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Geotechnical Properties of Vermicomposts of Press Mud using *Eisenia fetida*, *Eudrilus eugeniae* and *Megascolex megascolex*

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ABSTRACT

Studies were carried out to evaluate the geotechnical properties of vemicomposts (VCs) such as porosity, void ratio, density, air content, water holding capacity and particle size distribution (PSD) prepared from sugar industrial waste press mud (PM) using surface feeders *Eisenia fetida*, *Eudrilus eugeniae* and the deep burrower *Megascolex megascolex.* A comparison of the geotechnical properties of 40-day samples of VCs from field trials by a core cutter showed that the VC using *M. megascolex* was superior to *E. eugeniae* and *E. fetida* VCs in terms of water and air content and percentage void. The PSD of PM was higher than industrial soil, while *M. megascolex* VC > *E. fetida* VC > *E. eugeniae* VC ($P < 0.05$). This depicts an inverse bioconversion or grinding capacity of the three earthworms: *E. eugeniae* > *E. fetida* > *M. megascolex*. This study clearly indicates that the indigenous deep burrower *M. megascolex* can be used in the vermicomposting of PM while also enhancing the geotechnical properties, soil aggregation and water holding capacity of a VC.

Keywords: air content, particle size, percentage air voids, porosity, soil aggregation

INTRODUCTION

There are about 566 sugar industries in India generating a huge quantity of solid wastes: 43.13 mt y^{-1} baggasse and 5.5 mt y^{-1} press mud (PM) (NWMC, 1992). Selviraj *et al.* (2005) reported that 9 mt y^{-1} is organic in nature. These wastes, although rich in organic matter, are presently being disposed on land creating environmental problems (Munnoli 2007). PM of the Sanjeevani Sugar Factory, Dayanand Nagar, Goa, India, was selected for field experimentation to assess the amenability of PM to vermiprocessing, and to ascertain the geotechnical properties of the vermicompost (VC) derived from it.

Vermitechnology (VT) efficiently utilizes the synergistic work of earthworms and microorganisms in the bioconversion of organic wastes generated by agro-based and food processing industries (Singh 1997; Munnoli 2007; Munnoli and Bhosle 2008; Suhtar and Singh 2008; Sangawan *et al.* 2008). Earthworms consume organic wastes (OWs) and grind them in their gizzard, which results in an increase of specific surface area of OW, which helps to increase microbial enzyme activity allowing biowastes to be completely bioconverted (Edwards and Bater 1992). VT is being successfully utilized in the environmental management of slud-

Table 1 Significance of geotechnical properties in vermitechnology.

Parameter	Indicator	Reference
Specific gravity (G)	Comparison with other materials	Munnoli 2007
Water content (w)	Vermicast as a micro dam	Munnoli and Bhosle 2008a, 2008b Paradelo *et al*. 2009
Voids ratio (e)	Vermicomposting process; removal of odor of substrates Measure to demonstrate the aerobic nature of VC process	Munnoli 2007
Porosity (n)	Earthworm burrowing activity and microbial activity free capillary water flow through soils	Munnoli 1998; Singh and Dwivedi 2004; Munnoli 2007; Bottinelli *et al*. 2010
Bulk density ($\surd$)	Amorphous nature, light weight, volume to be handled; Important parameter for other GT properties Design parameter for VC systems	Munnoli 2007 Singh *et al*. 2003 Ruehlmann and Korschens 2009
Dry density ($\surd_d$)	Amorphous nature and water holding capacity	Munnoli 2007
Saturated density ($\surd_{sat}$)	>1 meaning moisture capacity above 100%	Punmia 2001
Degree of saturation (S_r)	Extent of moisture	Punmia 2001
Air content (a_c)	Air circulation and survival of earthworms and aerobic microorganisms	Munnnoli 2007
% Air voids (n_a)	Microbes and plants require an adequate level of oxygen in soil for their growth and activity; ensures sufficient availability of air surrounding the earthworm; prevents CO_2 toxicity	Munnoli 2007 Biswas and Mukherjee 1994
Particle size distribution	Gives comparison of changes in particle sizes and extent of aggregation, grinding/bioconversion capabilities of earthworms and also role of microbes	Munnoli1998; Munnoli *et al*. 2002; Munnoli 2007; Munnoli and Bhosle 2009; Abbasi *et al*. 2009; Paradelo *et al*. 2009; Bottinelli *et al*. 2010; Munnoli *et al*. 2010

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ges from paper mill and dairy industries using *Eisenia andrei* (Elvira 2006), agro-based industrial OW from tomato skin seed using *Pheritima elongata* (Singh 1997), potato peel OW using *P. elongata*, *Eisenia fetida* and *Eudrilus eugeniae* (Munnoli 2000), or treatment of a wide range of OWs (kitchen waste, agro residues, institutional and industrial wastes, including textile industry sludge and fibers) using *E. fetida* (Garg 2006). The species *E. fetida*, *E. eugeniae*, *Lampito mauritti*, *Amynths diffringes*, and the deep burrowers *P. elongata* and *Lumbricus terrestris*, *Lumbricus rubellus*, *Megascolex megascolex* and *Perionyx excavatus* play an important role in OW management (Munnoli and Bhosle 2008; Suthar and Singh 2008; Sangawan *et al.* 2008). Soil aggregation and geotechnical (GT) properties play an important role in VT (**Table 1**) (Munnoli 2002, 2007) in the retention and movement of water within a VC, and, together with its air content, provide drier conditions for plant growth (Butt *et al.* 2005). Bhawalkar and Bhawalkar (1992) reported the use of VT for treatment of sugarcane PM using the deep burrower *P. elongata*. Jambhekar (1992) recycled PM derived from the sugar industry in Maharashtra, India and assessed the ability of *E. fetida*, *E. eugeniae* and *Prionyx arboricola* to biodegrade it. These earthworms could be efficiently used for producing humus with the help of some industrial solid and agricultural wastes. Hedge (1995) investigated the suitability of different crop residues together with sugar industry wastes like PM and bagasse for treatment with *E. eugeniae.* Giraddi and Tippannavar (2000) reported the complete bioconversion of PM within 85 days with *E. eugeniae* whereas in earlier studies, Singh (1997) reported bioconversion within 35-40 days using *P. elongata*.

Therefore, in the present study an attempt has been made to recycle PM in field trials using three different species, the deep burrower *M. megascolex*, and two surface feeders *E. fetida* and *E. eugeniae*. The GT properties of the resulting VCs were evaluated. The study will be of importance in choosing a VC based on its GT and particle size distribution (PSD) for application on various types of degraded soils to improve soil fertility from the perspective of water holding capacity and soil aggregation and in reclaiming mining waste lands.

MATERIALS AND METHODS

Soil samples

Soil and fresh PM samples were collected from a vermiprocessing plant site of the Sanjeevani Sugar Factory, Dayananad Nagar, Goa, India. The PM was very good organic substrate available as a waste and was characterized at the source for GT properties (**Table 2**) and PSD of PM and soil (**Table 5**).

Earthworm species

E. fetida and *E. eugeniae* were obtained from the Institute of Natural Organic Agriculture (INORA), Pune. *M. megascolex* was collected from a local cashew plantation farm at Verna, Goa, India.

Vermi-beds

For *M. megascolex*, vermi-beds were prepared in a 1 m × 1 m × 0.6 m (w × l × h) tank. A 2.5 cm thick layer of soil + cow dung (CD) (1: 3) about 7-days old (i.e. an easily biodegradable substrate) and having a nearly neutral pH was spread evenly in the tank. 100 earthworms per tank were introduced evenly at the centre and corners. A 5-cm thick layer of CD was then applied. The earthworms developed within 3-4 weeks and the beds were used for experiments.

For *E. fetida* and *E. eugeniae* a 5-cm thick layer of bedding material (partially dried grass) was laid at the bottom of beds (same dimension as the *M. megascolex* tank) above which a 5-cm thick layer of CD (7-days old) was spread evenly. 100 worms each of *E. fetida* and *E. eugeniae* were introduced onto separate beds. The earthworms developed within 2-3 weeks and the beds were used for further experiments.

The beds were covered with paddy, a wire mesh and a jute bag above each tank to minimize evaporation. Relative humidity (RH) was maintained at 60-70%.

Vermi-beds were further uniformly covered with a 5-cm thick layer of PM. 70% RH was maintained by sprinkling water regularly.

Vermicompost samples

The VC samples were obtained from vermi-beds after 40 days as the bioconversion time required for *E. fetida*, *E. eugeniae* and *M. megascolex* was 40-45, 40 and 35-40 days, respectively based on juvenile predominance and the number of hand-sorted earthworms.

Analysis of samples

1. Water content

Water content was determined by oven drying. A known weight (W_1) of the VC was kept in an oven for 24 hrs at 100°C and reweighed (W_2) (Punmia 2002):

Water content $w = (W_1 - W_2)/W_1$.

2. pH

About 5 g of sample was placed in 100 ml distilled water and shaken vigorously. The sample was allowed to settle for 1 hr. These solutions were used to determine pH using a digital pH meter.

Geotechnical properties

GT properties were calculated using the procedures and derivations of Punmia (2001).

1. Specific gravity by density bottle

The empty weight of a density bottle (M_1) was noted, a known quantity of VC was added and its weight (M_2) was noted. The bottle was filled with distilled water and weighed once more (M_3). The control was weighed (M_4) by filling only with distilled water:

Specific gravity $G = (M_2 - M_1) / \{(M_2 - M_1) - (M_3 - M_4)\}$

2. Bulk density (BD) of VC

A core cutter of known volume was immersed in a vermi-bed slowly until it was completely filled with the VC:

$BD = \gamma = W/V$

where V = volume of core cutter; W_1 = empty weight of core cutter; W_2 = empty weight of core cutter + VC; W = weight of VC in the core cutter = $W_1 - W_2$.

3. Dry density (γ_d)

The dry density a_d was ascertained by the relation:

$\gamma_d = \gamma/(1+w)$

where γ = BD; w = water content.

4. Voids ratio 'e'

Voids ratio 'e' was calculated from the following relation using specific gravity G; dry density (γ_d) found above and the density of water (γ_w) was taken as unity:

$e = \{(G \times \gamma_w)/\gamma_d\} - 1$

5. Porosity n was obtained by the relation:

$n = 1 - \gamma d/(G \times \gamma_w)$

6. Saturated density was obtained by the relation:

$\gamma_{sat} = [(G+e) \times \gamma_w]/(1+e)$

7. Degree of saturation Sr was obtained from the relation:

$S_r = [w \times G]/e$

8. Air content was determined as:

$a_c = 1 - S_r$

9. Percentage air voids n_a was determined as:

$n_a = 1- \{\gamma_d \times (1+ w\ G)/G \times \gamma_w\}$

Particle size distribution (PSD)

PSD was determined in accordance with IS: 2720 (part IV). The oven-dried samples were machine sieved with a set of sieve sizes ranging form 4.75 mm to 90 μm. The percent finer (cumulative weight of oven-dried VC passing through a particular sieve taken as percentage) was calculated for soil, PM and VCs (**Table 5**).

The identification of soil type was carried out in accordance with IS: 1498–1970 by visual observation and based on the results of the sieve analysis.

Statistical analysis

Data was analyzed statistically using analysis of variance (ANOVA) to detect significant differences between the means of GT properties (**Table 4**) and PSD (**Table 6**) using Fisher's LSD test. All statistical computations were performed with Microsoft Excel 2007 (Mahajan, 2004).

RESULTS AND DISCUSSION

The PM OW openly stored on the ground was found to be soft and spongy with loose BD of 450 Kg/m^3, moisture content of 60-70%, pH 8.6, specific gravity 0.5. These properties, together with the GT properties (**Table 2**) indicate its suitability as a substrate for vermiprocessing.

Geotechnical properties

The results of the geotechnical properties of PM and VCs are presented in **Tables 2** and **3**, respectively.

The weight of the samples drawn in the core cutter shows the least weight is of PM VC from *M. megascolex* < *E. eugeniae* < *E. fetida* < soil + CD (1: 3) suggesting the amorphous/porous nature of VC occupying the same volume of the core cutter ($P < 0.05$). The specific gravity of VC from *M. megascolex* was also the lowest.

The water content of VCs was > 300% for *M. megascolex* and *E. eugeniae* and 225% for *E. fetida*. This is because moisture accumulated since regular sprinkling was maintained for 40 days. This also serves as an indicator of the water-holding capacity of VCs due to their porous nature, the presence of soluble aggregates, and retention of water on the skin of the earthworm (Kolher 1995; Kavian and Ghatnekar 1996).

Table 2 Geotechnical properties of press mud.

Parameter	Value
Specific gravity (G)	0.5 ± 0.05
Water content (w)	24.3 ± 0.6
Voids ratio (e)	1.0
Porosity (n)	0.5
Bulk density (√)	0.32
Dry density ($\surd_d$)	0.25
Saturated density ($\surd_{sat}$)	0.75
Degree of saturation (S_r)	0.14
Air content (a_c)	0.86
% Air voids (n_a)	93.9

All other GT properties of the VCs assist it in holding moisture hygroscopically within the VC solids. A specific moisture content of vermi-beds has to be maintained depending upon the initial moisture content of the substrates. For example, the moisture content of PM is 60-70%, less than that of potato waste which ranges from 90 to 94%, thus additional moisture has to be provided in the case of PM relative to treatments using potato waste (Munnoli *et al.* 2000).

Two parameters, dry density (γ_d) and BD (γ), indicate the amorphous nature of VCs. *M. megascolex* VC had the least bulk and dry density than other VCs: *M. megascolex* VC > *E. eugeniae* VC > *E. fetida* VC > soil + CD (1: 3). Compared with the density of PM all VCs suffered an increase in density, confirming previous reports of increased BD of VC of CD (Edwards and Lofty 1977; Edwards and Bohlen 1996; Munnoli 2007). BD is required to estimate, evaluate and calculate many physical properties and processes, is essential to convert data from weight-based to volume- and area-related data; one of the dominant factors changing BD is the soil OM (Munnoli 2007; Ruehlmann and Korschens 2009).

There was a decrease in the BD of soils treated with VC and VC + NPK compared to those treated with NPK alone, possibly due to increased porosity (Vasanthi and Kumarasamy 1999; Parthasarathi 2008). Azarmi *et al.* (2008) conducted *in-situ* experiments by incorporating sheep manure VC using *E. fetida* (0, 5, 10, 15 t ha^{-1}) into the top 15 cm of the soil surface. The soil samples collected from 15 cm depth after 3 months showed γ = 1.6933, 1.6300, 1.6133, 1.5633, respectively (Azarmi *et al.* 2008), clearly demonstrating that the soil becomes softer, looser and more porous in nature as the quantity of VC increased. The addition of VC can cause a significant decrease in BD, up to as much as 30% (Kolher 1995) due to the increased porosity of the soil (Bazzoffi *et al.* 1998). Ravikumar (2008) reported the BD of vermiash compost to vary from 0.65 to 0.90 Mg m^{-3} due to incorporation of organic residues and fly ash. The BD of soil after harvest of the crop onion (*Allium cepa* L.) was 1.53 Mgm^{-3} due to application of 100% recommended dose of nitrogen (RDN) through urea. BD decreased significantly due to a VC supplement (Mamatha 2006), consistent with a report by Nandani (2006) for the same crop. Lower

Table 3 Geotechnical parameters of vermicomposts of press mud (n = 3).

Parameter	Soil + CD (1: 3)	*Eisenia fetida*	*Eudrilus eugeniae*	*Megascolex megascolex*
Weight of sample in core cutter (g)	59.7	44	39	36.9
Specific gravity (G)	1.18	1.34	1.25	1.16
Water content (w)	1	2.25	3.01	3.23
Voids ratio (e)	1.43	5.09	6.81	7.16
Porosity (n)	0.589	0.84	0.87	0.88
Bulk density (γ) g/cm^3	0.97	0.72	0.64	0.60
Dry density (γ_d) g/cm^3	0.485	0.22	0.16	0.142
Saturate density γ (sat) g/cm^3	1.07	1.05	1.05	1.019
Degree of saturation (S_r) %	0.825	0.59	0.55	0.523
Air content (a_c)	0.125	0.41	0.45	0.48
Percentage air voids (n_a)	10%	34 %	40%	42%

Water content, Voids ratio, Porosity, air content is expressed as fraction.

Table 4 Analysis of variance of vermicomposts' geo-technical properties ($P < 0.05$).

Source of variation	Degrees of freedom (Df)	Sum of squares	Mean sum squares	Variance ratio (F)	F (Table)
GT parameters	11-1=10	9115.089915	911.5089915	24.1884057**	2.18
Vermicomposts	4-1=3	37.199457	12.399819	0.3290498 NS	2.92
Error	10*3=30	1130.511456	37.6837152		
Total	44-1=43	10282.80083			

** Highly significant; NS: Not significant

Note: Means of weight in core cutter, Percentage air voids differ significantly > LSD(CD) 8.85

All four groups do not differ significantly

GT = geotechnical

BD was reported for alfisol after harvesting maize and wheat using organic manure (Suresh and Mathur 1989). BD decreased from 1.68 to 1.39 by incorporating coir pith at 10 t ha^{-1} in sandy and clay loams (Durai 1982). Use of organic manures decreased BD of acid soil (Prasad, 1994), East Indian Galangal soil (Maheshwarappa *et al.* 1999) and alfisol (Prakash 2002). Ghosh *et al.* (2010) reported improved physical properties of sodic Australian vertisols with organic amendments (cotton gin trash (60 Mg ha^{-1}), cattle manure (60 Mg ha^{-1}) and composted chicken manure (18 Mg ha^{-1}) and a significant increase in nutrients (N, P, K, Na, Ca, Mg). A decrease in BD was reported in soils with high OM content (Arvidsson 1998) and application of an undecomposed organic resource, wheat straw (Sarkar 2003). A higher BD was noticed in chemical fertilizer-treated plots than in organic input treatment (*Sesbania aculeata* shoot and wheat straw) plots caused by a loss of soil organic carbon (Singh *et al.* 2009) and an increase of 12-19% after 20 years without worms (Clements *et al.* 1991).

The degree of saturation (Sr) was highest in the control soil + CD (1: 3), and there was no measurable difference in the saturation density (γ_{sat}) with VCs (**Table 3**).

The air content (a_c) of VCs was 3.84, 3.68 and 3.28 times more than CD + soil (1: 3) for *M. megascolex* VC > *E. eugeniae* VC > *E. fetida* VC > soil + CD (1: 3), respectively. *M. megascolex* is a deep burrower, is longer than *E. eugeniae* and *E. fetida*, has more movement in the soil at a greater depth and leaves large holes following burrowing, and these factors would surely contribute to the higher air content (Nobel *et al.* 1970), which in turn would increase the space for air circulation and survival of earthworms and aerobic microorganisms (Loquet *et al.* 1977; Kale 1994; Munnoli 2007).

The voids ratio (e) of VCs was 5, 4.76 and 3.55 times higher than that of soil + CD for *M. megascolex*, *E. eugeniae* and *E. fetida*, respectively in the order *M. megascolex* VC > *E. eugeniae* VC > *E. fetida* VC > soil + CD (1: 3). A VC unit that has a bad odor indicates that the system is overloaded with the possibility of anaerobic conditions due to a reduction in voids. Earthworms' activities improve soil aeration (Edwards and Lofty 1977; Munnoli 2007).

The porosity (n) of VCs was 1.5, 1.47 and 1.42 times higher than that of soil + CD (1:3) for *M. megascolex*, *E. eugeniae* and *E. fetida*, respectively in the order *M. megascolex* VC > *E. eugeniae* VC > *E. fetida* VC > soil + CD (1: 3). This indicates the porous nature of the VC, an important property pin pointing earthworm activity, which in turn shows the substrate preference of the earthworms: the greater the porosity, the greater the liking of a food substrate. In the present case *M. megascolex* VC has a higher porosity, implying that PM is a very good substrate for *M. megascolex*. An increase of porosity from 35.33 to 40.33% was recorded in VC-treated plots (Azrami 2008). Increased OM in soil influences aggregation and associated pore space distribution (Hudson 1994).

Water entry into soil is essentially a surface process in which porosity distribution of the soil material is the determining factor (Biswas and Mukherjee 1994; Stewart *et al.* 1988). Therefore activities of both surface feeders and deep burrower species are responsible for improved porosity (Aina 1995; Bottinelli *et al.* 2010) of soil with rounded pores (Marinari *et al.* 2000). When pore size increases from 30-50 to 50-500 μm and there is a decrease in the num-ber of pores >500 μm (Pagliai *et al.* 1980), this enables free capillary water to flow through soils (Singh and Dwivedi 2004; Nahamani *et al.* 2005a, 2005b; Prabhakar *et al.* 2006; Munnoli 2007). Aina (1984) noted a 2.5-fold increase in infiltrability due to earthworms (*Eudrilids*) in forest soils. 17% greater moisture capacity, doubled infiltration rates with *Lumbricids* (Stockdill 1966; Stockdill and Cossens 1966), and adding deep burrower species to earthworm-occupied soils resulted in about 4% additional soil moisture (Springett *et al.* 1985: Lal 1988) in New Zealand. The role of earthworms in increasing the mean weight diameter and macro porosity of water-stable aggregates has been reported for tropical alfisol (Lal and Akinremi 1983; Hulugalle and Ezumah 1991) for well graded soil using *M. megascolex* (Munnoli 2007), for loamy soil with *E. fetida* (Azrami *et al.* 2008) and with *Metaphire posthuma* (Bottinelli *et al.* 2010).

Porosity depends upon the texture and aggregation of the soil (Lee 1991). Application of sewage sludge compost at rates equivalent to 50 and 150 t ha^{-1} manure, based on organic carbon content, increased the porosity of a sandy loam soil at all times over two years (Guidi *et al.* 1983). The increased porosity in VCs and VC-treated plots is probably due to aggregation of the soil particles by the action of microorganisms in the VC, which produces polysaccharides providing a cementing action between soil particles (Six *et al.* 1995; Thakur et al. 1995; Sengar and Salni Gupta 2006; Munnoli 2007; Singh 2009) and possibly also by fungal mycelia (Edwards and Bohlen 1996; Tewatia 2007). The addition of organic manure affects soil aggregation and will have long-term implications on soil OM dynamics (Fonte *et al.* 2009).

The percentage air voids (n_a) of VCs was 4.2, 4.0 and 3.4 times higher than that of soil + CD (1: 3) for *M. megascolex*, *E. eugeniae* and *E. fetida*, respectively in the order *M. megascolex* VC > *E. eugeniae* VC > *E. fetida* VC > soil + CD (1: 3), which demonstrates the that deep burrower species are superior in terms of air voids ($P < 0.05$). Low porosity and hydraulic conductivity of soil can cause inadequate aeration which may lead to accumulation of salts and toxic substances (Biswas and Mukherjee 1994). Earthworm activity is also dependent on oxygen level in soil as earthworms breathe from the skin (Munnoli 2007). ANOVA shows that the sum of squares within GT parameters is significant but not between VCs ($P < 0.05$; within GT parameters F = 24.1884057**; between VCs F = 0.3290498) (**Table 4**). The two properties weight of sample in core cutter and percentage air voids differ significantly i.e., difference in means > LSD (CD) 8.85 (Fisher's LSD). This suggests that the GT properties do not differ significantly between species although *M. megascolex* VC GT properties are better than those of *E. fetida* and *E. eugeniae*.

Particle size distribution

The VC percent finer values in all IS sieves (**Table 5**) for *M. megascolex* are lower than those for *E. eugeniae* and *E. fetida* except for the 4.75 mm sieve. Therefore the percentage retained on each IS sieve for *M megascolex* was higher than that retained by the other two, depicting more aggregation in *M. megascolex*. The comparison of particle size distribution (PSD) curves of VC (**Fig. 1**) reveals an almost identical pattern for all three species and pin-points that earthworms are responsible for grinding the substrate,

Table 5 Cumulative percentage finer of press mud, soil, oven-dried vermicomposts of press mud.

IS sieve size (mm)	Soil	Press mud	*Eisenia fetida*	*Eudrilus eugeniae*	*Megascolex megascolex*
4.75	83.50	64.00	81.2	81.82	95.46
2.36	66.50	50.00	67.54	69.73	58.65
1.18	46.00	32.5	52.45	54.01	44.11
0.850	39.0	20.50	46.17	49.29	26.84
0.600	27.00	13.5	37.75	40.93	21.39
0.300	9.50	4.5	18.04	20.66	15.94
0.090	0.50	0.0	3.66	4.57	2.31
0.070	0.0	0.0	1.72	0.0	0.0
Pan (0.00)	0.0	0.00	0.0	0.0	0.0

ANOVA $P < 0.05$; $F = 9.60$; $F = 80.03$
Values are expressed as mean (n = 3)

Table 6 Analysis of variance of particle size distribution of vermicomposts ($P < 0.05$).

Source of variation	Degree of freedom (df)	Sum of squares	Mean sum of squares	Variance ratio F**	F (Table)
Between vermicomposts	4-2=3	1184.283389	394.7611296	9.60618831	3.01
Within particle size distribution	9-1=8	26312.16465	3289.020581	80.0356182	2.36
Error	8*3=24	986.2670611	41.09446088		
Total	36-1=35	28482.71			

** Highly significant

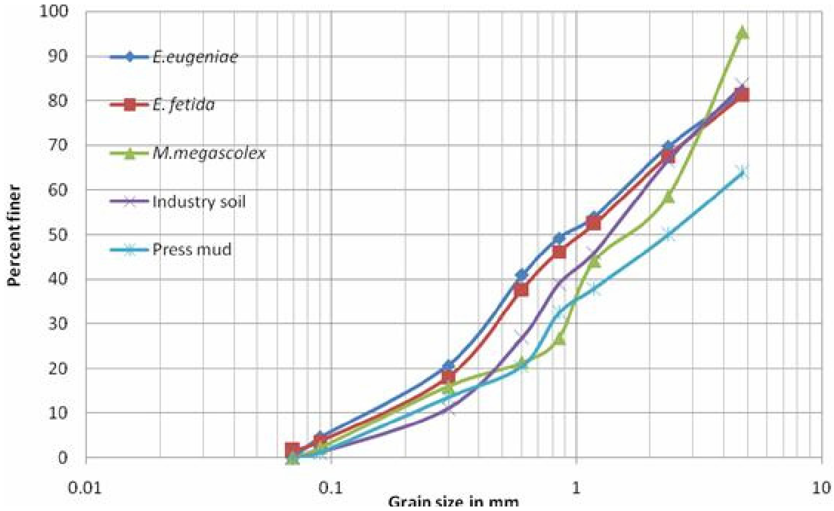

Fig. 1 Comparison of particle size distribution of vermicomposts with industry soil and press mud.

making the particle size of PM finer. The grinding capability of *E. eugeniae* was higher than that of *E. fetida* and *M. megascolex*. *M. megascolex* has a higher aggregation than the other two earthworms and industrial soil. During vermiprocessing at an intermediate stage of soil processes the PSD for *M. megascolex* increased beyond that of PM. This demonstrates that during initial periods of vermiprocessing grinding predominates and as vermi-beds stabilize, aggregation predominates.

Both grinding and aggregation are natural soil processes in a soil ecosystem. The role of earthworms in building soil and aggregating it was possible by using *P. elongata* (Singh, 1997; Munnoli, 2002). In the case of soil obtained from an ongoing vermiprocessing plant of Hindustan Lever Ltd., Zahura, Punjab, India (which treats tomato skin seed OW using *P. elongata*) after two years of commissioning there was significant aggregation compared to the soil from outside vermi-beds (Munnoli 1998). Aggregation has been reported by the pigmented species *L. terrestris*, *L. rubellus*, *L. costenus*, *Dendrobaena octaedra* and *Bimastos eiseni*, but no aggregation in unpigmented species *Octolasion cyaneum*, *Octolasion lacteum*, *Aporrectodea caliginosa*, and *Aporrectodea longa* (Svendsen 1957). Similarly, higher aggregation was reported for *M. megascolex* than for *E. eugeniae* and *E. fetida* in VC of CD (Munnoli 2009). *E. eugeniae*, with bacterial inoculum isolated from VC of PM, also demonstrated aggregation in a Petri dish experiment (Munnoli 2008b). This also fully confirms that the PM VC of *M. megascolex* was higher than that of *E. fetida* and *E. eugeniae.* This clearly depicts the functional role of deep burrower earthworms in building soil. Aggregation is a significant property (Edwards and Lofty 1977) used to develop degraded soils, as aggregation is the basic requirement on which all other geotechnical parameters depend (Munnoli 2007; Paradelo *et al*. 2009).

The ANOVA (**Table 6**) shows a significantly greater PSD between groups while that within groups is highly significant ($P < 0.05$; F** = 9.60 For VCs; F** = 80.03 PSD). In addition, there were no significant differences between the VC of *E. eugeniae* and that of *E. fetida*; all VCs differed significantly with PM (**Table 6; Fig. 1**).

The use of VC in improving soil characteristics is well documented (Stewart, 1988; Springett 1992; Munnoli 2002a 2007; Munnoli and Bhosle 2009). The VC of CD and green forage (GF) produced using *E. fetida*, when applied to Xerollic Calciorthid soil in Spain at a rate of 10.64, 21.28 and 7.71, 15.42 Mg ha^{-1} annually for three years showed improved biological properties and enzyme activities, respectively (Tejada *et al*. 2010). The VC of tomato skin seed using *P. elongata* on soil with no vegetative growth showed significant vegetation (Munnoli 1998) and a decrease in electrical conductivity of saline soils using PM VC (Munnoli 2007). Also, application of VC increased microbial growth and activity (Arancon 2006; Munnoli 2007; Munnoli *et al*. 2010).

Soil type

The soil type is SW, well graded (**Fig. 1**), loamy (Guild 1948); SM-SC: poorly graded sandy silt and clay mixture

(Singh 1997); SP; poorly graded, fine sand (Munnoli *et al.* 2002a). VT brought about changes in soil aggregation indicating that the classification needs to be determined occasionally.

CONCLUSIONS

E. eugeniae and *E. fetida* are suitable species for recycling PM based on their grinding capacities. GT and PSD values revealed that the PM VC using *M. megascolex* was far superior to those of surface feeders *E. eugeniae* and *E. fetida*. Therefore, this suggests that indigenous species of *M. megascolex* should be used in large-scale vermireactors for recycling PM and the use of this VC for developing waste lands should be increasingly advocated.

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