 ± 0.18	24.59 ± 0.08	38.86 ± 0.23	34.02 ± 0.07	51.80 ± 0.33
${}_{\mathrm{exch}}$Mg (mg kg^{-1})	285.7 ± 0.52	312.8 ± 0.85	314.8 ± 0.49	348.3 ± 1.18	305.4 ± 0.07	331.4 ± 0.49	312.7 ± 0.08	345.0 ± 1.02
${}_{\mathrm{ext}}$Fe (mg kg^{-1})	434.2 ± 0.05	480.2 ± 1.99	479.9 ± 0.16	542.7 ± 0.99	447.4 ± 0.07	490.4 ± 2.04	482.8 ± 0.08	545.2 ± 1.50
${}_{\mathrm{ext}}$Zn (mg kg^{-1})	189.1 ± 0.05	254.8 ± 3.47	253.6 ± 0.08	334.4 ± 2.37	192.5 ± 0.09	253.6 ± 2.02	260.1 ± 0.05	338.4 ± 2.61

	T_5		T_6		T_7		T_8	
pH	8.7 ± 0.01	7.6 ± 0.04	8.5 ± 0.02	7.4 ± 0.04	8.9 ± 0.02	7.5 ± 0.06	8.4 ± 0.01	7.0 ± 0.05
${}_{\mathrm{org}}$C (g kg^{-1})	352.6 ± 0.23	288.0 ± 3.9	348.4 ± 0.17	288.1 ± 3.0	348.0 ± 0.11	303.0 ± 5.07	332.7 ± 0.29	293.5 ± 2.6
${}_{\mathrm{tot}}$N (g kg^{-1})	9.82 ± 0.05	22.40 ± 0.35	13.25 ± 0.07	24.59 ± 0.37	11.78 ± 0.08	21.36 ± 0.29	16.72 ± 0.07	12.96 ± 0.17
${}_{\mathrm{avail}}$P (g kg^{-1})	9.89 ± 0.08	22.57 ± 0.33	9.69 ± 0.05	22.10 ± 0.24	12.78 ± 0.07	23.48 ± 0.35	12.96 ± 0.08	23.07 ± 0.13
${}_{\mathrm{exch}}$K (g kg^{-1})	8.41 ± 0.05	16.28 ± 0.26	10.78 ± 0.07	17.76 ± 0.23	5.83 ± 0.02	13.57 ± 0.30	8.79 ± 0.05	15.81 ± 0.23
${}_{\mathrm{exch}}$Ca (g kg^{-1})	48.11 ± 0.05	63.11 ± 0.29	49.84 ± 0.08	63.37 ± 0.37	43.13 ± 0.07	53.54 ± 0.39	43.62 ± 0.08	53.76 ± 0.34
${}_{\mathrm{exch}}$Mg (mg kg^{-1})	239.5 ± 0.06	262.4 ± 1.62	257.2 ± 0.05	279.1 ± 3.40	322.0 ± 0.08	339.7 ± 2.81	331.9 ± 0.05	348.6 ± 3.12
${}_{\mathrm{ext}}$Fe (mg kg^{-1})	378.1 ± 0.07	422.7 ± 0.94	376.7 ± 0.05	419.9 ± 1.51	526.5 ± 0.12	559.8 ± 1.43	529.2 ± 0.05	557.5 ± 7.87
${}_{\mathrm{ext}}$Zn (mg kg^{-1})	221.7 ± 0.07	283.2 ± 3.09	220.0 ± 0.07	281.8 ± 2.92	324.2 ± 0.08	358.8 ± 3.53	324.8 ± 0.05	363.4 ± 3.61

	T_9	
pH	8.2 ± 0.02	7.3 ± 0.04
${}_{\mathrm{org}}$C (g kg^{-1})	355.2 ± 0.23	322.8 ± 3.5
${}_{\mathrm{tot}}$N (g kg^{-1})	13.53 ± 0.07	21.53 ± 0.40
${}_{\mathrm{avail}}$P (g kg^{-1})	9.49 ± 0.05	17.48 ± 0.36
${}_{\mathrm{exch}}$K (g kg^{-1})	7.86 ± 0.07	14.78 ± 0.24
${}_{\mathrm{exch}}$Ca (g kg^{-1})	33.11 ± 0.05	41.06 ± 0.40
${}_{\mathrm{exch}}$Mg (mg kg^{-1})	312.7 ± 0.06	324.10 ± 1.94
${}_{\mathrm{ext}}$Fe (mg kg^{-1})	475.1 ± 2.31	513.0 ± 2.18
${}_{\mathrm{ext}}$Zn (mg kg^{-1})	249.5 ± 0.03	274.6 ± 11.3

the rapid colonization of major decomposer (bacteria and fungi) in decomposing waste feed stocks.

Organic C level was lower in vermicompost than initial feed mixtures (Table 5), indicating significant reduction in organic C contents. The maximum organic C loss, 27.5%, was in T_2 vermibed, while vermicomposted material from T_9 exhibited the minimum 9.12% organic C loss during the vermicomposting process (Table 4). The organic matter mineralization rate depends upon the proportion of industrial sludge and quality of amendment material. Since IS was in equal proportion in T_1 *vs* T_3 and T_2 *vs* T_4 but C loss was more prominent in bedding, those contained cow dung as amendment material with IS. This suggests the role of cow dung in microbial decomposition of wastes. Cow dung contains a number of fungal strains and greater population of other microbes, such as bacteria, protozoa, nematodes, fungi, actinomycets, which play an important role in organic matter decomposition by providing extra-cellular enzymes in vermibeds. In such beddings, the microbial respiration may lead to rapid C loss through CO_2 production. Also, digestion of carbohydrates and other polysaccharides from the substrates by inoculated earthworms may cause carbon reduction during the decomposition of organic waste. Some part may be converted to worm biomass through the assimilation process, which consequently reduces the carbon budget of vermicomposted wastes (Suthar, 2009a). Biological mutuality between earthworms and associated microbes is primarily responsible for C loss from the organic wastes. Organic C reduction in this study was in the order: $T_2 > T_4 > T_1 > T_3 > T_5 > T_6 > T_7 > T_8$. Observed difference for C loss could be due to amendment material type and microbial properties of feed stocks.

Total N was significantly higher in the end products than initial substrate material (Table 4). The N content in vermicomposted material was in the range of 12.96 g kg^{-1} (T_9) to 35.67 g kg^{-1} (T_4). During vermicomposting there was significant increase in N content and T_2 vermibed showed the maximum N increase

Table 5
C:N and C:P ratios of ready vermicompost (mean ± CD, $n = 3$) and its agronomic potential.

	C:N ratio		C:P ratio		Agronomic potential of vermicompost	
	Initial	Final	Initial	Final	Acceptable (C:N ratios > 20)	Preferable (C:N ratios > 15)
T_1	31.8 ± 0.41	12.1 ± 0.39 e	50.5 ± 0.63	15.3 ± 0.36 c	✓	
T_2	26.6 ± 0.35	7.80 ± 0.18 b	28.3 ± 0.19	9.11 ± 0.20 a		✓
T_3	16.3 ± 0.14	9.78 ± 0.10 c	44.8 ± 0.59	15.3 ± 0.16 c	✓	
T_4	15.2 ± 0.27	7.12 ± 0.20 a	26.1 ± 0.33	10.0 ± 0.33 a		✓
T_5	29.3 ± 0.40	12.9 ± 0.40 f	29.1 ± 0.52	12.8 ± 0.38 b		✓
T_6	21.8 ± 0.19	11.7 ± 0.07 de	29.7 ± 0.73	13.0 ± 0.27 b		✓
T_7	25.7 ± 0.55	14.2 ± 0.08 a	23.7 ± 0.44	12.9 ± 0.39 b		✓
T_8	18.0 ± 0.18	11.1 ± 0.28 d	22.6 ± 0.24	12.7 ± 0.09 b		✓
T_9	23.9 ± 1.03	15.0 ± 0.12 h	34.0 ± 0.50	18.5 ± 0.57 d	✓	

Mean value followed by different letters is statistically different (ANOVA; Tukey's *t*-test, $P < 0.05$).

(215.2% more than initial level, while T_9 vermibed exhibited the minimum increase (59.3%) in N level of vermicomposted material (Table 4). The initial level of N is important in N enrichment process of feed stock but quality as well as proportion of industrial sludge in vermibed may also important for mineralization process. Overall N increase in vermibeds was in the order: $T_2 > T_1 > T_4 > T_5 > T_6 > T_9 > T_7 > T_8$. The N mineralization rate was directly related to the earthworm mediated N enhancement. Earthworm enhances the N level of vermibed by adding excreta and other secretions. Also, mucus a polysaccharide is secreted by earthworm to moisten the body surface also important to enrich vermibeds with N fixers. Earthworms also alter the microclimatic conditions of vermibeds, which consequently promotes microbial populations responsible for N enrichment. Better microbial population in vermicomposting system (Suthar, 2008b, 2009a, 2010a) may be an advantage over traditional composting system. The type of amendment material appeared as an important factor for N enrichment of vermibeds. Beddings containing biogas slurry showed considerable N enrichments. It is suggested that digested biogas slurry contains several metabolites in easy forms which attracts the microbial colonization in vermibeds. Suthar (2009b) demonstrated significant waste mineralization rate in vegetable waste solids after mixing with biogas slurry. N fixers are important in N enrichment of vermicomposted materials. Study by Kavian and Ghatneker (1991) suggested the enhanced population of N fixers (Azotobacter and Rhizobium) in vermibeds, while working on vermicomposting of paper mill sludge. Earlier studies support the role of earthworm in N enrichment of ready materials at the end (Taylor et al., 2003; Oyedele et al., 2005; Suthar and Singh, 2008b; Suthar, 2010a).

Vermicomposted material at the end showed higher concentrations of available P in all vermibeds than initial levels (Table 4). The maximum and minimum level of available P was 28.9 ± 0.28 g kg^{-1} (T_2) and 17.5 ± 0.36 g kg^{-1} (T_9), respectively in ready vermicomposts. The P enhancement was the highest in T_1 (230.4%) followed by T_2 (210.8%), T_3 (192.5%), T_4 (161.2%), T_5 (128.2%), T_6 (128.0%), T_9 (84.2%), T_7 (83.7%) and T_8 (78.0%) than initial level. The considerable level of available P (plant available form of phosphorus) indicates the potential of ready vermicompost as soil amendment material. The level of P in vermicomposted material may reflects the amount of organic forms of phosphorus in waste mixture, but its mineralization rate is directly affected by nature of amendment material and activities of P mineralizing microflora in decomposing wastes. Few earlier studies indicate the highest plant available forms in vermicomposted wastes mainly due to activities of P-solubilizing bacteria and enzymatic activities of earthworm gut. The release of P in available forms is performed partly by earthworm gut phosphatases, and further release of P might be attributed to the P-solubilizing microorganisms present in worm casts. The earthworm gut produces a considerable amount of alkaline phosphatases; an essential enzyme involved in biogeochemical cycle of P (Le Bayon and Binet, 2006). Also, vermibeds that contained cow dung as amendment material showed the highest P mineralization rate, possibly due to direct role of cow dung microflora in P enhancement processes. The mineralization rate was low in bedding containing higher ratios of industrial sludge in worm feed. It was possibly due to retarding impact of industrial sludge, on associated microflora, at higher concentrations. Vermicomposted waste feed stocks were rich in exchangeable K contents. Exchangeable K shows the ranges of 21.4 ± 0.29 g kg^{-1} (T_3) to 13.8 ± 0.30 g kg^{-1} (T_7) in end material. The maximum increase was in 253.3% (T_2) followed by T_1 (210.2%), T_7 (132.9%), T_5 (93.6%), T_4 (88.1%), T_9 (87.9%), T_3 (81.8%), T_8 (79.8%) and T_6 (64.7%). Suthar (2008b) concluded that when organic waste passes through the gut of worm some quantity of organic minerals are then converted into more available forms (i.e. exchangeable forms). Vermicomposting plays an important role in microbial-mediated nutrient mineralization in wastes. The results of this study agree with previous reports that the vermicomposting process accelerates the microbial-mediate mineralization in waste and subsequently enriches the end product with more available forms of nutrients of agronomic importance.

Exchangeable Ca was higher in final product than initial levels in all feed mixtures (Table 4). Vermicomposted waste mixtures have exchangeable Ca in the range of 63.4 ± 0.37 g kg^{-1} (T_6) to 41.1 ± 0.40 g kg^{-1} (T_9). But, the maximum increase (compared to initial level) 58.0% was in T_3 followed by 57.9% (T_1), 56.1% (T_2), 52.2% (T_4), 31.2 (T_5), 27.1 (T_6), 24.1 (T_7), 24.0% (T_9) and 23.0% (T_8). Calcium metabolism in earthworm is primarily associated with gut secreted enzymes and further digestion in earthworm deposited casts by fugal hyphae and bacterial communities. However, in few endogeic and anecic worms the calcium gland is considered to play an important role in calcium secretion but in *E. fetida* such evidences is not clear. But here release of organically bound calcium in waste feed stocks is converted into free or plant available forms which makes vermicomposting techniques superiors than traditional composting method. The richness of waste feed stocks to be used for vermicomposting is also important and it directly contributes to calcium level in ready vermicompost. Nevertheless, further detailed studies are required to trace the Ca metabolism during vermicomposting process.

Trace nutrients, i.e. exchangeable Mg, extractable Fe and extractable Zn, showed drastic changes at the end of vermicomposting process. Exchangeable Mg contents in vermicomposted industrial mixtures were in the ranges of 348.3 ± 1.12 mg kg^{-1} (T_2) to 262.4 ± 1.62 mg kg^{-1} (T_5). The maximum increase in Mg was in $T_2 > T_4 > T_5 > T_6 > T_1 > T_7 > T_8 > T_9$ (Table 4). Although, the changes in Mg contents were not prominent (3.64–10.6% increase than initial level), but such plant available form increases the agronomic potential of the ready material. No direct contribution of earthworm in Mg metabolism is known, therefore it is hypothesized that fungal and micro-algal hyphae, which easily colonizes on freshly deposited worm casts, contributes to trace level of Mg in ready vermicompost. Iron and zinc are important micronutrients and play an important role in plant physiology. During vermicomposting earthworm caused significant increase in the ranges of 5.37% (T_8) to 13.1% (T_2) for Fe and 10.1% (T_9) to 34.8% (T_1) for Zn. The maximum level of extractable Fe, i.e. 559.8 ± 1.43 mg kg^{-1} was in T_7 followed by T_8, T_4, T_2, T_9, T_3, T_1 and T_9 (Table 4). Plant available Zn showed the maximum level in vermicompost obtained from 363.1 ± 11.3 mg kg^{-1} (T_9), while T_4 exhibited the minimum level (253.6 ± 2.02 mg kg^{-1} of it. Extractable Zn in ready vermicompost was in the order: T_8 (363.1 ± 3.6 mg kg^{-1}) $> T_7 > T_4 > T_2 > T_5 > T_6 > T_9 > T_1 > T_3$ (Table 4). The release of plant available forms of trace elements in vermicompost could be due to mineralization of partially digested worm faecal by detritus communities, such as bacteria and fungi. In general, earthworm fragments and modifies the physical structure of ingested wastes through muscular actions of foregut and consequently increases the surface area for microbial action (Suthar, 2008a, 2010a). Such biological coordination results in high level of extractable or available trace elements in ready vermicompost. Kizilkaya (2004) stated that earthworm directly affects the availability of Zn in ready worm cats due to mineralization during passing of substrate through worm's gut.

C:N was lower in all vermicomposted waste mixtures, indicating a significant N increase and organic C decrease. C:N ratios of initial feed mixtures decreased from its range (15.2–31.8) to lower range: 7.12 ± 0.20 (T_4)–15.0 ± 0.12 (T_9) (Table 5).

C:N ration in final product was in the order: $T_4 < T_2 < T_3 < T_6 < T_8 < T_1 < T_5 < T_7 < T_9$ (Table 4). The maximum reduction in C:N ratio was in T_2 (77.0%) followed by T_1 (70.1%), T_4

Table 6
Earthworm growth and biomass productions during vermicomposting process (mean ± CD, $n = 3$).

Vermibeds	Mean initial live weight of individual earthworm (mg)	Maximum individual live weight achieved (mg)	Maximum individual biomass achieved in (days)	Net individual live weight (mg) at the end (mg)	Maximum growth rate (mg wt. worm^{-1} day^{-1})
T_1	259.0 ± 0.99	684.5 ± 5.86 e	75	605.4 ± 6.09 e	5.67 ± 0.07 e
T_2	260.2 ± 0.66	734.8 ± 8.0 df	75	721.7 ± 3.20 g	6.33 ± 0.08 f
T_3	264.7 ± 0.41	664.0 ± 5.87 d	75	605.2 ± 4.79 e	5.32 ± 0.08 d
T_4	255.2 ± 0.59	718.9 ± 9.30 f	90	701.5 ± 8.05 f	5.15 ± 0.05 d
T_5	265.4 ± 0.70	501.1 ± 5.76 c	90	486.9 ± 3.10 d	2.62 ± 0.07 c
T_6	254.2 ± 0.22	442.4 ± 4.99 b	75	429.8 ± 3.05 c	2.51 ± 0.08 c
T_7	267.3 ± 0.74	428.7 ± 6.85 b	75	406.2 ± 5.91 b	2.15 ± 0.07 b
T_8	257.7 ± 0.35	405.4 ± 7.21 a	75	388.5 ± 1.98 a	1.97 ± 0.05 b
T_9	265.8 ± 0.50	396.2 ± 6.89 a	90	383.5 ± 2.83 a	1.45 ± 0.07 a

Mean value followed by different letters is statistically different (ANOVA; Tukey's *t*-test, $P < 0.05$).

(65.2%), T_5 (64.2%), T_6 (55.4%), T_7 (52.0%), T_3 (51.4%), T_8 (48.8%), and T_9 (42.9%). In general, C:N ratio of vermicompost reflects the waste mineralization rate and N enrichment process of ready material (Suthar and Singh, 2008b). Suthar (2009c) suggested that in vermicomposting sub-system, the loss of carbon as carbon dioxide due to respiratory activities of earthworms and associated microflora, and simultaneously adding of nitrogen in substrate material by inoculated earthworms (through production of mucus, enzymes and nitrogenous excrements) lowers the C:N ratio of waste mixtures. C:P ratio was also lower in vermicomposted materials than initial ratios. It reduced from range of 22.6–505 to 9.11 (T_2)–18.5 (T_9), at the end of process. The lower C:P ratio clearly indicates the P mineralization process and overall quality of vermicompost as potential plant growth media.

3.2. *Agronomic potential of vermicomposted industrial sludge*

The parameter traditionally considered determining the degree of maturity of compost and to define its agronomic quality is the C:N ratio. According to Morais and Queda (2003) a C:N ratio below 20 is indicative of acceptable maturity, while a ratio of 15 or lower being preferable for agronomic use of composts. Out of the nine ready vermicompost only three were acceptable limit i.e. <20, while remaining six, i.e. T_4–T_8 showed the C:N ratio within preferable range (<15). Apart to this the range of soil macro as well as trace elements in processed manure is of primary importance (Suthar, 2009d). NP and K are the basic nutrients for plant growth and its level in any manure or plant growth media determines the potential of ready product. As data suggested that bedding with greater earthworm decomposition rate showed a considerable range of N (up to 35.7 g kg^{-1}, dry weight basis). Approximately 89% vermicomposts showed total N more than 20 g kg^{-1}. The greater level of plant available forms of P and K in ready vermicompost also increases the agronomic potential of vermicompost. The most important fact is the presence of trace elements at higher concentrations in vermicompost, which are rarely available in any other natural compost. Ca, Zn and Fe are the important plant metabolite and their deficiencies cause a several physiological disorders and disease in commercial plants. In modern farming system the nutrient supply primarily focused on supply of N, P and K through synthetic fertilizers and no attempt, in general, is made to supply other important trace micronutrients in field crops. In this context the vermicompost may be a cost effective option to supply essential micronutrients in soils, other than NPK. In traditional composting system the thermal stage destroys the populations of beneficial microorganisms. But vermicomposting involves non-thermal stages and consequently retains a higher populations of beneficial microorganisms such actinomycetes, N fixers, protozoans, bacteria and algae. These microbes not only enhance the nutrient mineralization in vermicompost but at the same time also maintain the biological quality of arable lands, after its application in field. The associated microflora in vermicompost not only mineralize complex substances into plant available nutrients but can also synthesize a whole series of biologically active substances including plant growth regulators. Except to some essential micronutrients vermicompost contains of plant hormones such as auxins, gibberellins and cytokinins (Krishnamoorthy and Vajrabhiah, 1986; Tomati et al., 1988). The plant growth-promoting compounds elaborated by earthworm promote a significant increase in plant growth and N uptake. During vermicomposting, earthworm activity accelerates the humification of organic matter, and their influence in increasing microbial populations enhances the presence of auxins and gibberellin-like substances as well as humic acids (Muscolo et al., 1999). Vermicompost promotes favorable biochemical environment for plant growth by influencing enzyme and microbial profile in the rhizosphere. The level of some important soil enzymes, e.g. dehydrogenases, urease, acid phosphatase and alkaline phosphatases was significantly greater in plots receiving vermicompost than other manures. Urease plays a key role in the N-cycle since it hydrolyses urea, yielding ammonia and CO_2, and is important in regulating the efficiency of urea as a nitrogen fertilizer. Results thus clearly suggest that vermicompost from industrial sludge may be cost effective and ecologically safe option for sustainable soil fertility in degraded lands.

On the other hand, the maintenance of soil organic matter for sustained soil productivity requires the input of organic manures. Currently there has been more emphasis on use of organic manure all over the world. The use of organic wastes in the application to farmlands has increased over the years, since the use contributes to the disposal of wastes and enhances the preservation of the environment. The high organic matter content in the compost product also preserves soil fertility. Among various sources of organic matter, vermicomposts have been recognized as having considerable potential as soil amendments. So the vermicomposting technique has been adopted widely for organic farming.

3.3. *Biomass, cocoon production and fecundity by E. fetida in different vermibeds*

Earthworm productivity is an important indicator of vermicomposting process. Statistically, there was significant difference among vermibeds for growth parameters: the maximum individual live weight (ANOVA: $F = 1329.7$, $P < 0.05$), total individual biomass gain (ANOVA: $F = 1402$, $P < 0.05$), end biomass (ANOVA: $F = 2449.9$, $P < 0.05$ and maximum individual growth rate (mg wt. worm^{-1} day^{-1}) (ANOVA: $F = 1534.1$, $P < 0.05$). The maximum individual live weigh was 734.8 ± 8.0 mg in T_2,

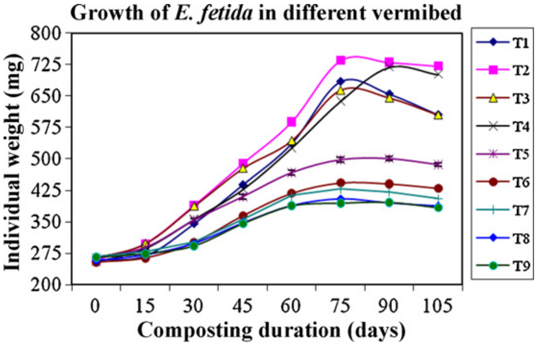

Fig. 1. The growth pattern of *E. fetida* in different treatments.

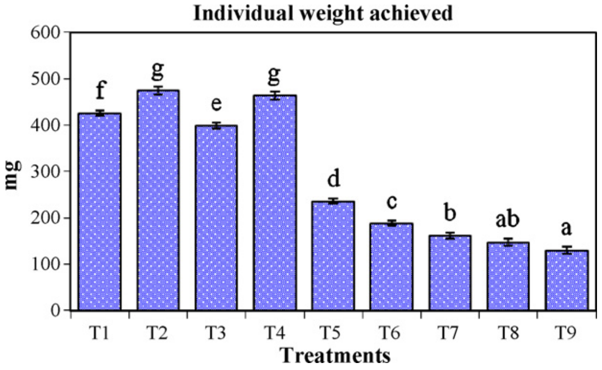

Fig. 2. Individual weight achieved by *E. fetida* in different vermibeds during vermicomposting. The significant difference ($P < 0.05$) is indicated by different letters.

while T_9 exhibit the minimum live weigh (396.2 ± 6.89 mg). The maximum live weight in *E. fetida* was in the order: $T_2 > T_4 > T_1 > T_3 > T_5 > T_6 > T_7 > T_8 > T_9$ (Table 6).

The observed difference among various treatments for earthworm weight achieve may be due to quality of feed stock which directly affects the feed palatability and assimilation rates (Suthar, 2007b). *E. fetida* showed better results in bedding that contained cow dung and biogas slurry up to 20–40%. Cow dung and biogas digester slurry is always ideal feed for earthworms (Kale et al., 1982; Suthar, 2009b) due to a good level of easily metabolizable organic matter, non-assimilated carbohydrates, microbial population and even low concentration of growth-retarding substances. The growth patterns of *E. fetida* in different treatments is illustrated in Fig. 1.

It clear from it that the maximum weigh achieved in earthworm followed a trend of partially stabilization of decrement up to last observation. Therefore, individual live weight was lower in all treatments than the maximum weight achieved (Table 6). In T_1, T_2, T_3, T_6, T_7 and T_8 *E. fetida* showed the maximum weight achieved after 75 days, while in T_4, T_5 and T_9 the maximum weight was after 105 days of experimentations. In earlier studies the loss in earthworm individual live weight is also reported (Suthar, 2009a). Possibly, food shortage in the later period of the vermicomposting may cause weight loss in inoculated earthworms. The weight achieved by individual earthworm was the maximum in T_2 (474.6 ± 7.35 mg) followed by T_4 (463.7 ± 9.41 mg), T_1 (425.6 ± 5.0 mg), T_3 (399.3 ± 5.46 mg), T_5 (235.7 ± 6.36 mg), T_6 (188.1 ± 5.19 mg), T_7 (161.5 ± 6.63 mg), T_8 (147.7 ± 6.90 mg) and T_9 (130.4 ± 7.27 mg) (Fig. 2).

The maximum growth rate ranged 6.33 ± 0.08 mg wt. $\text{worm}^{-1}\,\text{day}^{-1}$ (T_2) to 1.45 ± 0.07 mg wt. $\text{worm}^{-1}\,\text{day}^{-1}$ (T_9). The maximum growth rate was not statistically significant between T_5 and T_6 (ANOVA/Tukey's *t*-test; $P = 0.220$) as well as T_7 and T_8 (ANOVA/Tukey's *t*-test; $P = 0.785$). In this study, the difference in growth rate among different feed mixtures seems to be closely related to feed quality. The excellent growth rate in cow dung and biogas containing vermibeds could be due to its' palatability and more acceptability as food by worms. The slow growth in vermibeds with higher proportions of industrial sludge was possibly due to the presence of growth-retarding substances in it. Few earlier studies also indicate the slow growth rate in beddings containing greater concentration of industrial solid waste of sludges (Suthar and Singh, 2008a; Singh et al., 2009; Khwairakpam and Bhargava, 2009).

E. fetida exhibited excellent reproduction during vermicomposting process. But statistically there was significant among different treatments for cocoon numbers (ANOVA: $F = 45.61$, $P < 0.05$), reproduction rate (cocoon worm^{-1}) (ANOVA: $F = 27.99$, $P < 0.05$) and natality rate (hatchlings/parental worm) (ANOVA: $F = 259.82$, $P < 0.05$). The maximum cocoon numbers were in T_2 (129.3 ± 8.50), while T_9 showed the lowest cocoon numbers 35.7 ± 4.56 (Table 7). Total cocoon production was in order: $T_2 > T_1 > T_3 > T_4 > T_7 > T_8 > T_6 > T_5 > T_9$. But, difference among T_5, T_6 and T_9 vermibeds was not statistically significant (ANOVA/Tukey's *t*-test; $P = 0.131$). The reproduction rate (cocoon worm^{-1}) of *E. fetida* was highest in T_2 (5.47 ± 0.30) followed by T_1 (4.92 ± 0.50), T_3 (4.50 ± 0.28), T_4 (4.30 ± 0.22), T_7 (4.0 ± 0.56), T_8 (3.71 ± 0.31), T_5 (2.76 ± 0.51), T_6 (2.31 ± 0.21), T_9 (2.0 ± 0.43) (Fig. 3).

The results clearly suggested that reproduction pattern in composting earthworm was directly related to the quality of feedstock, as used for vermicomposting trial. The important difference between the rates of cocoon production in the two organic wastes must be related to the quality of the wastes. The ratio of bulking materials was also important in reproduction performances of earthworms in vermibeds. A better reproduction rate in bedding containing a lower proportion of IS suggests its retarding impact at higher concentration upon earthworm reproduction rates in vermibeds. However, cow dung and biogas slurry contains easy digestible food components. Similarly great population of microbes

Table 7
Cocoon numbers, total hatchlings and natality rate in *E. fetida* for different vermibeds (mean ± SD, $n = 3$).

Vermibeds	Total cocoons (fresh + residual) obtained at the end	Total hatchlings (adult and sub-adult) obtained at the end	Natality rate (new worms/parent worm)
T_1	115.0 ± 17.0 ef	175.3 ± 5.03 f	7.01 ± 0.20 f
T_2	129.3 ± 8.50 f	195.3 ± 5.69 g	7.81 ± 0.23 g
T_3	101.7 ± 4.72 e	154.0 ± 6.56 e	6.16 ± 0.26 e
T_4	97.3 ± 8.75 de	121.0 ± 3.0 d	4.84 ± 0.12 d
T_5	55.3 ± 5.03 abc	64.65 ± 6.11 bc	2.59 ± 0.24 bc
T_6	51.7 ± 4.51 ab	51.0 ± 10.5 ab	2.04 ± 0.42 ab
T_7	75.7 ± 4.51 cd	71.3 ± 6.03 c	2.85 ± 0.24 c
T_8	70.3 ± 3.51 bc	78.3 ± 4.73 c	3.13 ± 0.19 c
T_9	35.7 ± 4.51 a	43.3 ± 4.51 a	1.73 ± 0.18 a

Mean value followed by different letters is statistically different (ANOVA; Tukey's *t*-test, $P < 0.05$).

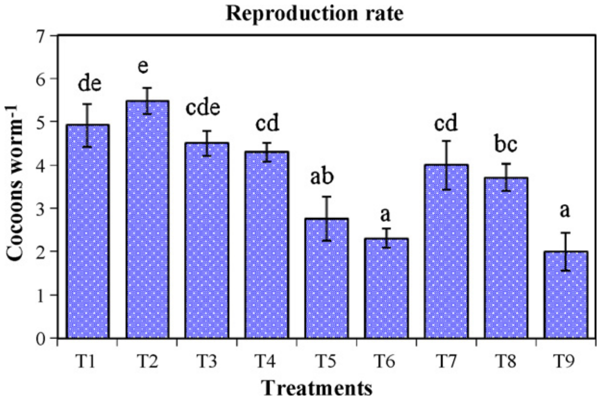

Fig. 3. Reproduction rate of *E. fetida* in different vermibeds during experimentations. The significant difference ($P < 0.05$) is indicated by different letters.

and microfauna (protozoans, and nematodes) in these bulky materials also attracts the earthworm and consequently earthworm feeding rate increases. Excellent diet may enhance the earthworm growth and reproduction performances and observed results in first four vermibeds, i.e. T_1–T_4, support the hypothesis. Suthar (2010b) suggested that livestock excreta are always favorable feed for epigeic earthworms and majority of vermiculture experiments are performed using cattle dung as substrate.

The adult and sub-adult population at the end of experiment varied significantly among vermibeds (ANOVA: $F = 259.8$, $P < 0.05$). But difference between: T_5 and T_6 (ANOVA/Tukey's *t*-test; $P = 0.203$) and T_6 and T_9 (ANOVA/Tukey's *t*-test; $P = 0.826$) was not statistically significant. The maximum population of *E. fetida* was in T_2 vermibed (195.3 ± 5.69), while T_9 showed the minimum population of earthworm, at the end. It is clear from Table 7 that earthworm showed better population growth in first four treatments: T_1–T_4, possibly due to favorable conditions (easy digestible and palatable food, microclimate, minimum chemical stress etc.). Natality rate in *E. fetida* was also calculated and it was statistically different among different treatments (ANOVA: $F = 259.8$, $P < 0.05$). Natality rate reflects the overall productivity of earthworm parental population in vermibeds. Apart to cocoon production rate the hatchling success and incubation period are also important here (Suthar, 2009d). The maximum and the minimum natality rate was 7.01 ± 0.20 (worms/parental worm) in T_1 and 1.73 ± 0.18 (worms/parental worm) in T_9, respectively. On average natality was excellent in first four vermibeds (T_1–T_4) that showed about 6.46 new worms/parental worm. It indicates that industrial sludges up to 20–40% in earthworm feed can support the earthworm population increases, while at higher contents it may slow down the overall reproduction potential of inoculated earthworms. But variation among T_5, T_7 and T_8 and also between T_5 and T_6 were not statistically significant (ANOVA/Tukey's *t*-test; $P = 0.203$, for both). A study by Suthar and Ram (2008) clearly demonstrated the impact of feed quality on cocoon production, hatchling success and hatchlings emergence from each cocoon in epigeic earthworms: *Eudrilus eugeniae*, *Perionyx excavatus* and *P. sansibaricus*. It is suggested here that earthworm natality is directly related to the quality of food and other microclimatic conditions in vermibeds. Moreover, numbers of viable cocoons are also important, which directly related to the diet of earthworm during reproduction stage (Suthar and Ram, 2008). Natality rate may be an important indicator of earthworm productivity in any vermicomposting systems, indicating suitability of waste feed stock for earthworm culture.

The mortality during initial critical period ranged 5.33–28% in different vermibeds (Fig. 4).

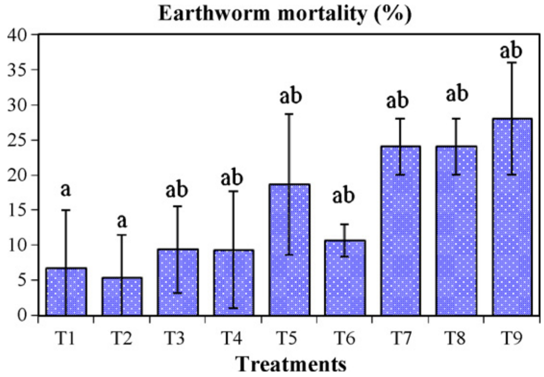

Fig. 4. Earthworm population mortality (%) during experimentations. The significant difference ($P < 0.05$) is indicated by different letters.

Although statistically total earthworm mortality showed significant variations (ANOVA: $F = 4.78$, $P = 0.003$), the difference among T_3–T_9 was not of significance (ANOVA; Tukey's test: $P = 0.066$). In general, the survival of earthworms in waste decomposing subsystem mainly depends on physical and initial chemical profile of the feedstuff (Suthar, 2008a). The changed chemical condition in vermibeds could lead to rapid mortality in composting worms. The greater earthworm mortality in beddings with higher proportion of industrial sludge indicates the non-suitability of such combinations of sludge with amendment materials. The production of toxic gases e.g. ammonia, nitrogen oxide, carbon dioxide etc. in vermireactors could affect the earthworm survival in bedding substrates. The food consumption rate in earthworms during the initial critical period (period of acclimatization of earthworms in waste system) also determines the survival rate of earthworms in vermibed. Nevertheless, detailed study is needed to support the statement.

4. Conclusions

Industrial sludges need close attention for their safe disposal and meaningful utilizations. Due to excellent level of soil nutrient, these sludges may be a potential resource for compost preparation, and vermitechnology seems an appropriate tool for this option. The industrial sludge, up to 20–40% in the vermibed, may be a suitable substrate for vermicomposting after mixing in an appropriate amendment material (cow dung or biogas slurry). Earthworms convert the industrial sludge amended with bulky material into fine and odor-free material containing considerable amount of N, P, K, Ca and trace elements (Mg, Fe and Zn). C:N ratio of ready product was up to its' acceptable limit, at the end. The industrial sludge mixture also supported the growth and reproduction in *E. fetida*, during vermicomposting process. Industrial sludge showed better results of mineralization rate and earthworm productivity at low concentrations only. The results suggested that vermicomposting can be a potential ecological engineering to convert noxious industrial wastes into value-added materials for sustainable farming.

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