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Dynamics of the Soil-Earthworm-Plant Relationship: A Review

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ABSTRACT

Increases in the human population, indiscriminate growth of cities, industrialization, and agricultural practices have led to an increased accumulation of waste materials. The present method of disposal by open dumping has made the problem more acute by disturbing the soil-air-water ecosystem, thus needing urgent attention by planners. Moreover, the most abundantly available biomass, the lignocelluloses, has attracted considerable attention as an energy resource because of their large quantity. The recovery of nutrients by modification of wastes like municipal solid waste, industrial solid waste, agricultural residues, and animal wastes, etc. is important for their management and for reducing environmental degradation. Also, the deleterious impact on the environment by chemical fertilizer urges the need for production of organic manure out of waste. Recycling organic wastes through vermiculture biotechnology is being considered as an economically viable solution. Earthworms are considered as natural bioreactors which proliferate along with other microorganisms and provide required conditions for the biodegradation of wastes. The present study examines the various dynamics of the soil-earthworm-plant relationship with special emphasis on vermiculture. The review assesses the following topics: earthworm biodiversity, earthworm species for waste management, substrates, consumption rates, enzyme activities, medicinal uses of earthworms, and methods of vermi-composting along with their advantages and disadvantages, impact of application of vermicompost to soil fertility, soil microorganisms and crop yield, characteristics of vermicomposts, sustainable agriculture, economic importance and future prospects.

Keywords: biodegradation, bio-reactor, *Eisenia* sp., earthworm diversity, *Lampito* sp., microbial activity, soil fertility, soil aggregation, vermicomposting, vermiculture

Abbreviations: CD, cow dung; **ISW**, industrial solid waste; **MSW**, municipal solid waste; **OW**, organic waste; **SP**, poorly-graded sand; **SW**, solid waste; **VC**, vermicompost; **VW**, vermiwash

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INTRODUCTION

Recognizing that the world is finite and that continued pollution of our environment, if uncontrolled, will be difficult to rectify in the future, the subject of solid waste (SW) management is both timely and important. The overall objective of SW management is to minimize the adverse environmental effects caused by the indiscriminate disposal of SWs (Pevey *et al.* 1985). Further, the disposal of wastes through the use of earthworms also upgrades the value of original waste materials *in situ* and allows a final product to be obtained free of chemical or biological pollutants

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(Bouche 1979; Divya 2001). In the last 20 years environmental pollution caused by population pressure, urbanizetion, industrialization and mechanized agricultural activities has increased. Treatment of SWs has therefore become an essential part of life almost all over the world. Even though the government of India has made efforts to tackle SW problems, the alarming increase in their quantity and the mixing of biodegradable and non-biodegradable wastes at the generation point makes it complicated to handle them with limited resources.

This review compiles the assessment of management possibilities or feasibility of treatment of industrial solid waste (ISW), various available technologies and detailed information on vermiculture biotechnology, hereafter vermitechnology.

Studies on the soil-air-water-plant ecosystem reflects that the soil macrofauna, especially earthworms, is a major component, together with microbes in a wide variety of soils and climates, which is involved directly or indirectly in organic matter decomposition, stabilization, nutrient turnover, modification of soil physico-chemical properties, water holding capacity and infiltration (Edwards and Lofty 1977; Edwards *et al*. 1988; Edwards and Bohlen 1996; Singh 1997a; Lavelle and Spain 2001). Many of these effects are associated with the symbiotic relationships between earthworms and microorganisms, which mainly occur in the earthworm gut, casts, burrows, and middens. Casting is very important considering the high rate at which casts are produced and strong modifications in biochemical properties with respect to ingested material (Scheu 1987; Aira *et al.* 2003). It is generally accepted that microbial biomass and respiration are greater in earthworm casts than in the parent soil (Tiunov and Scheu 2000; Aira *et al.* 2002, 2003). However, earthworms can feed on these selectively (Moody *et al.* 1995; Edwards 2004), resulting in an increase in culturable aerobic microorganisms in the gut contents of earthworms, as seen with studies on *Lumbricus terrestris* and *Lumbricus rubellus* (Kristufek *et al*. 1992; Fisher *et al.* 1995; Schönholzer *et al.* 1999). Such earthworms are therefore considered as potential for use in SW management through the use of vermitechnology.

VERMITECHNOLOGY

Vermi means earthworm and culture means rearing or farming, much the same as other specialized farming (e.g. fish farming or aquaculture, etc.), which involves the following steps: procuring of seed stocks, culture of the proper variety and providing optimum food, moisture, air and temperature conditions.

Vermicomposting involves bio-oxidation and stabilization of organic material through the interactions between earthworms and microorganisms. Although microorganisms are mainly responsible for the biochemical degradation of organic matter, earthworms play an important role in the process by fragmenting and conditioning the substrate, increasing the surface area for growth of microorganisms, and altering its biological activity (Domínguez 2004; Domínguez and Edwards 2004).

Earthworms are well-known soil-inhabiting animals, having a cylindrical body and marked external and internal metameric segmentation. They do not have any appendages or suckers but have a few hooks like chaetae for gaining hold onto the substratum. Hence they are called Oligochaeta (oligo = few; chetae = hair) and belong to the Phylum Annelida. Earthworms are hermaphrodites and sexually matured worms have a distinctive epidermal ring-shaped clitellum, which has gland cells that secrete materials to form the cocoon (Edwards and Lofty 1977; Edwards and Bohlen 1996; Gajalakshmi and Abbasi 2004). Earthworms are major components of the soil fauna in a wide variety of soils and climates and are involved directly or indirectly in biodegradation, stabilization through humus formation, and various soil processes (Edwards and Bohlen 1996; Lavelle and Spain 2001). SW management leading to the production of bio-fertilizers through vermiculture has a bright future. However, it is essential to select suitable species of earthworms capable of consuming organic-rich matter, that are efficient decomposers and stress-resistant so as to sustain adverse environmental conditions, and have high fecundity rates (Satchell 1971; Edwards and Lofty 1977; Mohammad 1993).

Several methods are employed for collecting earthworms: digging and hand sorting, extraction using 0.55% formalin, extraction by passing electricity through soil (Walton 1993), and heat extraction (Reynolds 1977). When the relative efficiencies of extracting earthworms by several methods were compared, hand sorting and washing were shown to be best for most species, but they are time consuming (Satchell 1971; Edwards and Lofty 1977; Reynolds 1977).

EARTHWORM BIODIVERSITY

More than 4200 species of Oligochaetes are known in the world, of these, 280 are microdrili and about 3200 belong to megadrili (earthworms). In the Indian subcontinent earthworms also form the bulk of the Oligochaete fauna (Thomas and Trivedy 2002) and are represented by 509 species and 67 genera (Julka 1993).

A total of 28 earthworm species belonging to three families (Monilgastridae – genus *Drawida* (7), Megascolecidae (3), Octochaetidae (18)) from Western Ghats (Blanchart and Julka 1997); 9 belonging to four families (Glossoscolecidae, Megascolecidae Ocenerodrilidae, Octochaetidae) from the arid regions of Rajasthan (Tripathi and Bhardwaj 2004); 51 belonging to 23 genera and seven families identified from Western Himalaya States (Poliwal and Julka 2005); 10 belonging to seven genera and six families from Pondicherry Region (Sathinarayanan and Khan 2006) and 6 belonging to two families (Octochaetidae and Megascolecidae) from the foothills of Shivalik Himalaya (Namita and Swati 2009) indicate a high degree of diversity in this region compared to other areas of India. Though the majority of forms have a specific habitat preference, a few ubiquitous species also occur. It is important to critically assess the existing diversity in Indian earthworms and their ecological requirements for evolving suitable vermicomposting techniques. The ecological classification along with adopted species of earthworms and the rate of consumption of food substrates are described in **Tables 1** and **2**.

Commonly adopted worms in vermiculture are *Bimastos parvus*, *Dendrobaena rubida*, *Dendrobaena veneta*, *E. fetida*, *Eisenia hortensis* and *Eisenia andrei* belonging to the family Lumbricidae; *E. eugeniae*: family Eudrilidae; *Amynthas diffringens*, *Amynthas morrisi*, *Lampito mauritii*, *Metaphire anomala*, *Metaphire birmanica*, *Perionyx excavatus*, *Perionyx sansibaricus*, *Megascolex megascolex*, *Notoscolex*, *Pontoscolex corethrurus*, *Octochaetona serrata*, *Octochaetona surensis*, *Pheritima elongata*, *Pheritima posthuma*: Megascolecidae.

There are several reports indicating the efforts made to explore the possible potential use of earthworm biodiversity (Edwards and Lofty 1977; Satchell 1983; Greg and Smith 1992; Julka and Senapati 1993; Edwards and Bohlen 1996; Meyer and Bouwman 1997). Wide biodiversity has been reported from around the world by several groups: Sims and Gerard (1985) for the British Isles (44 species); Bouché (1972) for France (180 species), Easton (1980) for Japan (over 70 species); Reynolds (1977) for Ontario, Canada (about 20 species); Lee (1959) for New Zealand (192 species); Shahnaz *et al*. (2002) for Gujranwala, Pakistan (15 species); Achithan Nair *et al*. (2005) for Libya (3 species); Jamieson (1981) for Australia (300 species).

The other species are *Drawida willsi*, *Dichogaster bolaui* and *Lumbricus rubellus* (Dash and Senapati 1985; Singh 1997a). The deep borrower *Pheretima elongata* has been used for treatment of industrial wastes (Singh 1997b). The species identified for economic multiplication of earthworms and vermicomposting are i) *Esenia fetida* – Euro-

Table 1 Characteristics of earthworms of different ecological categories.

Characteristics	**Epigeic**	**Endogeic**	**Anecic**
Habitat	Litter dwellers	Naturally found in upper organic rich soil layers	Deep burrowing
Food	Litter and humus feeder	Litter and organic rich soil feeder	Litter and soil feeder
Burrow formation	Do not construct burrows and remains active in litter layers	Construct horizontal burrows lined by mucus and excretory products	Construct vertical burrow
Microbial communities in burrows	–	Well documented in literature	Positive evidences are available
Cocoon production rate	Highest	Moderate–high	Low
Life cycle	Short	Intermediate	Long
Efficiency in waste Recycling	Well established	Well established in some species	Efficiency data is not available
Species adopted in waste management	*Eisenia fetida* *Bimastos parvus* *Dendrobaena rubida* *Eisenia hortensis*	*Eudrilus eugeniae*	*Pheretima elongata* *Megascolex megascolex* *Perionyx excavatus* *Lumbricus terristris* *Amnthus diffringens* *Lampito mauritii* *Perionyx sanisbaricus* *Lumbricus rubellus*

Sources: Bouche 1977; Munnoli 2007; Suthar 2008a

Table 2 Consumption rates of earthworms.

Earthworm species	**Consumption rate (mg g^{-1})**	**Food substrate**	**Reference**
Allolobophora longa	20	Soil	Satchel 1983
Eisenia fetida	10-5000	Activated sludge	Mitchell 1978
Eisenia fetida	200-20000	Activated sludge	Hartenstein *et al.* 1979
Eudrilus eugeniae	2000-5000	Activated sludge with dead leaves	Jayshankar 1994
Eudrilus eugeniae	3000-7000	Activated sludge mixed along with sludge	Balaji 1994
Lampito mauritii	700-2800	Soil	Dash *et al.* 1980
Lumbricus terrestris	27-80	Elm leaves	Needham 1957
Lumbricus terrestris	10-30	Soil	Satchell 1967
Octolasium sp	29	Soil	Crossly *et al.* 1971
Pheretima elongata	375-700	Potato peel	Munnoli 1998
Eudrilus eugeniae	300-600	Potato peel	Munnoli 1998
Eisenia fetida	300-600	Potato peel	Munnoli 1998
Megascolex megascolex	715-1400	Press mud	Munnoli 2007
Eudrilus eugeniae	625-1250	Press mud	Munnoli 2007
Eisenia fetida	600-1200	Press mud	Munnoli 2007
Megascolex megascolex	650-1300	Cow dung	Munnoli 2007
Eudrilus eugeniae	1000-2000	Cow dung	Munnoli 2007
Eisenia fetida	800-1650	Cow dung	Munnoli 2007
Eisenia fetida	30-35	Garlic waste	Mishra *et al.* 2009
Eudrilus eugeniae	30-35	Onion waste	Mishra *et al.* 2009

Sources: Edwards and Lofty 1977; Thomas and Trivedy 2002; Munnoli 2007

pean worm, ii) *Eudrilus eugeniae* - African worm, iii) *Perionyx excavatus* - indigenous to India are prolific breeders, have a high multiplication rate, are voracious feeders and are easy to handle, having 1-3 years longevity, and survive under aberrant weather conditions (Kale *et al.* 1992; Kale 1994). The latter were successfully employed for both household and industrial organic waste (OW) (Divya 2001; Munnoli 2007). In contrast, Gautam and Choudhary (2002) suggested *Perionyx excavatus*, *Pontoscolex corethrurus*, *Dichogaster modiglianii* and *Polypheretima elongata* as continuous breeders with high fecundity, *Lampito mauritii* and *Drawida nepalensis* as semi-continuous and *Eutyphoeus gammiei* as discrete breeders.

Sulata *et al.* (2008) studied the role of *Lampito mauritii* (Kinberg) in amending lead- and zinc-treated soil. The growth, reproductive biology and life cycle of the vermicomposting earthworm, *Perionyx ceylanensis* Mich. (Oligochaeta: Megascolecidae) was reported by Natchimuthu and Thilagavathy (2009) and Suthar (2009) introduced *Allolobophora parva* (Oligochaeta) in vermicomposting.

Earthworms commonly found in Sub-Saharan Africa suitable for vermicomposting are *Dichogaster annae*, *Dichogaster bolaui* (West Africa) and *Eudrilus eugeniae Hyperiodrilus africanus* (Ghana, Ivory Coast, Nigeria, West Africa) Mainoo (2007).

Earthworms vary greatly in size though not in shape. In India, some peregrine species like *Microscolex phosphoreus* (Drugs), *Dichogaster saliens* (Beddard) and *Bimastos parvus* (Eisen) are < 20 mm long while some endemic geophagus forms, such as *Drawida nilamburensis* (Bourne) and *Drawida grandis* (Bourne) may reach up to 1 m in length. *Megascolides australis* (McCoy) from Australia is reported to attain a length of over 4 m while *Microchaetus microchaetus* (Rapp) reaches up to 7 m (Mohammad 1993).

The presence of a species in a particular habitat and its absence from other habitats shows the species-specific distribution of earthworms in pedoecosystems. *Metaphire posthuma* and *Lampito mauritii* were observed in most habitats of Jodhpur, India (Tripathi and Bhardwaj 2004). Similarly, earthworm composition in a variety of soils has been reported: effect of earthworms on orchard productivity (van Rhee 1967) or on forest and grasslands (Satchell 1983). The effects of processes at the individual level on the velocity of population expansion were studied for two species (*Aporrectodea caliginosa* and *Lumbricus rubellus*) along with the parameters of active and passive dispersal, which were calculated from field experiments in a Dutch polders (Marinissen and van den Bosch 1992); The effectiveness of earthworm species as bio-indicators of forest site quality was tested by a data set of 180 plots in temperate lowland forest (Flanders, Belgium) (Muys and Granval 1997).

The application of different types of species is not reliable unless it is compatible with the specific substrate being studied. The species good for one region may not necessarily be good in another. This is especially true for the deep burrowers as they require more time to acclimatize to a new environment (Singh 1997b). As such, deep burrowers undergo diapause when subjected to shocks of vibrations (Munnoli 1998). It is therefore advisable to transport the vermicompost (VC) containing earthworms and cocoons in the new environment. In the case of surface feeders, the biomass of earthworms or even cocoons can be easily transported and placed in a new environment.

The management of organic SWs through composting is a time-consuming process. Vermitechnology utilizes earthworms as versatile natural bio-reactors to convert OW into value-added products, the vermicasts (EPA 1980), at a faster rate and can be applied to industries producing OWs through the synergistic effect of microorganisms and earthworms (Roig 1993; Bhawalkar 1995; Bhattacharya 2007; Surekha and Mahadev Kumar 2007).

Vermiculture, which began in the United States in the 1930's, developed in Italy only from the second half of the 1970's. The treatment of organic wastes was realized in the late 1970's in the USA. In India, the importance of OW management has only been realized in the last 15-20 years (Piccone *et al*. 1986; Ranganathan and Christopher 1996).

In 1995, community rural vermicomposting was initiated by the Punjab State Council for Science and Technology Punjab India and in Goa, India by Agnel Charities, an NGO working in the rural development in rural areas of South Goa India in 2003.

METHODS OF SETTING VERMICOMPOST UNITS *IN SITU*

There are three different methods practiced for setting vermicomposting units (Bhawalkar 1995; White 1996; Singh 1997; Munnoli 1998; Divya 2001; Rao and Lakshmi 2002; Munnoli 2007): 1) Circular vermicomposting unit; 2) Rectangular vermicomposting unit; 3) Strip method.

The first two methods require a complete roof so that no direct sunlight enters the vermi beds, which are covered with jute bags to enhance the reaction and to maintain moisture content. Such organic manure helps to increases the soil fertility level, water holding capacity, and aeration. The general health of the soil increases, no chemical sprays are employed and the VC itself is insect resistant. The technology eliminates pathogens, does not produce odor and also heavy machinery is not required. The various designs adopted for vermiculture based on the topography, type of soil and amount of rainfall are discussed below (Munnoli 2007).

VARIOUS DESIGNS ADOPTED IN VERMICULTURE

1) Pit method

The pit is below the ground level and depends on the type of soil. Pits of different dimensions can be chosen as per the individual requirements. However, in regions with moderate rains many pits under a common roof can be built, but this is not advisable for sandy silt soils and regions with rain intensity of 3000 mm per year.

This design has some disadvantages, as the pit is open at the ground level therefore predators like rats, bandicoots, ants and centipedes enter the pit easily and it is difficult to take any measures to tackle such predators. Also worms can move out if they obtain favorable moisture, hence it is not suitable for periodic harvesting. Furthermore, there is no sustainability as the pit may close by itself with ground water or soil.

2) 10-cm thick rectangular tank with holes

This is constructed with brick masonry above the ground level. It is convenient where under a common roof many units can be built in regions where the cost of transportation is less with locally available materials. Here also holes serve an entry to predators and the worms move out of the system. The structure is not suitable and wet materials exert horizontal pressure on walls. As such, a 10-cm thick wall built on an open space does not provide any stability. Therefore, it can be adopted only for internal vermicomposting with full roofing material cover. Against heavy coastal rains efflorescence is the main problem, wear out, collapse, bricks also absorb moisture from compost and become weak. Hence, it is very good for research work with a common glass and asbestos sheet roofing with sides protected from predators.

3) 10-cm thick complete wall without plaster

This construction is at the above-ground level, with many units built under a common roof using locally available materials and semi-skilled labor which will reduce the cost. As there are no holes left, entry of predators and exit of worms is restricted. 10-cm thick is not a stable structure against horizontal liquid pressure of wet materials and does not offer any stability as it absorbs moisture and protection from rain; a roof cover is a must. It is not suitable for outside composting. The thickness of organic loading should be in 10-cm layers and restricted up to a maximum of 50 cm.

4) 20-cm thick laterite masonry

Masonry has to be carried out with semi-skilled labor and construction is at the above-ground level. This method is suitable for individuals, safe against predators, has a long life and is permanent in nature, and therefore can be a continuous economic resource for farmers. The structure is completely sustainable, even if the watering of beds is missed by farmers or failure of the system due to overloading; the vermibed can be reloaded easily because of greater stability of the structure compared with the other types. It is also suitable for research using surface and deep burrower species on agricultural residues with periodic harvesting.

The above methods 3 and 4 constructed with a water channel around the structure will safeguard the vermicomposting unit against red ants.

5) Heap method

This method is suitable for setting up a vermicomposting unit both indoors and outdoors, basically for protection purposes. Many heaped rows are possible depending on the space available. It is very good for large-scale production under green- or glasshouse; rooms should be reserved for this purpose only. It is sustainable for farmers with a field farmhouse or sheds. If carried out outdoors, frequent inspection for predators is necessary.

6) Indoor vermicomposting

The whole system is completely protected with a thatch or bamboo roof or carried out inside existing cowsheds, abandoned sheds, poultry sheds or temporary thatch roof sheds. It is preferred for protection from adverse climates and predators.

The above mentioned methods were successfully adopted in villages of Goa and Karnataka India (**Table 3**).

SUBSTRATES USED FOR VERMICULTURE

Thomas and Trivedy (2002) rated substrates based on physical and chemical characteristics (**Table 4**). The use of different organic substrates and species employed and their

Table 3 Vermicomposting operational units.

Name of farm/Organization/Village Species employed/year of commencement	Quantity tw^{-1}	Type of organic waste	Species adopted	Type of VC unit adopted
Dr. Jeevannavar Farm Hubli, Karnataka, India (2003)	1-2	Teak wood leaves, agricultural residues, cow dung	*Pheritima elongata* *Eudrilus eugeniae*	Circular below ground/ rectangular above ground/strips; Brick masonry
Magadum Farms Sankeshwar, India (2002)	2-4	Sugar cane trash	*Pheritima elongata*	Rectangular above ground Brick masonry
Villages (20 Units) Malcornem, Majorda, Betal batim, Ambaulim, Goa, India (2002-2003)	0.1-0.25	Cow dung and agricultural residues	*Eudrilus eugeniae* *Eisenia fetida*	Above ground Laterite masonry
MES Collge of Arts and Science, Goa India (2005)	0.10	Canteen waste	*Eudrilus eugeniae*	Above ground Laterite masonry
Mr Babushan Farm Majorda Village (2009)	1.-2	Cow dung and agricultural residues	*Eudrilus eugeniae*	Above ground Laterite masonry

Sources: Munnoli 2002, 2007

Table 4 Rating of substrates for composting.

Examples of substrates	C:N ratio	Suitability
Fish, scrap poultry manure, night soil, activated sludge, pig manure, sheep dropping, meat scraps, cotton seed meal and other oil seed residues	1-19	Most suitable due to high Nitrogen content
Garbage, sea weed, butter cup, amaranthus, lettuce, cabbage and vegetable waste which are fresh, green and succulent including wastes from food processing industries	19-27	Moderately suitable
saw dust flax, waste straw, coir waste, etc. including all crop residues with high lignocellulose content, high carbon and low moisture	27-208	Less suitable

Source: Thomas and Trivedy 2002

Table 5 Various species employed for vermiprocessing of organic wastes.

Waste/substrate	Species employed	Reference
Potato peels	*Pheretima elongata*	Munnoli *et al*. 2000
Press mud	*Pheretima elongata*	Singh 1997b
	Eudrilus eugeniae, *Eisenia fetida*	Munnoli 2007
	Megascolex megascolex	Munnoli and Bhosle 2008
Canteen waste	*Eisenia fetida*	Kale 1994; Narayan 2000
Tomato skin seed	*Pheretima elongata*	Singh 1997
Onion residue	*Eisenia fetida / Eudrilus eugeniae*	White 1996
Sericulture waste	*Perionyx excavatus*	Guthilingaraj and Ravignanam 1996
Sericulture waste	*Phanerochaete chrysosporium*	Kallimani1998
Board mill sludge	*Lumbricus terrestris*	Butt *et al*. 2005
Sugar cane residues	*Pheretima elongata*	Bhawalkar 1995
Gaur gum	*Eudrilus. eugeniae*	Suthar 2006, 2007
Agricultural residues	*Eudrilus eugeniae*	Kale 1994
Municipal wastes	*Megascolex mauritii*	Ravichandran *et al*. 2003
Municipal solid wastes	*Eudrilus eugeniae*, *Perionyx excavatus*, *Perionyx sasibaricus*	Ranganath Reddy *et al*. 2002
Distillary sludge	*Eisenia fetida*	Munnoli 1998
	Eudrilus eugeniae	Suthar 2008b, 2008d
	Pheretima elongata	Munnoli 1998
Tannery waste	*Perionyx excavatus*	Shahul Hameed 2002
Kitchen waste	*Perionyx excavatus*	Shahul Hameed 2002
Spent straw	*Perionyx excavatus*	Shahul Hameed 2002
Newspaper	*Perionyx excavatus*	Shahul Hameed 2002
Wood shavings	*Perionyx excavatus*	Shahul Hameed 2002
Forest litter: *Tectona grandis* (teak), *Madhuca indica* (mahua) and *Butea monosperma* (palas)	*Eisenia fetida*, *Perionyx excavatus* and *Dicogaster bolaui*	Manna *et al*. 2003
Domestic/municipal sewage sludge mixed with sugarcane trash	*Eisenia fetida* *Lampito mauritii*	Suthar 2008a, 2008b, 2008c
Sago waste	*Lampito mauritii*	Rajesh Banu 2008
Sago waste	*Eisenia fetida*	Subramaniana *et al*. 2010
Onion waste	*Eudrilus eugeniae*	Mishra *et al*. 2009
Garlic waste	*Eisenia fetida*	
Source separated human faeces	*Eisenia fetida*	Yadav *et al*. 2010
Paper mill sludge	*Eisenia fetida*	Kaur *et al*. 2010
Press mud, bagasse, sugar cane trash	*Drawida willsi*	Kumar *et al*. 2010
Press mud	*Perionyx ceylanensis*	Mani and Karmegam 2010

suitability in vermicomposting is presented in **Table 5**.

The various substrates used for vermiculture are cow dung (CD), agricultural residues, industrial wastes, etc. Substrates, especially agricultural residues, have been tested extensively in combination with an easily biodegradable substrate such as CD. Kale *et al.* (1986) reported the suitability of neem cake as an additive in earthworm feed and its significance in the establishment of the microflora. *E. eugeniae* was tolerant to neem cake in the culture medium up to a concentration of 1.6-6.4% and had a positive effect on earthworm biomass production.

E. eugeniae was mass cultured on 6 different feed formulae prepared by mixing CD, sheep and horse dung with other OWs such as rice polish, wheat barn, and green gram bran vegetable waste and eggshell powder in various combinations (Bano *et al.* 1987). The worm casts obtained from

Table 6 Increase in number of earthworms due to application of dung.

Species	**Grass land**		**Arable land**	
	Park grass Rothamsted		**Barn field Rothamsted**	
	Unmanured	**Dung**	**Unmanured**	**Dung**
Lumbricus terrestris	13.1	22.5	0.23	10.8
Lumbricus castaeneus	16.0	59.6	-----	-----
Allolobophora caliginosa	2.9	8.0	0.8	15.4
Allolobophora chlorotica	1.6	-----	3.2	44.6
Allolobophora rosea	10	21.3	-----	0.23
Allolobophora longa	----	------	0.46	1.8
Allolobophora nocturna	1.3	18.9	----	----
Octolasion cyanaeum	6.9	24.5	----	-----
Total	51.8	154.8	4.69	72.83

Source: Edwards and Lofty 1977

6 different feeds were analyzed for pH, EC, organic C, N, P and K. All casts were slightly acidic to neutral pH and the percentage N remained the same more or less in all casts. However, EC, organic C, P_2O_5 and K_2O contents varied greatly.

A laboratory-scale study was conducted to assess the suitability of powdered rubber leaf litter as vermiculture substrate for *P. excavatus*, *E. eugeniae* and *E. fetida*. Earthworm mortality, biomass production and reproduction were measured during the investigation. Rubber leaf litter was a suitable substrate for vermiprocessing (Choudhary *et al.* 2001).

The number of earthworms in Park Grass, a permanent pasture fertilizer experiment in the UK, was three times greater in plots receiving 35 t/ha of dung than in unmanured plots. In a barn field, an arable permanently growing mangolds, there were about 15 times more earthworms in plots receiving dung annually than in unmanured plots (Edwards and Lofty 1977). Satchell (1955) and Edwards and Lofty (1977) reported an increase in the number of earthworms in a barn field, Rothamsted (grassland) and Park Grass, Rothamsted (arable land) (**Table 6**), suggesting CD as an easily biodegradable substrate to start vermiprocessing.

In a laboratory-scale experiment, three species of worms (*E. fetida*, *E. eugeniae* and *M. megascolex*), when introduced to soil + CD in a 1: 3 proportion, *E. eugeniae* showed highest numbers after 32 days, suggesting a 1: 3 proportion for setting vermicomposting units (Munnoli and Bhosle 2009). Source-separated human faeces were successfully utilized with bulking agent vermicompost (Yadav *et al.* 2010) and food wastes using *E. fetida* (Rostami *et al.* 2010).

ENVIRONMENTAL FACTORS GOVERNING VERMITECHNOLOGY

pH

Earthworms are very sensitive to pH, thus pH of soil or waste is sometimes a factor that limits the distribution, numbers and species of earthworms. Little information is available on the effect of substrate pH during vermicomposting. In a vermicomposting experiment with different soil proportions (1: 2, 1: 3, 1: 4, 1: 6) of CD the earthworms reduced the pH: *E. fetida*, 6.7 to 6.1; *E. eugeniae*, 6.7 to 6.0; and *M. megascolex*, 6.7 to 6.4 (Munnoli and Bhosle 2009). Several researchers have stated that most species of earthworms prefer a pH of about 7.0 (Singh 1997a; Narayan 2000; Pagaria and Totwat 2007; Suthar 2008b; Panday and Yadav 2009) although Edwards (1995) reported a wide pH range (5.0-9.0) for maximizing the productivity of earthworms in OW management. *Lumbricus terrestris* occurs in soils with pH 5.4 in Ohio, USA (Olson 1928). Bhawalkar (1989) suggested a neutral substrate pH for vermicomposting using deep burrower species *Pheritima elongata*.

Satchell (1955) reported that *Bimastos eiseni*, *Dendrobaena octaedra* and *Dendrobaena rubida* were acid-tolerant species, while *Allolobophora caliginosa*, *Allolobophora nocturna*, *Allolobophora longa* were acid-intolerant. Satchell also reported that *L. terrestris* was not very sensitive to pH and Guild (1951) agreed with this conclusion. Singh *et al.* (2005) reported that *P. excavatus* performs well in a wide range of substrate pHs. The decrease in pH values when press mud was treated with *M. megascolex*, *E. eugeniae* and *E. fetida* showed a decreasing trend in pH from 8.6 to 6.7 during vermiprocessing over a period of 60 days (Munnoli 2007). A decrease in pH was recorded in CD vermicomposting using *E. fetida* and *L. mauritii* (Suthar 2008a) and *Pheritima elongata* using tomato skin seed waste as substrate (Singh 1997b), or kitchen waste (Narayan 2000).

Moisture

Water constitutes 75-90% of earthworms' body weight and prevention of water loss is a major factor in successful vermireactors, especially when the unit is constructed outside. In the natural soil-earthworm interaction, when there is a loss of soil moisture, earthworms tend to move to a safer area with more moisture. When the whole area is dry the earthworms adjust themselves and survive through large water loss from the body: *L. terrestris* can loose up to 70% and *A. caliginosa* 75% (Edwards and Lofty 1977). Experiments conducted using *P. elongata* showed optimum moisture of 70% for the treatments of potato peel waste (Munnoli 1998) whereas press mud required 60-70%. Trials for vermicomposting CD showed optimum moisture of 60-70% with a higher number of *E. eugeniae*, *E. fetida*, and *M. megascolex* earthworms (Munnoli 2007; Munnoli and Bhosle 2008). Strains associated with endospore-forming *Bacillus* survive extreme weather conditions and become active when favorable soil moisture conditions are regained (Munnoli 2007). Evans and Guild (1948) reported that *A. chlorotica* produced more cocoons at a moisture content of 28 to 42%. Juveniles, which show high tolerance to low moisture, when transferred to a new environment with favorable moisture, adjust faster than adult worms (Edwards and Lofty 1977; Singh 1997b). Such experiments were also carried out with the cocoons of *E. fetida* and *E. eugeniae*, which were transferred to culture boxes containing CD while adult earthworms were separately transferred. More juveniles were found in culture boxes with cocoons than in culture boxes with adults (Singh 1997b; Munnoli 1998, 2007). Therefore, moisture level is a significant factor in the set-up of a vermicomposting unit (Scheu 1987: Parthasarathi and Rang Nathan 2001; Parthasarathi 2006); in village environments units need to be carefully designed to hold water without causing water logging.

Temperature

Evans and Guild (1948) reported that the activity, metabolism, growth, respiration and reproduction, fecundity, and growth period from hatching to sexual maturity of earthworms are greatly influenced by temperature. Cocoons hatch sooner at high temperatures (Edwards and Lofty 1977). A temperature range of 20-30°C for vermibeds was suggested using *E. fetida*, *E. eugeniae* and *P. exavatus* (Bhi-

Table 7 Optimum temperature range for activity of earthworm species.

Temperature range (°C)	Species	Reference
15-23	*Pheretima hupiensis*	Grant 1955
15.7-23.2	*Eisenia fetida*	Grant 1955
10-23.2	*Allolobophora caliginosa*	Grant 1955
26-35	*Pheretima californica*	El-Duweini and Ghabbour 1965
22-29	*Eudrilus eugeniae*	Viljoen and Reinecke 1992
25	*Eisenia fetida*; *Eudrilus eugeniae*	Reinecke *et al.* 1992
43	*Peryonyx excavatus*	Reinecke *et al.* 1992
10	*Lumbricus terrestris*	Edward and Lofty 1977
20-35	*Peryonyx excavatus*	Bhoyar and Bhide 1996
20-35	*Barogaster annadeli*; *Lampito mauritii*	Bhoyar and Bhide 1996
25-35	*Perionyx excavatus*	Edwards 1988
15-35	*Eudrilus eugeniae*; *Eisenia fetida*; *Pheritima elongata*	Munnoli 1998
28-32	*Periyonyx excavatus*; *Lampito mauritii*; *Drawida nepalensis*	Gautam and Chaudhuri 2002
28-32	*Polypheritima elongata*; *Dichogastermodiglianii*	Gautam and Chaudhuri 2002
28-32	*Pontoscolex corethrurus*	Gautam and Chaudhuri 2002
25-34	*Eisenia fetida*	Pulakeshi *et al.* 2003
25	*Eisenia fetida*	Tripathy and Bharadwaj 2004
30	*Lampito mauritii*	Tripathy and Bharadwaj 2004
20	*Eisenia fetida*; *Eisenia andrei*	Dominguez *et al.* 2005
20	*Eudrilus eugeniae*	Aira *et al.* 2006
15-35	*Eudrilus eugeniae*; *Eisenia fetida*; *Megascolex Megascolex*	Munnoli 2007
28.9	*Eisenia fetida*; *Lampito mauritii*	Suthar 2008a
26-35	*Eisenia fetida*; *Eudrilus eugeniae*	Mishra *et al.* 2009
5-25	*Eisenia fetida*	Yadav *et al.* 2010
28-32	*Lampito mauritii*	Kale and Karmegam 2010
27-28	*Octochaetona serrata*	Kale and Karmegam 2010

Table 8 Optimum temperature for setting vermicomposting units.

Temperature range (°C)	Species	Reference
25-35	*Eudrilus eugeniae*	Munnoli 2007
20-35	*Eisenia fetida*	Munnoli 2007
20-35	*Megascolex megascolex*	Munnoli 2007
20-30	*Eisenia fetida*, *Eudrilus eugeniae*	Bhiday 1994; Ruikar 1997
20-34	*Pheretima elongata*	Munnoli 1998
25-29	*Perionyx excavatus*	Shahul Hameed 2002

day 1994; Ruikar 1997), 15-23°C for *P. hupeiensis* and *E. fetida* and 10-23°C for *A. calignosa* (Grant 1955). The optimum temperature range for earthworm activity and for setting vermicomposting units are presented in **Tables 7** and **8**, respectively.

Soil organic matter

Earthworms use a wide variety of organic materials for food, and even in adverse conditions, extract sufficient nourishment from the soil to survive. The kind and amount of food available influences not only the size of an earthworm population but also the species present and their rate of growth and fecundity. Zazone and Sidor (1990) reported that greatest weight increase in *E. fetida* was obtained when 50 g of soil was mixed with 150 g cellulose waste; Nayak and Rath (1996) claimed that organic residues comprising city, industrial, agricultural farm, household and kitchen waste with dead or decaying materials can be used as bedding materials for vermicomposting. Joshi (1997) suggested that animal manure, dairy and poultry waste, food industry waste; slaughterhouse waste or biogas sludge could be used for recycling through vermicomposting. The best results of vermicomposting were obtained from paper and food manufacturing industries when treated with *E. fetida*, *E. andrei* and *P. excavatus* (Piccone *et al.* 1986).

Soil type

There have been very few studies and reports on the direct influence of soil type or earthworm populations. Guild (1948) surveyed the main soil types in Scotland and reported that there were differences both in total and relative numbers of each species. Light and medium loams soils had a higher population of worms than heavier clays or gravely sand and alluvial soils (Nair *et al.* 2005). Singh (1997b) reported border zone soils silt and clayey sand (SM-SC) to be suitable for vermicomposting whereas poorly graded silt and sandy with fine (SP-SM), well-graded (SW) soil were suggested by Munnoli *et al.* (2000) and Munnoli (2007), respectively. The abbreviations used are as per Indian Standards IS; 1478 (1970). Soil type affected the impact of *L. terristris* on microbial respiration which increased in clay loam and silty clay loam soil but decreased in sandy loam soil (Shaw and Pawluk 1986).

EARTHWORM GUT MORPHOLOGY AND CONTENTS

The earthworm gut is basically a straight tube extending from the mouth to the anus; its different regions are the muscular pharynx, oesophagus, intestine and associated digestive glands. The oesophagus may be further differentiated into two bulbous chambers, a muscular gizzard and a thin-walled crop (**Fig. 1A, 1B**). There may be more than one gizzard depending upon the species. There are various modifications in the digestive system in different worms depending upon the food taken. For example, the gizzard is generally absent or rudimentary in earthworms which thrive on a liquid or semi-liquid diet. Litter-feeding species lack a typhlosole which is well developed in soil-feeding worms (Senapati 1993).

The gut contents usually comprise mucus, organic and mineral matter. An analysis of gut contents in earthworms revealed the occurrence of different kinds of symbiont-like microfungi, bacteria, protozoa, etc.; most microfungal species are found in the foregut, gradually decreasing in number in the mid- and hindgut with fewest in freshly laid casts (Dash *et al.* 1980a).

It is well established that the earthworm gut provides suitable conditions for the development of bacterial colonies since earthworm casts contain significantly higher counts of bacteria than in the surrounding soil (Edwards and

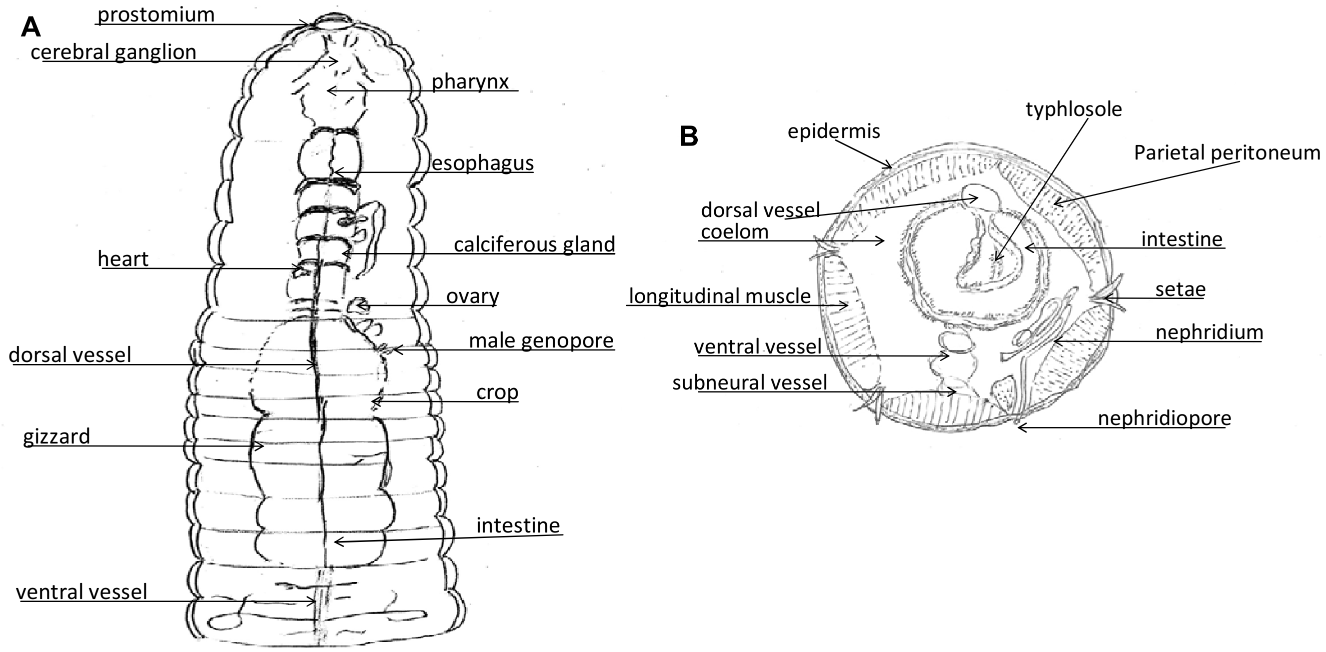

Fig. 1 (**A**) Internal anatomy of earthworm; (**B**) Transverse section of earthworm. Modified (improved) from **Meglitsch PA, Schram FR** (1991) *Invertebrate Zoology* (3rd Edn), Oxford University Press, New Delhi, 336 pp, ©1991, with kind permission from Oxford University Press, Inc. (www.oup.com).

Lofty 1977; Kale *et al*. 1992; Singh 1997b; Munnoli 1998; Bhattacharyya *et al*. 2000; Munnoli 2007). Microorganisms may constitute an important part of the diet of earthworms, which can feed on them selectively (Moody *et al*. 1995; Edwards 2004). A 13.76- and 572.96-fold increase in actionmycetes and 700.8- and 927.78-fold increase, respectively in bacteria in the mid- and hindgut as compared with the foregut was reported (Parle 1963; Edwards and Lofty 1977).

The presence of digestive enzymes like amylase, cellulase, protease, lipase, chitinase and a variety of digestive enzymes have also been reported from the alimentary canal of earthworms. These enzymes are usually related to the preferred diet of the organism (Wallwork 1984) in the intestine, signifying the digestive ability of earthworms (Abbasi and Ramasamy 2001); these enzymes operate in a medium with remarkably stable pH ranging between 6.3 and 7.3 (Wallwork 1984). Zhang *et al.* (1993) found strongest enzyme activities in the fore- and midgut. The activity of cellulase, starch, glucomannan and glactomannan predominated; they also concluded that cellulase and mannase activities were mainly due to microorganisms. Dash and Senapati (1986) also reported the gut enzymes of earthworms such as amylase cellulose, chitinase, protease, and urease. The literature pertaining to enzyme activities associated

Table 9 Enzyme activity associated with earthworm gut/vermicasts/tissue bacterial isolates.

Earthworm species		A	C	Ch	P	U	I	E	AP	NR	G	L	Reference
Detochaetona surensis	gut	+	+	-	+	+	-	-	-	-			Mishra and Dash 1980b
Dichogaster balaui	gut	+	+	-	+	+	-	-	-	-			Mishra and Dash 1980b
Drawida celebi	gut	+	+	-	+	+	-	-	-	-			Mishra and Dash 1980b
Perionyx millardi		+	+		+	+							Mishra and Dash 1981
Hemienchytraeus khallikotosus	tissue	+	+		+	+	+						Dash *et al*. 1981
Enchytraeus berhampurosus	tissue	+	+		+	+	+						Dash *et al*. 1981
Fridericia kalinga	tissue	+	+		+	+	+						Dash *et al*. 1981
Dichogaster bolaui	gut	+	+	-	+	+							Dash and Senapati 1986
Drawida calebi	gut	+	+	-	+	+							Dash and Senapati 1986
Drawida willsi	gut	+	+	-	+	+							Dash and Senapati 1986
Eutyphoeus sp.	gut	-	-	-	+	+							Dash and Senapati 1986
Lampito mauritii	gut	+	+	-	+	+							Dash and Senapati 1986
Dendrobaena octoedra	gut	-	+	-	-	-							Dash and Senapati 1986
Eisenia fetida	gut	-	-	-	+	-							Dash and Senapati 1986
Eisenia fetida	vc	+	+		+								Munnoli 1998
Eudrilus eugeniae	vc	+	+		+								Munnoli 1998
Pheritima elongata	vc	+	+		+								Munnoli 1998
Lampito mauritii	vc	+	+		+		+						Parthasarathi and Ranganathan 2000
Eudrilus eugeniae	vc	+	+		+		+						Parthasarathi and Ranganathan 2000
Eudrilus eugeniae	gut	+	+					+	+	+			Prabha *et al*. 2007b
Eisenia fetida	gut	+	+					+	+	+			Prabha *et al*. 2007b
Eudrilus eugeniae	gut/vc	+	+	-	+	+	+			+			Munnoli 2007
Eisenia fetida	gut/vc	+	+	-	+	+	+			+			Munnoli 2007
Megascolex megascolex	gut/vc	+	+	-	+	+	+			+			Munnoli 2007
Eudrilus eugeniae	skin	+	+	+	+								Munnoli 2007
Eisenia fetida	skin	+	+	+	+						+	+	Munnoli 2007
Megascolex megascolex	skin	+	+	-	+						+	+	Munnoli 2007

A, Amylase; AP, Acid phosphatase; C, Cellulase; Ch, Chitinase; E, Endogluconase; G, Gelatinase; L, Lipase; NR, Nitrate reductase; P, Protease; U, Urease; + Positive; - Negative; vc, vermicast with gut/tissue/VC/earthworm skin (**Table 9**) has been reported in several studies.

Vermicomposting involves bio-oxidation and stabilization of organic material through the interactions between earthworms and microorganisms. Although microorganisms are mainly responsible for the biochemical degradation of organic matter, earthworms play an important role in the process by fragmenting and conditioning the substrate, increasing the surface area for growth of microorganisms, and altering its biological activity (Domínguez 2004; Domínguez and Edwards 2004; Sangwan 2007). High population densities of earthworms in vermicomposting systems result in a rapid turnover of fresh organic matter into earthworm casts (Aira *et al.* 2003) or VCs. These casts can be deposited both inside and outside of a fresh organic matrix, thereby affecting the decomposition rates in their proximity because of their different microbial composition. During the vermicomposting process, earthworms can modify the diversity and abundance of the micro flora directly, by selective feeding, or by stimulation of a particular group of microorganisms (Pedersen and Hendriksen 1993; Devliegher and Verstraete 1995; Wolter and Scheu 1999; Tiunov and Scheu 2000); moreover, earthworms exert other indirect effects on microbial communities, such as microbial dispersion and the release of additional food resources in their casts. For all these reasons, better knowledge of the changes in the chemical and biochemical properties of organic wastes during the vermicomposting process is required to understand the effect of the earthworms' activities on the process of biodegradation. Plaza *et al.* (2004) used pig slurry as the organic waste since the number of pig-breeding farms in Spain is increasing and because most of the produced pig slurry is applied without any treatment to the soil. The main objective of their study was to monitor the short-time changes (fresh manure to casts) of pig manure, after passing through the gut of the epigeic earthworm *E. eugeniae* under controlled environmental conditions. They also monitored the changes in available pools of C and N of pig slurry; moreover, they analyzed microbial biomass and activity (respiration and substrate utilization patterns, Biolog Ecoplate) and enzyme activities, since these have been shown to be reliable indicators of the response of microbial communities to variations in environmental conditions (Carreiro *et al.* 2000); microbial activities are very important in regulating soil properties (Nannipieri *et al.* 1990; Dick 1992).

The gut environment is anoxic, pH 6.9 with about 50% water content. The gut bacteria are enriched in total carbon, organic carbon, and total nitrogen with a carbon to nitrogen ratio of 7 (Horn 2003). The bacteria isolated from vermicasts and earthworm skin were endospore-forming Gram$^+$ *Bacilli* (Munnoli 2007). The bacterial counts in gut/VC was higher than the surrounding soil (Edwards and Lofty 1977; Edwards and Bohlen 1996; Munnoli 1998, 2000, 2007; Suthar 2008a; Nechitaylo *et al.* 2010) and as the organic matter ingested passes through the gut, it undergoes biochemical changes effected by gut-inhabiting bacteria (Munnoli 2007).

Therefore there is a greater role played by the DNA of microorganisms and earthworm species. The genetic make-up of the strains and environment has a profound influence on the efficiency of earthworms in the bioconversion process (Giraddi 2009) and in the assessment of diversity and community composition (Thakuria *et al.* 2010).

The extraction of genomic DNA from various parts of the adult *E. eugeniae* entire worm, gut, clitellum, prostomial, and tail region using the CTAB method with few modifications (Murray and Thompson 1980) suggested that the clietellum was the best region to get high quality DNA. The studies on genetic diversity pin pointed clitellum to be the best part for DNA extraction for *E. fetida* and *P. excavatus* (Giraddi *et al.* 2009).

This technique is also suitable for extraction of DNA from other earthworm species such as *Lumbricus terrestris* (El Adloun *et al.* 1995) and *Lumbricid* earthworms (Pop *et al.* 2002). The extraction of DNA from *L. terrestris* (Hammond *et al.* 1998), *Lumbricus rubellus* (Morgan *et al.* 1999) and *Octolaseum lacteum* (Erseus 2000). The high quality of DNA suggests the efficiency of *E. eugeniae* in the bioconversion process. Our study on bioconversion of press mud supports the superiority of *E. eugeniae* over *E. fetida* and *M. megascolex* (Munnoli 2007).

The diversity of eight bacterial groups from fresh soil, gut, and casts of the earthworms *L. terrestris* and *Aporrectodea caliginosa* were studied by single-strand conformation polymorphism (SSCP) analysis using both newly designed 16S rRNA gene-specific primer sets targeting *Alphaproteobacteria*, *Betaproteobacteria*, *Gammaproteobacteria*, *Deltaproteobacteria*, *Bacteroidetes*, *Verrucomicrobia*, *Planctomycetes* and *Firmicutes* and a conventional universal primer set for SSCP, with RNA and DNA as templates. Whereas using fluorescence *in situ* hybridization. *Bacteroidetes*, *Alphaproteobacteria*, and *Betaproteobacteria* were predominant in communities from the soil and worm cast samples, some specific bacterial taxonomic groups maintain their diversity and even increase their relative numbers during transit through the gastrointestinal tract of earthworms (Nechitaylo *et al.* 2010).

Bacterial communities were detected using automated ribosomal intergenic spacer analysis of 16S and 23S genes and ribotype data was used to assess diversity and community composition. Using soil and earthworm samples collected from adjacent wheat–barley and grass–clover fields showed that the anecic *Lumbricus terrestris* and *L. friendi*, the endogeic *Aporrectodea caliginosa* and *A. longa* (classically defined as anecic, but now known to possess endogeic characteristics) contain ecological group-specific gut wall-associated bacterial communities. The abundance of specific gut wall-associated bacteria (identified by sequence analysis of ribotype bands), including *Proteobacteria*, *Firmicutes* and an *Actinobacterium*, was dependent on the ecological group (Thakuria *et al.* 2010).

Therefore studies on DNA extraction from earthworms and bacteria isolated from various body parts will be of significance in bioconversion of organic wastes and in increasing the efficiency of vermicomposting systems (Munnoli 2007).

EFFECT ON SOIL FERTILITY

Effect of vermicompost on nutrients and microbial population

Soil microorganisms play an important role in improving soil fertility and crop productivity due to their capability of fixing atmospheric N, solublizing insoluble P and decomposing farm wastes resulting in the release of plant nutrients (Joshi and Kelkar 1952; Tewatia *et al.* 2007). There are varying reports on the nutrient contents of vermicasts (Narayan 2000; Hameed 2002; Reddy *et al.* 2002; Manna *et al.* 2003) whereas Rao and Lakshmi (2002) ascertained nutrient values for a good VC based on their study on urban wastes also suggested the rate of application of VC (**Table 10**). Along with soil microorganisms, the addition of VC also benefits soil fertility in terms of nutrients and microbial population, as presented next.

Teotia *et al.* (1950) reported a 3.4- to 5.4-fold increase in bacteria compared to the surrounding soil. Ghilarov (1963) claimed that the number of microorganisms in earthworm casts was 1.64-, 1.35- and 1.97-fold higher than in regular soil in three different fields, namely oak forest, rye and grass, respectively. A 5- and 40-fold higher level of bacterial counts was reported in vermicasts more than the surrounding soil in the case of potato peel waste (Munnoli 1998) and paper industry sludge (Kavian *et al.* 1996), respectively. An increase in hydrolytic microflora in vermicomposting of organic solid wastes was reported by Singh (1997b) and Munnoli (2007). The moisture content of VC is an essential environmental condition for the survival of beneficial microorganisms, irrespective of whether earth-

Table 10 Composition of good quality vermicompost and rate of application for various crops.

Parameter	Vermicompost	Crop	Rate/Th^{-1}
pH	7-8.5	Cereals	5
Organic carbon (%)	20-30	Pulses	5
Nitrogen (%)	1.5-2.0	Oil seeds	12.5
Phosphorus (%)	1-2	Spices	10
Potassium (%)	1-2	Vegetables	12.5
Calcium (%)	1-3	Fruits	7.5
Manganese (pap)	1-2	Cash crops	15-17.5
Sculpture (%)	<1	Plantations	7.5
Moisture (%)	15-20	*Horticulture crops	100-200 g/tree
C/N ratio	15-20:1	*Kitchen garden and pots	50 g/pot
Micronutrients (pap)	200		

Sources: *Purakayastha and Bhatnagar 1997; Rao and Lakshmi 2002

Table 11 Comparison of microbial counts of traditional and vermicomposts.

Type of microbes	Traditional compost	Vermicompost
Bacteria	$143 \times 10^{+7}$ g^{-1}	167.29×10^{7} g^{-1}
Fungi	39.61×10^{5} g^{-1}	96.25×10^{5} g^{-1}
Actinomycetes	365.27×10^{6} g^{-1}	419.62×10^{6} g^{-1}
PP solution	195.61×10^{5} g^{-1}	168.20×10^{5} g^{-1}
N_2 fixing bacteria	92.58×10^{5} g^{-1}	96.62×10^{5} g^{-1}
Thio-sulphate oxidizer	315.38×10^{5} g^{-1}	569.29×10^{5} g^{-1}

Source: Bhattacharya *et al*. 2000

Table 12 Vermicompost contents.

Humus	30-50%
N	0.72%
K	0.74%
Carbon	40-57%
Hydrogen	4-8%
Oxygen	33-54%
pH	4 to 9
C/N	20

Source: Senthil Kumar 2002

Table 13 Comparison of **c**haracteristics of human faeces and its vermicomposts.

Parameter	[a]Values for faeces	[a]VC of faeces
Moisture content %	80 ± 5	43 ± 5
Bulk density Kg/M^3	1200 ± 200	720 ± 100
pH	5.3 ± 0.2	8.0 ± 0.3
Electrical conductivity mmho/cm	60 ± 15.0	28.5 ± 3.0
Total Nitrogen mg/g dry weight	41 ± 4.0	28 ± 0.2
Total organic carbon mg/g dry weight	415 ± 15	175 ± 10
C:N	10.5 ± 1.0	6.5 ± 0.5
Phosphorous as P_2O_5 mg/g dry weight	11 ± 2.0	23.5 ± 2.5
Potassium as K_2O mg/g dry weight	28.0 ± 1.7	65.0 ± 7.5
Total coli forms MPN/g	5.0×10^{9}	<3.6

[a]Values are mean ± standard deviation based on 48 samples
Relative humidity: 50-80%; reactor surface area 0.135 m^2
Stocking density: 4 Kg/m^2; feed application rate: 1.2-1.5 Kg/m^2 ; replicates 4
Source: Yadav *et al*. 2010

worms continue to live or not. The decrease in moisture content will bring down the level of CFUs (colony forming units) and organic carbon (Scheu 1987; Parthasarathi and Ranganathan 2001; Parthasarathi 2006).

A study on microbes in the gut of earthworms revealed an increase in the number of bacteria and actinomycetes compared to soil, following an exponential law (Edwards and Lofty 1977; Parle 1963). In general, the level of microorganisms in the gut and vermicasts of earthworms can be used as one of the measures to evaluate VCs, allowing us to say that earthworms are important in inoculating the soil and their casts are the foci for dissemination of soil microorganisms, which will elevate the overall fertility of soil. Monson *et al.* (2007) reported an increase in nutrients of kitchen waste vermicomposted by *E. eugeniae*: in N, from 1.31 to 2.12%; in P, from 0.121 to 0.7%; in K, from 0.45 to 0.48% and the C: N ratio decreased from 32.45 to 13.66%. A significantly higher number of microbes were observed in experimental plots treated with VC. N-fixing bacteria were also higher in plots to which VC was applied after harvest of the crop. A higher microbial load was also observed in paddy fields to which VC was applied (Kale *et al.* 1992). An increase in the microbial population was recorded with potato waste using *Pheritima elongata* (Munnoli 1998) and with press mud waste using *E. fetida*, *E. eugeniae* and *Megascolex megascolex* when compared with the surrounding soil (Munnoli 2007). Meena and Renu (2009) reported a increase in nutrients when press mud was blended with saw dust and treated using three different earthworm species *E. fetida*, *E. eugeniae* and *P. excavatus* individually (monocultures) and in combination (polycultures).

The effect of VC on the microbial population in a soil environment was reported to be best with VC prepared out of a combination of leaf litter; straw, grass and water hyacinth (VC1) compared to VC of leaf litter (VC2), home garbage (VC3) and partially decomposed cow dung (VC4) when applied at a rate of 5% (w/w). The fold increase was 2.16, 1.83, 1.71 and 1.69 in bacteria, 1.49, 1.30, 1.52 and 1.40 in actinomycetes, 2.89, 2.76, 2.38 and 2.47 in fungi for VC1, VC2, VC3, VC4, respectively (Sahu *et al.* 2000). Fragoso *et al.* (1993) also reported similar findings. Kale *et al.* (1992) reported that earthworm burrows lined with earthworm casts are an excellent medium for harboring N-fixing bacteria; Loquet *et al.* (1977) and Bhattacharya *et al.* (2000) also recorded an increase in the microbial count of VCs compared to traditional compost (**Table 11**). The major part of inorganic N occurred as ammonia, which was rapidly converted to nitrate (Parle 1963). Kumar (2000) reported the contents of VCs (**Table 12**). The characteristics of source-separated human faeces and VC prepared out of source separated human faeces by precomposting faeces using bulking materials (VC) using *E. fetida* (**Table 13**) showed that pathogens were eliminated and nutrients were enhanced (Yadav *et al.* 2010).

The water-holding capacity of soil increased due to an increase in colloidal materials like earthworm mucus, a good absorbing agent in VC, and the polysaccharide content of earthworm casts was much higher than the soil but did not vary with changes in stability of total and mineral N. Earthworms increased the water-holding capacity of New Zealand soils by about 17% (Stockdrill and Lossens 1966).

E. fetida vermicasts from sheep manure alone and mixed with cotton wastes were analyzed for their properties and chemical composition every 2 weeks for 3 months and compared with the same manure without earthworms. Earthworms accelerated the mineralization rate and resulted in castings with a higher nutritional value and degree of humification, suggesting that this kind of industrial waste can be used in vermicomposting (Albanell *et al.* 1988). Similarly, accelerated mineralization and humification of solid paper pulp mill sludge with earthworms in comparison to without earthworms was reported by Elvira *et al.* (1996). Athanasopoulos (1993) used vermitechnology to manage aerobically stabilized effluents of the dried vine fruit industry using *L. rubellus*. The COD removal was 95% with 0.1 loading and 0.15 Kg COD/m^{-2} d.

Bird and Hale (1982) undertook work on sludge contaminated with heavy metals from industrial sources and found an increase in heavy metal concentration in VC-applied soil above the prescribed limits, suggesting that vermicomposting could be used for treating waste contaminated with metals, etc. The best results of cotton waste with cattle manure was reported by Zajonc and Sidor (1990) whereas Edwards and Bater (1992) tried vermicomposting using urban and industrial sources. Madhukeshwar *et al.* (1996) claimed that any kind of organic waste generated in an agro-based industry or biotechnology unit when treated with earthworms would be a resourceful VC.

In Columbia, more than 1 metric tonne of coffee pulp was produced every year treated by composting by using turned piles into low quality compost. When E. *fetida* was used for vermicomposting it resulted in an increase in P, Ca, and Mg and a decreased of K (Orozco *et al*. 1996).

Giraddi and Tippanavar (2000) studied the biodegradation of organic solid wastes using earthworms. Waste from the fruit pulp, biscuit and sugar industries were bio-degradable in field designs using *E. eugeniae*, *E. fetida*, and *P. excavatus* for waste management. The wastes were bio-converted to compost in 40-90 days. The quality of the compost obtained had increased micro- and macronutrients. Waste from the olive oil industry, either alone or mixed with cattle manure, was a suitable substrate for VC (Moreno *et al.* 2000). Kalpana (1978) reported the possibility of mixing sewage sludge and other materials like pulp paper sludge or lignin-rich waste and inoculating earthworms for biodegradation. Butt (1993) explored the possibility of treating paper mill sludge with spent yeast from the brewery industry using *L. terrestris* whereas the same industrial waste was treated with *E. andrei* by Elvira *et al.* (1998). They also investigated the vermicomposting of sludge from paper mill and dairy industries mixed with cattle manure using *E. andrei* in 6-month pilot scale experiments where the number of earthworms and biomass increased significantly. The VCs were rich in N, P, and K and had good structure, a low level of heavy metals, lower conductivity, high humic acid contents and good stability and maturity. They also reported the growth of *E. andrei* by using paper mill and dairy mill sludges in pure waste by mixing with different proportions of cattle manure (Elvira *et al.* 1998). Studies of the possible use of paper and dairy mill sludge during vermicomposting confirmed that such material might be a valuable component of breeding medium for *E. fetida* earthworms. But the contents of mineral N and total K were low (Zablocki *et al.* 1999).

Soil aggregation

Soil aggregation plays an important role in the soil-air ecosystem and provides a base for the life-supporting system of microflora and -fauna. Aggregates are mineral granules joined together in such a manner that they can resist wetting erosion or compaction and remain loose when the soil is either dry or wet. A soil that is rich in aggregates remains well aerated and drained, so that formation of new aggregates is therefore of prime importance in soil fertility (Edwards and Lofty 1977; Carpenter *et al.* 2008; Munnoli and Bhosle 2008).

Due to earthworms' activity extensive borrows are formed, which result in loose and porous soil. These macropores improve water absorption, drainage, aeration to roots and root propagation (Nobel *et al.* 1970). Degraded soils with earthworms alone, or in combination with plants, can develop decreased bulk density and enlarged porosity and structural stability (McColl *et al.* 1982; Aina 1984). Shaw and Pawluk (1986) reported that earthworm activities tend to increase microbial respiration in casts, burrow walls or in bulk soils. Zhang and Schrader (1993) compared the effect of earthworms *L. terrestris*, *Allolobhophora longa* and *Apporrectodea caloginosa* on stabilization of soil aggregates from casts and burrow walls with those of natural soil and revealed that total content of polycharides increased by 35 to 87% for casts and by 33 to 46% for the burrowing wall material which showed the strongest effect on the interparticle bonding of the reformed aggregates in terms of tensile strength and water stability.

Stewart *et al.* (1988) reported that defecated casts became stable after drying and also presented evidence that earthworms initiate the formation of stable soil aggregates in land degraded by mining practice. Earthworm burrows and soil aggregates promote the infiltration rate and reduce soil surface erosion (Springett *et al.* 1992). Abbasi and Ramasamy (2001) reported the burrowing activity of *L. terrestris* and *A. nocturna* up to a depth of 150-240 cm, which translates into the subsoil to the top layers. The unproductive subsoil undergoes chemical changes during its passage through the alimentary canal of the earthworm and is immediately available for crop growth.

According to Edwards and Thomson (1973) earthworms can act as bioconcentrators for heavy metals and toxic materials. These toxic materials are stored in the tissues of earthworms, which help to detoxify polluted soil. The resinous substances excreted by earthworms together with humus produced help to increase the water-retaining capacity of soils. Besides, bulk density of soil was reduced by 30%, which provides vast internal spaces to accommodate air and moisture and an enormous surface upon which hydrolytic and oxidative catalyses can be affected by soil micro-organisms, enzymes and humid substances (Kolher 1995).

The best soil: cow dung proportion is 1: 3 (Munnoli and Bhosle 2009). The soil used for the purpose of experimentation was 850 µm sieve size and below. The particle size distribution was based on the results of sieve analysis. 50.06% of soil was retained above 850 µm, which indicates the aggregation of soil particles with *E. fetida*; 45.23% of soil was retained by *E. eugeniae* and 54.85% by *M. megascolex.* Therefore, aggregation was greater in *M. megascolex*. The comparison of particle size distribution of vermicomposts reveals that earthworms are responsible for grinding the substrate, which makes the particle size distribution finer. The grinding capacity of *E. eugeniae* was greater than that of *E. fetida* and *M. megascolex*; *M. megascolex* had the highest aggregation capacity (Munnoli and Bhosle 2009). These results correspond to those for *P. elongata* when employed for the treatment of potato peel and canteen wastes (Munnoli *et al*. 2000, 2002).

In a laboratory experiment 1 g of press mud vermicompost obtained using *E. eugeniae* and bacterial inoculum (bacterial consortia prepared from vermicompost of press mud using *E. fetida*, *E. eugeniae* and *M. megascolex* had a viable count of 168 × 10^9 g/ml) retained 74.10% on a 90 µm sieve indicating that the soil passed through a 90-µm sieve aggregated by the vermicompost (Munnoli and Bhosle 2008). This indicates the clear role of earthworms and microbes in aggregating soil, which is of utmost importance in increasing water holding capacity and changing particle size.

Soil and water

The essential part of plant growth is the continuous availability of water, but the requirement of water varies depends upon the atmospheric condition and nature of plants.

Soil is capable of being a storehouse of water and becomes a main source of water for land plants. The major losses of soil water are through the process of transpiration by plants and evaporation from the soil surface and the combined process is known as evapo-transpiration (Biswas and Mukharjee 1994). If the organic content in a given soil is more than about 10% the max dry density of compaction decreases considerably. The optimum moisture content increases with an increase in organic content (Braja Das 1987). A similar experiment on compaction conducted by adding 200 g of VC of press mud prepared by employing *E. fetida*, *E. eugeniae* and *M. megascolex* to 3 kg of soil

Table 14 Effect of vermicompost on growth parameters of selected vegetable and medicinal plants after (90 days values).

Parameter studied	**Vegetable plants**				**Medicinal plants**			
	Hibiscus esculentus		***Salanum melongena***		***Adhatoda vasica***		***Solanum trilobatum***	
	Control	**VC**	**Control**	**VC**	**Control**	**VC**	**Control**	**VC**
Root length	2.90	4.00	3.25	3.90	2.25	3.90	2.1	4.3
Shoot length	14.65	22.9	19.10	27.25	12.25	17.9	11.95	18.25
No of leaves	10	25.0	19.0	27.0	14.0	17.0	24.0	29.0
Germination percentage *	40	75.0	42	79.0	-------	-------	------	-----
Source : Prabha *et al.* 2007								

*Values are expressed as mean of four replicates

showed lower densities compared to the density of soil indicating an increase in voids and water holding capacity (Munnoli 2007). Therefore adding VCs with aggregation properties and higher water holding capacitates will not only increase the yield of crops but also provide nutrients required for growth. When applied to the surface it takes part in maintaining the soil evaporation to a minimum by absorbing atmospheric moisture as a good adsorbent and influences the energy balance (Rodale 1967; Nobel *et al.* 1970 Edwards and Lofty 1977; Munnoli and Bhosle (2008).

APPLICATION OF VERMICOMPOSTS

Crop growth and yield

To conclude, this review will now cover the application of VCs with special emphasis on fruit-bearing plants and their yield. The species of earthworms that have been reported as effective for *in situ* vermiculture are *Lumbricus rebellus* (Edwards and Lofty 1977), *Lumbricus terrestris* (Atlavinyte and Zim-kuviene 1985), *A. calignosa*, *A. chlorotica*, *A. longa*, *L. terrestris* (Edwards and Barer 1992), and *E. eugeniae*, *E. fetida*, and *M. megascolex* (Munnoli 2007).

Banana plants grew well when VC was applied (Barve 1992) with a mean bunch weight of 15 kg/plant, more fingers/branch and more reducing sugars. VC at a rate of 250,000 worms/ha resulted in a significantly reduced harvesting time in 'Rajapuri' banana (Athani *et al.* 1999). More total sugar, non-reducing sugar, maximum shell life, highest total suspended solids (TSS), less acidity and maximum TSS: acid ratios were obtained by applying *in-situ* vermicomposting at 125,000 worms/ha in both plant and ratoon crop in banana cv. 'Rajapuri' (Athani *et al.* 2000). Incorporation of VC at 4 t/ha improved the quality of grapes (*Vitis vinifera* L.) with respect to taste and firmness of attachment (Barve 1992).

Venkatesh (1995) observed a significantly higher amount of ascorbic acid, total sugars and decreased titrable acidity in grape when applied with VC at 4 t/ha and farm yard manure 2.5 t/ha compared to inorganic fertilizers. Venkatesh *et al.* (1997) revealed that *in situ* vermiculture and use of VC with graded levels of chemical fertilizers or VC alone increased the yield of grapes (*V. vinifera*) significantly more than the control which had also been reported earlier (Gunjal and Nikam 1992; Haung and Zhao 1992).

Application of VC at 2.5 t/ha was reported to significantly increase the yield and sweetness, and reduce the harvesting period compared to the control, whereas application in combination with neem cake gave significantly higher and better yield than control and higher yield and improved quality of custard apple (*Annono squamosa*) (Patnaik 1992) by sole application of VC. The application of VC increased the growth and yield of peppers (*Piper nigrum*) significantly, including increased leaf area, plant shoot biomass, and marketable fruit weights. The increase in growth and yield of pepper may be due to the application of VCs to soils which increased the microbial biomass, humic materials, and plant growth-influencing substances (Norman *et al.* 2005). Similarly strawberry (*Fragaria ananassa*) growth and yield increased significantly, including increases of up to 37% in leaf area, 37% in plant shoot biomass, 40% in number of flowers, 36% in number of plant runners and 35% in marketable fruit weight (Arancon 2004). Higher growth, yield, quality of turmeric (*Curcuma longa* L.). (Sanwal *et al.* 2007) and tomato (*Solunum lycopersicum*) and okra (*Hibiscus esculanta*) were also reported when VC was applied (Premshekhar and Rajashree 2009a, 2009b). Schrader *et al.* (2008) reported the decline of immunoreactive Cry1Ab proteins from maize (*Zea mays* L.) residues using *L. terrestris* and *Aporrectodea caliginosa* in separate incubations with earthworms compared to the absence of earthworms. Prabha (2007a) showed that growth parameters (root length, shoot length, number of leaves) of vegetables *Hibiscus esculentus* and *Salanum melongena* and medicinal plants (*Adhatoda vasica* and *Solanum trilobatum*) showed higher values in VC applied after 90 days; the germination percentage was also higher in vegetable plants to which VC was applied (**Table 14**).

Vermicomposting of rice-straw using three species of earthworms viz., *Perionyx excavatus* Perrier, *Octochaetona phillotti* (Michaelsen) and *Octonochaeta rosea* (Stephenson) was pre-pared. Plant nutrient contents of these VCs and their effects on sorghum growth in relation to the effects of normal compost (without earthworms), that of chemical fertilizers (urea and single super-phosphate applied at 40 kg/ha) and sole soil were investigated. VC produced by the three species of earthworms differed in their nutrient concentrations, but possessed higher concentration of total N and Ca than that of the normal compost. VC produced by *P. excavatus* possessed higher concentrations of total N, available P and K and Ca and Na than the compost produced by *O. rosea*. The growth of sorghum in the mixtures of 75% of VC produced by *P. excavatus* and 25% soil was significantly higher than that of the plants grown in mixtures of VC produced by *O. phillotti* and *O. rosea* and soil, normal compost, soil mixed with chemical fertilizers and sole soil (Vikram Reddy and Katsumi 2004).

The application of VC provided better yield than other organic manures and the control in marigold (*Calendula officinalis*) (Singh *et al.* 2007) cv. 'Pant Hartima'. Coriander growth improved was observed with treatment of 50% (recommended dose of fertilizer, 60: 30: 20 Kg/ha) + 50% VC (Bodamwad *et al.* 2009). A laboratory experiment conducted using *Octolasion tyrtaeum* on maize, barley, and wheat showed better growth parameters shoot/root (Bisht *et al.* 2006). The application of VC on the growth/yield of sugarcane (*Saccharum officinarum*) was reported (Katharissan 1991; Varamali 1993); the yield of sugarcane increased from 125-135 to 200 tha^{-1} when VC + CD together with agricultural residues were applied (Laxmanan 2006). Experiments conducted on separate garden plots (1 × 0.5 m) using VC of press mud (2 Kg/m) employing *E. eugeniae* gave higher growth and yield for the vegetables brinjal (*Solanum melongena*) and ladyfinger (*Hibiscus esculenta*) than VC from *E. fetida* and *M. megascolex*, but always higher than the control plot without VC. The order of increase in growth/yield was *E. eugeniae* > *E. fetida* > *M. megascolex* (Munnoli 2007). Yield of onion (*Allium cepa*) increased significantly when 100 and 50% N was applied through VC produced by *E. eugeniae* using decomposed tendu leaf powder along with 50 kg /ha P + 50 kg/ha K in separate plots (Rao *et al.* 2010). The rate of application of earthworms for *in-situ* vermiculture along with the species employed (**Table 15**) and application of VC (**Table 16**)

Table 15 Experimental studies on *in-situ* vermiculture showing growth/yield attributes.

Earthworm species	**Crop/fruit/vegetable**	**Rate of application of verms/ amendment**	**Reference**
Eudrilus eugeniae	Sapaota (*Manilkara achras*)	2 00000 h^{-1}	Baphana 1992
Aporrectodea. trapezoids	Wheat (*Triticum sativum*)	100 or 300 m^{-2}	Stephens and Davoren 1996
Eudrilus eugeniae	Papaya (*Glomus fasciculatum*)	200000 h^{-1}	Shivaputra 2002
Eudrilus eugeniae	Papaya (*Glomus fasciculatum*)	2 t/h^{-1}	Shivaputra 2002
Eisenia fetida	*Capsicum anuum* (cv. Punjab Lal)	400 g fym + 400 g vc/plot	Neena and Battish 2005
Eudrilus eugeniae	Okra (*Hibiscus esculenta*) (Bhindi)	2 t/h^{-1}	Birader *et al.* 2006
Eudrilus eugeniae	Safflower (*Carthamus tinctorius* L.)	2 t/h^{-1}	Naik *et al.* 2007
Megascolex mauritii	Sorghum bicolor or *Sorghum japonicum*	50 kg/m^{-2}	Vannessa and Rajeswari Anad 2008
Eudrilus eugeniae	Banana cv. Rajpuri (*Musa* AAB)	250000 h^{-1}	Athani *et al.* 2009
Eudrilus eugeniae	Citrus leaf miner (*Phyllocnistis citrella* Stainton)	250000 h^{-1}	Birader *et al.* 2009

FYM = farm-yard manure; VC = vermicompost

Table 16 Experimental studies on application of vermicompost (VC) showing growth/yield attributes.

Crop/fruit/vegetables/garden plants	**Rate of application of VC**	**Reference**
Banana cv. Rajpuri (*Musa* AAB)	1.25 lakh h^{-1}	Athani and Hulamani 2000
Diffenbachia/Aglonima	500 g pot^{-1}	Munnoli 2007
Diffenbachia/Aglonima	500 g pot^{-1}	Munnoli 2007
Diffenbachia/Aglonima	500 g pot^{-1}	Munnoli 2007
Wheat (*Triticum sativum*)	3.8 vc + 2.4 pm t h^{-1}	Channabasanagouda *et al.* 2008
Amaranthus L.	NA	Sreedevi *et al.* 2008
Spinach (*Spinacia oleracea* L.)		
Tomato *Solunum lycopersicum*		
Rice (*Oryza sativa* L.)	50% amended with VC	Panday and Yadav 2009
Tomato (*Solanum lycopersicum*)	5t h^{-1}	Premshekhar and Rajashree 2009a
Okra (*Hibiscus esculenta*) (Bhindi)	5t h^{-1}	Premshekhar and Rajashree 2009b
Soybean (*Glycine max* L.)	2 t h^{-1}	Meenatchi *et al.* 2010

NA: not available

which have shown growth and yield attributes (increase in height, mean bunch weight, leaves, fruits, nutrients) for horticultural crops suggest the significance of VC in the field of agriculture and food production, which is of prime importance for a developing country like India.

Vermiwash

Providing a proper bed slope to vemibeds facilitates the collection of vermiwash (VW; Kale 1994) which is essentially a bio-liquid consisting of colloidal matter/particles of VC in suspension that can be used as a spray which will act as an insecticide and or can be applied in the form of a liquid fertilizer (Munnoli 2007). VC can be collected by using a plastic container/metal drum of suitable capacity with a tap at the bottom (Gorakh Nath 2009) by culturing *E. eugeniae* on organic substrates (65% pre-composted crop wastes and 35% animal manure; Giraddi 2001). VC has been used as a rooting material and for establishment of tomatoes in nurseries with improved germination and seedling growth when medium was treated with VC extract (Anad *et al.* 1995). Earthworm body fluid or VW formed clear inhibitory zones against some plant pathogens in Petri dishes (Shobha 2005). VC as produced from fruit, vegetable and cotton waste by redworms (*E. fetida*) while tap water served as the control (Zaller 2006). Foliar application (spraying) of VC extracts did not affect plant growth, biomass or nutrient allocation, or yields and number of fruits of three tomato varieties. Natural infection of leaves, stems and fruits by *Phytophthora infestans* was generally very low under the experimental conditions; however, across varieties, only half as many VC-sprayed plants showed clear signs of *P. infestans* infection as water-sprayed plants; the severity of infection was unaffected by the two spraying treatments. The use of VC might be considered more in organic farming not only as a substitute for peat in potting media but also as foliar sprays for fertilization and biological disease prevention (Zaller 2006).

VC extract and VW have been used as a media for induction for two varieties of carnation, *Dianthas caryophyllus* L. (Edwards and Bohlen 1996) whereas Ashwini (2004) showed a similar effect on root induction in cuttings of two varieties of carnations. Zambre *et al.* (2008) reported the presence of various enzyme activities associated with VW like amylase, protease, urease and phosphatase and nitrogen-fixing bacteria like *Azotobacter* sp., *Agrobacterium* sp. and *Rhizobium* sp., all phosphate-solubilizing bacteria. They also showed the effectiveness of VW on cowpea (*Vigna sinesis*) plant growth under laboratory conditions: Higher plant growth was noticed on the 3rd and 15th day with test plant supplied with VW than without VW. A similar effect of VW prepared from dried cowdung using *Eudrilus eugeniae* on productivity of African marigold (*Tagetes erecta* L.) was observed with pot-culture experiments (Shivasubramanain and Ganeshkumar *et al.* 2004). Higher yield in chilli (*Capsicum annuum* L.) and lower populations of thrips (*Scirtothrips dorsalis*) and mites (*Polyphagotarsonemus latus*) were recorded when 2.5 t/h VC along with six sprays of 1:1 VW using *E eugeniae* (George *et al.* 2007). A weekly application of VW increased radish (*Raphanus sativus*) yield by 7.3% (Buckerfield *et al.* 1999). Thangavel (2003) observed both growth and yield of paddy (*Oryza sativa* L.) increase with the application of VC and VW. The chemical analysis of VC and VW obtained from different waste combinations using *E. fetida* contained increased levels of plant growth supplements (**Table 17**) (Gorakh Nath *et al.* 2009). The moisture content, moisture retention capacity, nutrition levels (and subsequent palatability for silk worms) of mulberry (*Morus alba* L.) leaves were higher in VW when applied as a foliar application 150-200 mg/l (Venkataramana 2009, 2010). The impact of VW on seed germination, seedling growth and biochemistry of *Cyamopsis tertagonoloba* and *Trigonella foenum-graecum* was assessed under lab conditions with four experimental solutions, i.e. 100% VW, 50% VW, 5% urea solution and distilled water. Maximum germination occurred in 50% VW, while plant growth parameters (root length, shoot length, shoot/root ratio and leaves/plant) and chlorophyll in fresh leaves, total protein, total soluble sugars, starch were all significantly higher in their tissues in 100% VW. This suggests the use of VW as an ecologically safe and cost-effective alternative of synthetic plant growth promoters for sustainable farming practices (Suthar 2010).

Organic amendments, including VW collected from

Table 17 Nutrient content and different physio-chemical parameter in vermiwash (VW) obtained from vermicomposts (VC) of sheep, cow and horse dung using Eisenia fetida.

Parameter	**Sheep dung**		**Cow dung**		**Horse dung**		
	VW	**VC**	**VW**	**VC**	**VW**	**VC**	**Observation**
TOC (g/kg)	321.01 ± 1.80	216.01 ± 2.62	480.35 ± 4.21	199.00 ± 0.84	470.02 ± 1.34	215.15 ± 2.02	VW>VC
TKN (g/kg)	4.1 ± 0.08	08.0 ± 0.06	6.0 ± 0.02	15.2 ± 0.05	4.0 ± 0.08	8.0 ± 0.14	VC>VW
C:N ratio	85.81 ± 0.8	25.7 ± 0.60	86.2 ± 2.40	13.1 ± 1.71	132.0 ± 1.20	27.0 ± 1.40	VW>VC
TK (g/kg)	6.9 ± 0.12	7.4 ± 0.13	4.7 ± 0.07	4.8 ± 0.07	7.9 ± 0.06	8.0 ± 0.06	VC>VW
TP (g/kg)	3.0 ± 0.05	6.2 ± 0.08	3.7 ± 0.03	7.0 ± 0.05	6.8 ± 0.03	9.9 ± 0.05	VC>VW
pH	9.0 ± 0.06	7.3 ± 0.08	8.0 ± 0.02	6.8 ± 0.31	8.1 ± 0.06	7.0 ± 0.02	VC<VW
EC ds/m	0.94 ± 0.04	0.78 ± 0.02	2.15 ± 0.03	1.30 ± 0.02	2.10 ± 0.04	1.27 ± 0.08	VC<VW
TCa (g/kg)	1.3 ± 0.3	3.1 ± 0.3	1.3 ± 0.2	1.9 ± 0.3	1.3 ± 0.5	3.8 ± 0.6	VC>VW

Each value is the mean ± SE of six replicates. Significant variance ($P<0.05$) two way analysis of variance (ANOVA) was applied in between the different paramagnet of vermiwash of initial feed mixture and Final Vermicomposts.

Source: Gorakh Nath 2009

Table 18 Essential-amino-acid of *motto* and *kuru* compared with the WHO ideal protein.

Amino acid	**Percentage of (amino acid/ideal) x 100%**				**Per cent of total amino acids**
	***motto* smoked**	***motto* body**	***kuru* body**	***kuru* gut organs$_a$**	**WHO ideal protein$_b$**
Histidine	118	129	135	228	1.9
Isoleucine	167	164	165	214	2.8
Leucine	129	130	129	125	6.6
Lysine	128	133	128	131	5.8
Methionine	139	131	128	154	2.5
Phenylamynine	115	116	109	105	6.3
Threonine	146	137	138	162	3.4
Tryptophan	134	120	103	119	1.1
Valine	142	140	133	145	3.5

a: parts not eaten; b: Percent of total

Source: Paoletti *et al.* 2003

VC trays and diluted (1:20) could effectively control natural enemies *Nomuraea releyi* as indicated by mycosed *Spodoptera litura* larvae in a soybean (*Glycine max* L.) ecosystem (Abhilash and Patil 2008). Organic amendments (VC and VW) did not affect the activity of predator fauna (*Menochilus sexmaculatus* (F.) and *Chrysoperla cornea* (Stephens)) of chilli insect pests (Giraddi 2007).

Although there is limited literature on the use and quality of VW, many vermicomposting projects are being implemented in India, for example in Goa (Munnoli and Shivapur 2002; Munnoli 2007) and Chennai (Ismail 1997). In these locations, the beneficiaries are being trained well to collect VW, which is then used as a liquid biofertilizer.

EARTHWORMS: NUTRITION AND MEDICINAL VALUE

Ghatnekar *et al.* (1995) investigated the nutritional status of earthworms: 72% crude protein; worm meal was much better than yeast and fish meal; it has a biological value of 84% and 85% digestibility of protein with 79% net protein utilization and a protein efficiency ratio of 4%. The amino acid composition is far superior to snail, meat and fish meal, e.g. arginine is 4.13% in worm meal vs 3.4% in fish meal. Likewise, tryptophan is 2.29% in worm meal vs 1.07% in meat meal and 0.8% in fish meal (Ghatnekar *et al.* 1995). The amino acid composition of earthworm homogenate was found to correspond fairly well with the amino acid requirements of chickens (Tabago 1980).

The dry matter of an earthworm's body consists of 60-70% protein, 7-10% fat, 8-20% carbohydrate, 2-3% minerals, and a variety of vitamins (Edwards 1985; Ghatnekar 1995, 2000). Many scientists have reported high levels of nutrients in dried and powdered earthworms (Schulz and Graff 1977; Alberts *et al.* 1988; Edwards and Niederer 1988; Reinecke 1990; Ghatnekar 2000). Besides, earthworms can be used as a feed additive for pigs, fish and poultry since they have medicinal therapeutic value (Yoshida and Hoshii 1978; Nandeesh *et al.* 1987; Edwards and Niederer 1988; Edwards and Bohlen 1996; Ghatnekar 2000; Deolkar 2005). Several reports show the use of earthworms as fish bait: *Dendrobaena veneta* (Foyolle *et al.* 1997), *Pheritima elongata* (Bhawalkar 1995; Singh 1997); *Megascolex megascolex* (Munnoli 2007). The nutritional evaluation of dried earthworm meal (*Eisenia fetida*, Savingly, 1826)) included low levels in production diets for rainbow trout, *Salmo gairdneri* Richardson. There was no adverse effect on the growth performance or feed utilization efficiency of fish fed with diets (5-30%, w/w); however, a significant increase in the whole lipid content of fish fed with diets containing 5, 10 and 20% dried *E. fetida* meal (Stafford and Tacon 1985).

A number of soil animals are used as a source of protein in human populations in most regions of the world (DeFoliart 1989, 1999) and the number of invertebrates used exceeds 2000 (Ramos-Elprduy 1997). The earthworm species *Andiorrhinus motto* (Righi and Araújo 1999), *Andiorhinus kuru* are new species (Moreno and Paoletti 2002), both *Anellida: Glossoscolecidae*, commonly referred to as *mottu*

Table 19 Macromineral content of the *Kuru* and *Mottu* mgg^{-1} dry weight.

Earthworm species	**Ca**	**Mg**	**K**	**Na**	**P**
Kuru body (n=1)	2650	527	3430	997	3500
Kuru gut (n=1)	12900	457	4510	1240	4220
Motto body (n=1)	7070	792	897	548	3560
Motto smoked (n=7) mean	1020	730	6810	2160	5620

Source: Paoletti *et al.* 2003

Table 20 Essential-amino-acid composition (g/16N) dry matter and amino acids indices of earthworm meal and fish meal.

Essential amino acid /animal protein sources	**Earthworm meal**	**Fish meal (Chipeids)**
Arginine	2.83^a	5.34^b
Histidine	1.47^a	4.19^b
Isoleucine	2.04^a	2.62^b
Leucine	4.11^a	8.331^b
Lysine	6.35^a	10.96^b
Methionine	5.30^a	2.26^b
Phenylamynine	6.26^a	5.52^a
Threonine	4.33^a	5.28^a
Valine	4.33^a	5.88^b
Tryptophan	0.88^a	0.97^a

All values on the same row with different superscripts are significantly different $p<0.05$

Source: Sogbesan *et al.* 2007

Table 21 Amino acid concentration (g/100 g crude protein) in earthworms (this study) compared with earthworms (other sources).

Essential amino acids	*Eudrilus eugeniae*	*Libyodrilus violaceus*	*Hyperiodrilus africanus*	*Alma millsoni*	*Eisenia fetida*	Earthworm meal
Lysine	5.70	5.50	4.95	5.00	6.8	4.3
Histidine	3.30	3.36	2.80	3.01	2.6	1.6
Arginine	8.66	8.01	8.25	7.25	6.0	4.2
Threonine	0.95	1.02	1.12	0.80	5.2	3.0
Valine	4.22	4.00	4.09	3.96	4.7	3.0
Methionine	2.24	2.30	2.19	2.08	NG	NG
Isoleucine	5.50	4.80	5.00	4.50	4.3	2.6
Leucine	6.51	6.71	6.05	7.02	7.2	4.8
Phenylalanine	4.52	4.40	4.32	4.05	3.8	2.3

NG: Not given

Source: Dedeke *et al.* 2010b

Table 22 Macromineral profile of the four species of earthworm in this study.

Earthworm species	% Ca	% Mg	% K	Na (ppm)	% P
Libyodrilus violaceus	0.395	0.118	0.028	23.120	0.508
Hyperiodrilus africanus	0.494	0.154	0.027	19.813	0.456
Eudrilus eugeniae	0.476	0.148	0.032	39.896	0.528
Alma millsoni	0.318	0.146	0.045	74.209	0.701

* values indicate mean of ten replicates

Source: Dedeke *et al.* 2010a

and *kuru*, are widely consumed in Venezuela. The analysis of eviscerated *kuru* body proper, and whole and smoked preparations of *motto* for their content of protein and amino acids, fatty acids and 20 minerals and trace elements showed that the samples contained large amounts of protein (64.5–72.9% of dry weight), essential amino acids (**Table 18**), Ca and Fe together with notable quantities of other important elements (**Table 19**), indicating that these earthworms contain potentially useful quantities of many nutrients that are critical to the health of humans who consume them (Paoletti *et al.* 2003). In a similar study conducted on earthworms essential amino acids by Sogbesan *et al.* (2007) and Dedeke (2010b) (**Tables 20, 21**) and macrominerals by Dedike (2010a) (**Table 22**) highlight the nutrients for consumption by humans.

History as far back as 2600 BC mentions about the medicinal value of earthworms. The diseases for which earthworms were used as a remedy range from pyorrhea to post partial weakness, and from jaundice to an increase in sperm count and as an excellent aphrodisiac. In fact even today the Japanese put them in hot sake (wine made from rice) allowing them to secrete a milky liquid and then drink the protein brew, which they consider as an aphrodisiac (Ghatnekar *et al.* 1995). Nevertheless, scientific experimentation inclusive of double-blind clinical trials is quite limited (Ghatnekar 2002a, 2002b). Anti-inflammatory and antipyretic activities of *L. mauritii* (Kinberg) extract have been reported (Ismail 1992; Balamurugan *et al.* 2009).

SUSTAINABLE AGRICULTURE

Sustainable agriculture is the management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the quality of the environment and conserving natural resources (Bheemappa 1996). Vermitechnology can be a successful tool for utilizing agricultural residues and livestock dung to obtain a valuable organic manure, VC, which is a peoples' acceptance of ecological principles through low input agriculture which can be used to tackle many serious problems affecting world food production (Nayak and Rath 1996; Ranganathan and Christopher 1996; Anad Kumar *et al.* 1997; Divya 2001; Thimakareddy 2001).

For successful promotion of sustainable agriculture components like improving productivity (Sundari and Mathew 2010), crop diversity, integrated management of soil nutrients and crop pests, water management/suitable post harvesting technology and sound extension programmes need to be considered. This includes convincing rural populations to adopt different technologies in the farm sector and prepare compost and VC and use biogas individually or as a community effort to bring about sustainability in agriculture; use of agricultural residues would also indirectly alleviate poverty and ultimately increase the quality of life (Julka and Senapati 1993; Kamalabai and Suresh 2000; Munnoli and Shivapur 2002).

Increasing organic wastes due to human activities in rural and urban areas and industries is globally a serious constraint in the maintenance of a clean and healthy environment. Earthworms are effective converters of these wastes. Experiments have been successfully conducted for recycling organic wastes (Michell and Horner 1980; Singh 1997b; Munnoli 2007; Suthar 2007). Press mud is one such waste that, though a good organic amendment, contains an appreciable amount of toxicants and heavy metals although there is the potential to use it to extact nutrients (Pagaria and Totwat 2007). The use of biofertilizer prepared from press mud (VC and VW) will have beneficial effects on soil without any build up of toxicants (Munnoli 2007).

The bio fertilizer prepared out of organic wastes pro-

Table 23 Advantages of vermicomposts.

- General fertility level of the farm/garden is greatly improved
- Increased water holding capacity
- It makes ease of cultivation
- Eliminates valuable waiting time
- It reduces soil erosion and reduces flood hazards
- Increase the soil layer thickness every year
- It multiplies the microbial population
- Land can safely be plowed more deeply
- Hard pans will not form
- Heavy machinery not required
- The soil has greater aeration
- Soil made darker by humus absorbs heat more quickly and effectively
- Dry weather advantage
- It transpires less water through the leaves
- It is weed resistant
- Continuous application of vermicompost reduces the further requirement of manures year by year.
- It has residual no effects
- Aesthetically farms look better
- Less risk of crop failure
- It is much more immune to plant resistant
- The insect menace is reduced to minimum
- Very few poison sprays are required
- No chemical treatment are needed to seeds
- Farm animals fed on organically produced feeds are healthier
- Food tastes better when it is raised organically.
- Earthworms have high nutritional value to be used as medicine/food
- It will actually improve rain conditions
- Eliminates pathogens
- Higher residual nutrients leading to continuous enrichment of soil

Table 24 Large-scale vermicomposting operational units.

Name of the company/organization/village	Quantity TW^{-1}	Type of organic waste	References
Indian Aluminum Co. Ltd., Belgaum, India	18-20	Garbage	Jamble and Manivannan 1996
Venkateshwara Hatcheries, Pune, India	28	Poultry residue	White 1996
Karnataka Compost Development Corp., India	560-700	City waste	Naik and Gracy 1996
Hindustan Lever Ltd., Zahura, Punjab, India	7	Tomato skin seed	Singh 1997
Pepsi Foods Ltd., Channo, Punjab, India	7.0	Potato peel waste	Munnoli 1998
Doaba Cooperative Sugar, Punjab, India	4-6	Press mud	Singh 1997
FDC Ltd., Roha, India	21	Soya Residue	Singh 1997
American Resource Recovery (ARR), Westley, California, USA	650	Paper pulp generated from recycled cardboard, tomato residuals, manure, green waste	Anonymous 2000
Crow Worm Farms, Cleburne, Texas, USA	175	Dairy manure	Anonymous 2000
Paper Mill, Shimoga, India	10.5	Paper sludge	Ghatnekar *et al*. 2002b
Fruit and Vegetable Processing Industry Nasik, Maharashtra, India	NA	Organic waste	Ghatnekar *et al*. 2002a
Soyabean oil extraction plant, Madhya Pradesh, India	NA	Soybean residue	Ghatnekar *et al*. 2002a
Marmgoa Port Trust, Goa, India	5	Canteen waste	Munnoli 2007
Aoka Sangyo Co. Ltd., Japan	33	Pulp and food industry waste	Asha *et al*. 2008

vides several advantages (**Table 23**) which will lead to income generating activity and alleviation of poverty.

CONCLUSION AND FUTURE PROSPECTS

In recent years the ecological characteristics and beneficial effects of earthworms have been clearly demonstrated, focused by scientific research. Earthworms' activity influences the rate of soil turnover, mineralization and humification of soil organic matter. Improvement in the consistency of soil texture with a concomitant increase in porosity, infiltration and soil-water retention are other characteristics of worm-worked soils (Nobel *et al*. 1970; Edwards and Lofty 1977; Edwards and Bohlen 1996; Suthar 2008c; Munnoli and Bhosle 2009). There are multiple benefits of vermitechnology: low cost production of bio-fertilizer, environmental management of solid wastes and agricultural residues, enhanced soil productivity, tastier quality food, among others. Vermitechnology also aids in the reduction of soil salinity, soil erosion, with less runoff and wasteland development (Rodale *et al*. 1967; Kuhad and Singh 1993; Munnoli 2002, 2007).

Agro-based industries and food processing industries are yet to recognize the potential application of vermitechnology even though there has been stabilization of the use of this technology over the past 15-20 years, at least in India (Senapati 1992; Singh 1997b; Munnoli 2007). Many developed countries like the USA, UK and Japan have large-scale manufacture of VC from agricultural, municipal and industrial organic wastes on commercial basis (Raganathan and Christopher 1996); Cuba has 172 vermicomposting centers generating revenue (Nayak and Rath 1996). 3000 VC plants in Japan have a 5-50 t/m treatment capacity (Asha *et al*. 2008). Data available on organizations, industries and countries using VT as well as the treatment capacity is provided in **Table 24**.

As far as rural areas are concerned; it has to go a long way in educating rural people to adopt this technology. Non-Governmental organizations have to put in a lot of effort to extend this technology to the grass-root level. Development programs imply reassessment of farming practices to ensure the survival of earthworms, which then act as bio-indicators of sustainability (Munnoli and Shivapur 2002). Such an option becomes more attractive, economically and environmentally, as our understanding of the beneficial activities of balanced soil communities accrues and as the problems of soil degradation become more critical.

As far as scientific communities are concerned, there is an urgent need to develop research in the field of understanding biodegradation of organic matter by earthworms and microorganisms. The microbes isolated from VCs could separately be tested for biodegradation. The use of consortia developed based on enzyme activities and characteristics of particular industrial wastes could be used for designing an industrial waste treatment unit (Munnoli 2007). The application of VC for increasing crop yield has yet to be compiled region-wise based on the type of crops grown along with standards for the rate of application (Thomas and Trivedy 2002), although this review goes a long way towards covering that information gap in the dynamics of the soil-air-water-earthworm interface.

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