Dynamic Soil, Dynamic Plant ©2010 Global Science Books

Vermitechnology - The Emerging 21st Century Bioengineering Technology for Sustainable Development and Protection of Human Health and Environment: A Review

Rajiv K. Sinha[1*] • Sunil Herat[1] • Natchimuthu Karmegam[2] •
Krunal Chauhan[1] • Vinod Chandran[1]

[1] Griffith School of Engineering, Griffith University, Brisbane, QLD – 4111 Australia
[2] Department of Biotechnology, VMKV Engineering College, Vinayaka Missions University, Salem-636 308, Tamil Nadu, India
Corresponding author: * **Rajiv.Sinha@griffith.edu.au; rajivksinha@hotmail.com**

ABSTRACT

Vermitechnology is emerging as an environmentally sustainable, economically viable and socially acceptable technology all over the world consisting of several categories: vermi-composting (management of most organic wastes); vermi-filtration (treatment of municipal and several industrial wastewaters); vermi-remediation (treatment and clean up of contaminated lands); vermi-agroproduction (production of chemical-free foods by worms and vermicompost); vermi-protection (protection of human health by medicines from worms); vermi-production (production of valuable industrial raw materials from worms). The use of earthworms in composting of waste and in farm production were known for ages but have now been scientifically and commercially revived. The other uses of earthworms for the benefits of environment and society (wastewater treatment, land remediation and production of valuable medicines even to combat cancer and heart diseases are some new discoveries). We have successfully experimented with the first four technologies for management of municipal solid wastes, treatment of municipal and industrial wastewater, remediation of polycyclic aromatic hydrocarbon (PAH)-contaminated soils and production of wheat and corn crops by use of vermicompost at Griffith University, Australia, with excellent results. Wastes are degraded >75% faster than conventional systems and compost produced are disinfected, detoxified, richer in nutrients and beneficial soil microbes; BOD loads and TSS of wastewater is reduced by over 95%; PAHs from contaminated soils are removed by over 80% in just 12 weeks; and growth of crops is promoted by 30-40% more than with chemical fertilizers. Earthworms are both protective and productive for environment and society.

Keywords: vermiagroproduction, vermicompost, vermicomposting, vermifiltration, vermimeal, vermimedicines, vermiproduction, vermiprotection, vermiremediation

Abbreviations: **AVPF**, antibacterial vermipeptides family; **BERI**, Bhawalkar Ecological Research Institute; **BOD**, biological oxygen demand; **COD**, chemical oxygen demand; **DDT**, dichloro-diphenyl-trichloroethane; **dw**, dry weight; **EDC**, endocrine disrupting chemical; **EFE**, earthworm fibrinolytic enzyme; **GLA**, gamma linoleic acid; **GEORG**, Good Earth Organic Resources Group; **HA**, humic acid; **HCH**, hexachlorocyclohexane; **HPCD**, hydroxypropylb-cyclodextrin, **HRT**, hydraulic retention time; **LK**, lumbrokinase; **MSW**, municipal solid waste; **NMR**, Nuclear magnetic resonance; **NPK**, nitrogen, phosphorus and potassium; **PAH**, polycyclic aromatic hydrocarbon; **PCB**, polychlorinated biphenyl; **POP**, persistent organic pollutant; **STP**, sewage-treatment plant; **TCDD**, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin; **TDS**, total dissolved solid; **TDSS**, total dissolved and suspended solid; **TERI**, Tata Energy Research Institute; **TSS**, total suspended solid; **VC**, vermicompost; **VmC**, vermicasts; **VF**, vermifilter; **VSS**, volatile suspended solid

CONTENTS

Received: 15 September, 2009. Accepted: 15 November, 2010.

Invited Review

INTRODUCTION

The global scientific community today is searching for a technology which should be economically viable, environmentally sustainable and socially acceptable. Vermiculture technology combines all these virtues and qualities together (Sinha *et al*. 2010a).

A revolution is unfolding in vermiculture studies for multiple uses in environmental protection and sustainable development (Sinha and Valani 2011). Earthworms have over 600 million years of experience as ecosystem engineers. Vermiculture scientists all over the world knew about the role of earthworms as waste managers, as soil managers and fertility improvers for long time. But some comparatively new discoveries about their role in wastewater treatment, contaminated soil remediation, and more recently about their potential use in modern medicine for protection of human health such as in lowering of blood pressure, thinning of blood and dissolving blood clots for stroke and heart patients, cure for cancer, cure for arthritis and rheumatisms, as an anti-inflammatory agent, source of antibiotics and as a rich source of high quality protein have brought a revolution in the vermiculture studies (Sinha *et al.* 2009a; Sinha and Valani 2011). About 4.400 different species of earthworms have been identified, and quite a few of them are versatile waste eaters and bio-degraders and several of them are bio-accumulators and bio-transformers of toxic chemicals (Baker and Barrett 1994).

TECHNOLOGIES FOR SUSTAINABLE DEVELOPMENT BY USE OF EARTHWORMS

Following technologies for sustainable development with environmental protection can be envisaged by the use of useful earthworm species which promises to provide cheaper solutions to several social, economic, environmental and health problems plaguing the human society (Sinha *et al.* 2010a):

1. Vermi-composting for efficient management of municipal and industrial solid wastes (organics) by biodegradation and stabilization and converting them into useful resource [vermicompost (VC)-nutritive biofertilizer].
2. Vermi-filtration for treatment of municipal and some industrial wastewater, their purification and disinfection for reuse.
3. Vermi-remediation for cleaning up chemically contaminated sites (lands) while also improving their physical, chemical and biological properties for reuse.
4. Vermi-agroproduction for restoring and improving soil fertility to produce safe and chemical-free food for the society by the use of VC and without recourse to the destructive agro-chemicals.
5. Vermi-protection for use of earthworms to develop potential modern vermi-medicines to combat some chronic and deadly diseases and protect human health.
6. Vermi-production for use of earthworms to produce some valuable raw materials to be used in rubber, lubricant, soaps, detergent and cosmetics industries and use of rich worm proteins as feed materials (vermi-meals) to promote fishery, dairy and poultry industries to produce more nutritive foods for the society.

Bioengineering technologies based on earthworms are self-promoted, self-regulated, self-improved and self-enhanced, low or no-energy requiring zero-waste technologies, easy to construct, operate and maintain. They excel all bioconversion, bio-degradation and bio-production technologies by the fact that they can utilize organics that otherwise cannot be utilized by others. They excel all bio-treatment technologies because they achieve greater utilization than the rate of destruction achieved by other technologies. They involve about 100-1000 times higher value addition than other biological technologies (Wang 2000; NIIR 2004). Technologies based on earthworms are also environmentally and economically sustainable as the worms are highly renewable resources regenerating at a rapid rate (by 2^8 i.e. 256 worms every 6 months from a single individual and each of the 256 worms multiplying in the same proportion) and the products are completely biodegradable. The best part is that vermi-agroproduction, vermi-protection and vermi-production are based on by-products (worm biomass and VC) generated in the operation of other three technologies, vermicomposting, vermifiltration and vermiremediation and therefore, more sustainable. It is like killing several birds in one shot (Sinha and Valani 2011).

VERMI-COMPOSTING FOR EFFICIENT MANAGEMENT OF WASTES WITH RESOURCE DEVELOPMENT

Earthworms have over 600 million years of experience as waste managers. The Greek philosopher Aristotle called them as the intestine of earth, meaning digesting a wide variety of organic materials including the waste organics, from earth. They feed lavishly on the organic waste, and also on the microorganisms (bacteria, fungi and the actinomycetes) that invade and colonize the waste biomass. Most earthworms consume, at the best, half their body weight of organics in the waste in a day. *Eisenia fetida* is reported to consume organic matter at the rate equal to their body weight every day (Visvanathan *et al*. 2005). Earthworms have real potential to both increase the rate of aerobic decomposition and composting of organic waste, and also to stabilize the organic residues in them, while removing the harmful pathogens and heavy metals from the end products.

Earthworm participation enhances natural biodegradation and decomposition of organic waste from 60 to 80%. The process becomes faster with time as the worms multiply rapidly doubling its population in every 60-70 days. Waste degradation and composting by earthworms is proving to be environmentally preferred technology over the conventional microbial degradation and composting technology as it is rapid and nearly odorless process, reducing composting time by more than half. On an average, 2000 adult worms weigh 1 kg and one million worms approx. 1 ton. Given the optimum conditions of temperature (20-30°C) and moisture (60-70%), about 5 kg of worms can vermiprocess 1 ton of MSW into VC every month, 1000 worms can degrade 10 kg waste every month and 50 million worms can vermiprocess 90 tons of waste every week (Datar *et al*. 1997). Our study indicates 1000 worms (*E. fetida*) compost 4 kg of mixed food wastes in 2 weeks (15 days) (Sinha *et al*. 2002).

Community wastes used for compost production by vermicomposting

Waste eater earthworms can physically handle a wide variety of organic wastes from both municipal and industrial streams. They are highly adaptable to different types of organic wastes (even of industrial origin), provided, the physical structure, pH and the salt concentrations are not above the tolerance level (Loehr *et al*. 1984; Edwards 1988; Datar *et al*. 1997; Fraser-Quick 2002; Sinha *et al*. 2005).

Municipal organic wastes

1) The food waste from homes (some raw, but all cooked kitchen wastes – fruits and vegetables, grains and beans, coffee grounds, used tea leaves and bags, crushed egg shells) and restaurants and fried food wastes from fast-food outlets (**Table 1**) (Patil 2005; Kristiana *et al*. 2005; Chauhan 2009; Valani 2009).

2) The garden yard) wastes (leaves and grass clippings) from homes and parks constitute an excellent feed stock for vermi-composting. Grass clippings (high carbon waste) require proper blending with nitrogenous wastes (Chauhan 2009; Valani 2009).

3) The sewage sludge (biosolids) from the municipal wastewater also provides a good feedstock for the worms. The worms digest the sludge and convert a good part of it into vermi-compost (Sinha *et al*. 2009a).

4) Paunch waste materials (gut contents of slaughtered ruminants) from abattoir also make good feedstock for earthworms (Fraser-Quick 2002).

Table 1 Some of the industrial wastes and other organic substrates utilized for vermicomposting using different earthworm species.

Earthworm species employed	Organic substrate used	Reference
Eisenia andrei	Paper mill sludge and dairy industry sludge	Elvira *et al.* 1998
	Municipal solid waste	Visvanathan *et al.* 2005
Eisenia fetida	Leaf litter + cow dung	Karmegam and Daniel 2000a
	Press mud	Garg and Kaushik 2005
	Dried sewage sludge + cow manure + oat straw	Contreras-Ramos *et al.* 2005
	Textile mill waste water sludge + biogas plant slurry	Garg *et al.* 2006
	Food industry waste	Yadav and Garg 2009
	Activated sewage sludge + paper mulch	Ndegwa and Thompson 2001
	Vegetable waste + tree leaves	Kalamdhad *et al.* 2009
	Municipal sewage sludge + sugarcane trash	Suthar 2009
	Paper mill sludge + cattle dung	Kaur *et al.* 2010
	Beverage industry biosludge + cattle dung	Singh *et al.* 2010
	Sugar industry waste (press mud + cowdung)	Sangwan *et al.* 2010
Eudrilus eugeniae	Aromatic oil extraction industry waste	Kale and Sunitha 1995
	Distillery waste	Seenappa *et al.* 1995
	Leaf litter + cow dung	Daniel and Karmegam 1999
	Green gram pods + cow dung	Karmegam *et al.* 1999
	Weeds + cow dung	Karmegam and Daniel 2000b
	Press mud	Lakshmi and Vijayalakshmi 2000
	Pineapple wastes	Mainoo *et al.* 2009
Perionyx ceylanensis	Leaf litter + cow dung	Prakash *et al.* 2008
	Silk worm waste + leaf litter	Raja Sekar and Karmegam 2009a
	Press mud	Prakash and Karmegam 2010
Perionyx excavatus	Press mud	Parthasarathi 2007
Perionyx sansibaricus	Agriculture waste, farm yard manure and urban solid waste	Suthar 2007a
	Guar gum industry waste	Suthar 2007b
Polycultures of earthworms (*Eudrilus eugeniae*, *Perionyx excavatus* and *Eisenia fetida*)	Perishable market and slaughter house wastes and municipal wastes	Giraddi *et al.* 2008
Eudrilus eugeniae, *Lampito mauritii* and *Perionyx ceylanensis*	Press mud	Jayakumar *et al*. 2009
Perionyx ceylanensis and *Lampito mauritii*	Leaf litter, weed and agricultural waste	Karmegam and Daniel 2009a
Eisenia fetida, *Eudrilus eugeniae* and *Perionyx excavatus*	Press mud	Khwairakpam and Bhargava 2009
	Municipal solid waste	Pattnaiak and Reddy 2009

Agriculture and animal husbandry wastes

Farm wastes such as crop residues, dry leaves and grasses. Livestock rearing waste such as cattle dung, pig and chicken excreta makes excellent feedstock for earthworms (Hartenstein and Bisesi 1989; Edwards and Bohlen 1996). Animal excreta containing excessive nitrogen component may require mixing of carbon-rich bulking agents e.g. straw, saw dust, dried leaves and grasses, shredded paper waste etc. to maintain the proper C/N ratio) (**Table 1**).

Some industrial organic wastes

Solid waste including the wastewater sludge from paper industry, textile mills, food processing industries, vegetable oil factory, potato and corn chips manufacturing industry, sugarcane industry, aromatic oil extraction industry, sericulture industry logging and carpentry industry also offers excellent feed material for vermi-composting by earthworms (**Table 1**). Even the fly-ash from coal power plants, considered to be a hazardous waste, can be composted by earthworms (Saxena *et al*. 1998; Venkatesh and Eevera 2008).

Worms can feed upon meat waste products if driven to starvation

Our studies (Sinha *et al*. 2008c, 2009a) found that worms can even eat chicken flesh if other feed materials are not available and driven to starvation. They are last food preferences. But the system is invaded with maggots and some foul odour for few days until worms eliminate them too by their ant-pathogenic actions.

Vermicomposting of human excreta (faeces) and removal of pathogens

Yadav *et al.* (2010) examined the suitability of vermicomposting technology for processing source-separated human faeces using the earthworm *E. fetida*. The study indicated that SVFV combination (soil, VC, faeces and VC – bottom to top layers) was the best for vermicomposting of human faeces. A year-long study conducted with VFV combination to assess the quality and quantity of VC produced showed an average VC production rate of 0.30 kg-cast/kg-worm/day. The VC produced was mature as indicated by low dissolved organic carbon (2.4 ± 0.43 mg/g) and low oxygen uptake rate (0.15 ± 0.09 mg O_2/g VS/h). Complete inactivation of total coliforms was noted during the study, which is one of the important objectives of human faeces vermiprocessing. Eastman *et al.* (2001) had also reported pathogen reduction by vermicomposting. In vermicomposting, killing of pathogens is prominently achieved through earthworm's intestinal action, secretion of fluids and selective grazing (Bhawalkar 1995; Domínguez and Edwards 1997).

Earthworm species suitable for waste degradation and composting

Long-term researches into vermiculture have indicated that the tiger worm (*E. fetida*), red tiger worm (*E. andrei*), the Indian blue worm (*Perionyx excavatus*), the African night crawler (*Eudrilus eugeniae*), and the red worm (*Lumbricus rubellus*) are best suited for vermicomposting of variety of organic wastes (Graff 1981; Reinecke *et al.* 1992; Beetz 1999; Sinha *et al.* 2002; Kale and Karmegam 2010).

Critical factors affecting worm function and vermicomposting

a) Temperature

Vermicomposting is a mesophilic composting where temperature does not increase beyond 30°C. Most worms require moderate temperature (20-30°C) for best function (Edwards and Bohlen 1996).

b) Moisture

It is also a critical factor in vermicomposting process. It helps in the biochemical reactions and also retains heat. Moisture content of 60-70% of total weight of waste is considered to be ideal for vermicomposting (Edwards and Arancon 2004).

c) Aeration

As vermicomposting is an aerobic process, needs adequate flow of air in the waste biomass and also essential for worm function (Edwards and Arancon 2004).

d) pH of medium

Earthworms are sensitive to pH change. Although they can survive in a pH range of 4.5 to 9, but functions best at neutral pH of 7.0 (Edwards 1998). Worms and their vermicasts reduce the acid-forming carbon in the soil and help maintain neutral pH.

e) Calcium

Calcium appears to be important mineral in worm biology (as calcarious tissues) and biodegradation activity. Pramanik *et al.* (2007) found that application of lime (calcium carbonate) at 5 g/kg of substrate not only enhances the rate of vermicomposting but also results into nutritionally better VC with greater enzymatic (phosphatase and urease) activities.

f) C/N ratio

Nitrogen is a critical factor in any aerobic composting system. Generally 25 parts carbon to 1 part nitrogen by weight (C/N=25:1) is considered ideal for rapid vermicomposting (Visvanathan *et al*. 2005).

g) Worm number and biomass

The number and quantity (biomass) of earthworms is also a critical factor for vermicomposting. More number of worms, rapid is the decomposition and also odor-free. A minimum of about 100-50 adult worms per kg of waste in the initial stage is considered ideal (Sinha *et al*. 2002; Visvanathan *et al*. 2005).

Important studies on vermicomposting system

1) Kale (1998), Kale and Sunitha (1995), Seenappa *et al.* (1995), Gunathilagraj and Ravignanam (1996), Lakshmi and Vijayalakshmi (2000) and Suthar (2008) studied the degradation and composting of some municipal and industrial wastewater sludge by earthworms. Suthar (2007a) also studied the vermicomposting of gaur gum industrial waste. Kale and Sunitha (1995) studied the vermicomposting of waste from the mining industry which contains sulfur (S) residues and creates disposal problems. They can also be fed to the worms mixed with organic matter. Optimum mixing ratio of the S waste residues to the organic matter was 4%.

2) Saxena *et al.* (1998) studied the vermicomposting of fly-ash from the coal power plants which is considered as a hazardous waste and poses serious disposal problem due to heavy metal contents. As it is also rich in nitrogen and microbial biomass it can be vermicomposted by earthworms. They found that 25% of fly-ash mixed with sisal (*Agave sisalana* Perrine) green pulp and parthenium (*Parthenium hysterophorus* L.) formed excellent feed for *E. fetida* and the VC was higher in NPK contents than other commercial manures. The earthworms ingest the heavy metals from the

fly-ash while converting them into VC.

3) Contreras-Ramos *et al.* (2005) studied the vermicomposting of biosolids (dried sewage sludge) from various industries but mainly from textile industries and some households (municipal) mixed with cow manure and oat straw. 1,800, 1,400 and 1000 g of aerobically digested biosolids were mixed with 800, 500 and 200 g of cow manure and 200, 100 and 0 g of oat straw. Cow manure was added to provide additional nutrients and the oat straw to provide bulk. 50 earthworms (weighing 40 g live weight) were added in each sample and the species used was *E. fetida*. They were vermicomposted at three different moisture contents – 60, 70 and 80% for 60 days. The best results were obtained with 1,800 g biosolids mixed with 800 g of cow manure and no straw at 70% moisture content.

4) Pramanik *et al.* (2007) studied the vermicomposting of four substrates *viz.* cow dung, grass, aquatic weeds and municipal solid waste (MSW) to know the nutritional status and enzymatic activities of the resulting VCs in terms of increase in total N, total P and K, humic acid (HA) contents and phosphatase activity. They found that cow dung recorded maximum increase in N content (275%) followed by MSW (178%), grass (153%), and aquatic weed (146%) in their resulting VCs over the initial values in their raw materials.

5) Pattnaik and Reddy (2009) reported the changes in the concentrations of major nutrients of VC produced from MSW processed by three species of earthworms viz., *E. eugeniae*, *E. fetida*, and *P. excavatus* and its simple compost were assessed during different intervals. The bulk mass of MSW was reduced up to 65, 55 and 40% by vermicomposting mediated by *E. eugeniae*, *E. fetida* and *P. excavatus*, respectively, and up to 20% in the compost. The pH, conductivity (EC), and concentrations of major nutrients – nitrogen, phosphorus, potassium, calcium and magnesium in the VC and compost gradually increased while the organic carbon, C/N and C/P ratios decreased as the composting process progressed. The VC of all the earthworm species possessed higher concentrations of nutrients than that of the compost and the substrate. Moreover, the nutrients were found higher in VC of *E. eugeniae* than that of *E. fetida*, *P. excavatus*, and compost. Thus, *E. eugeniae* may be chosen for vermicomposting of MSW over the other two species of earthworms.

Our studies on vermicomposting of municipal solid wastes

a) Sinha *et al.* (2002) studied the degradation and composting abilities of three species of earthworms on cattle dung, raw food wastes and garden wastes and found that the worm *E. eugeniae* was a better waste degrader followed by *E. fetida.* It was also found that the cattle dung was among the loved food for the earthworms (**Table 2**).

Table 2 Vermicomposting of cattle dung, kitchen wastes and garden wastes by individual composting worms (time taken in days for complete degradation).

Waste materials used (1 kg of each)	**Earthworm species used (150 worms)**		
	E. eugeniae	***E. fetida***	***P. excavatus***
1. Cattle dung	44	59	62
2. Raw food wastes	61	78	83
3. Garden wastes	69	89	91

Source: Sinha *et al.* 2002

b) Valani (2009) studied the vermicomposting of mixed food and garden wastes and compared with conventional aerobic composting without worms. 1000 worms (*E. fetida*) were used. Mixed food waste consisted of both cooked and raw e.g. boiled rice, noodles, pasta and potatoes; baked bread and buns; cooked and raw green vegetables; fruits and vegetable peels and cuts. Garden wastes consisted of mostly grass clippings. Food wastes degraded 100% in just 15 days while garden wastes in 60 days. Degradation of food wastes had started within hours (5% after 24 h). Cooked food wastes were more easily degraded. In wastes where the primary cellulosic materials were intact e.g. leaves and grasses, raw vegetables and fruits or where there are brittle calcium compounds e.g. egg shells, were degraded rather more slowly by the earthworms. In the conventional composting system without worms, maximum degradation of both food and garden wastes were only 35% even after 90 days of the study period.

He also studied the two composting systems when done in methodical way (e.g. periodical addition of water and turning of the waste biomass to maintain adequate moisture and aeration in the system, addition of lime to maintain neutral pH in the waste biomass) and when done in casual way where none of the above composting conditions were maintained regularly. Significantly, the casual vermicomposting by worms was still more efficient in degrading food and garden wastes (90 and 80%, respectively) even as compared to the methodical conventional composting system where all optimal conditions for efficient composting was maintained, but without earthworms. It infers therefore, that earthworms are able to maintain optimal conditions for rapid biodegradation and composting of wastes as long as they exist in the system with minimum maintenance. They aerate the waste biomass by burrowing actions and maintain near neutral pH by secretion of calcium (**Table 3**).

Table 3 Degradation of mixed food and garden wastes by vermicomposting *vis-à-vis* conventional composting systems in methodical and casual ways.

Waste materials	**Vermicomposting with earthworms (1000) (Degradation in %)**		**Conventional composting without worms (Degradation in%)**	
	Methodical	**Casual**	**Methodical**	**Casual**
1. Mixed food waste (4 kg)				
After 24 hours	5	0	0	0
After 15 days	100	60	0	0
After 30 days	100	60	0	0
After 45 days	100	70	5	0
After 60 days	100	70	25	10
After 75 days	100	80	30	15
After 90 days	100	90	35	20
2. Garden waste (1 kg)				
After 15 days	15	15	0	0
After 30 days	35	15	0	0
After 45 days	40	18	0	0
After 60 days	100	70	15	10
After 75 days	100	70	20	10
After 90 days	100	80	35	12

Source: Sinha *et al.* 2009d

c) Sinha *et al.* (2009a) also studied about the food preferences of waste eater earthworms when provided with different food wastes of both plant and meat products. They showed clear likings for baked bread and buns followed by raw tomato, boiled potato, lettuce, pumpkin and baked beans and then for boiled rice and noodles and banana peels. They do not like raw potato and onion. A most significant finding was that when left to starve without any vegetable food products, they are forced to feed upon even on meat products as the last food preference. Food wastes containing meat products were however, badly infected by fungus and maggots for few days emitting foul odour, but eventually controlled by the worms.

d) Sinha *et al.* (2010c) studied the vermicomposting of sewage sludge (biosolids). Ten kg of dried sludge was taken and five treatments were organized. T1 (Treatment 1) was control with only sludge. In T2, 250 earthworms (mixed species of *E. fetida*, *E. eugeniae* and *P. excavatus*) were released. In T3, 5 kg of cow dung was added to worms. In T4, only cow dung was added and in T5, 5 kg of garden soil was added. T1 was organized to know the fate of sludge upon natural ageing with time and by the natural microbial activity occurring within the sludge. T2 and T3 were organized to know the fate of sludge upon vermi-composting and worm action on sludge - if it has to feed only on sludge (T2), and if it is provided with additional feed materials (cow dung) (T3). T4 and T5 were organized to know the fate of sludge upon conventional microbial composting by decomposer microbes present in cow dung and in garden soil.

Experiments were carried on for 12 weeks. There were no significant changes in the control (T1). Most significant and rapid changes were observed in T2 and T3 which contained earthworms. Foul odor disappeared by week 2 and by week 12, the black and brittle sludge became a homogenous and porous mass of brown vermicast with light texture. The changes occurring in T4 and T5 were also very slow. Upon chemical analysis, the vermicomposted sludge (T2 and T3) was over 80% free of heavy metals cadmium (Cd) and lead (Pb) and almost completely free of pathogens.

e) Karmegam and Daniel (2009a) evaluated the vermicomposting ability of *Lampito mauritii* (Kinberg) and *Perionyx ceylanensis* Michaelsen by using three different types of organic substrates such as leaf litter of *Polyalthia longifolia*, *Pennisetum typhoides* cobs (pearl millet) and a weed, *Rottboellia exaltata* (whole plant except the roots) in combination with cowdung (1: 1). Vermicomposting studies (120 days) conducted to optimize the number of worms required for efficient conversion based on the reduction of C/N ratio, percentage decomposition of organic substrates, total number and biomass of earthworms recovered from the vermibed substrates clearly showed that vermibeds with 4 kg of organic materials can hold about 60–80 *L. mauritii* and about 90–120 *P. ceylanensis* for efficient decomposition. The percentage decomposition of each organic substrate treated with different numbers of *L. mauritii* (20, 40, 60, 80 and 100 earthworms) and *P. ceylanensis* (30, 60, 90, 120 and 150) showed significant difference ($P < 0.001$) between numbers of worms introduced per vermibed but the difference between substrates was not significant within the treatments. Vermicomposting resulted in significant increase in electrical conductivity (28.54–49.82%), total nitrogen (43.96–90.83%), total phosphorus (27.42–68.10%) and total potassium (27.42–113.18%), whereas decrease in organic carbon (35.05–49.74%), C/N ratio (55.48–73.18%) and C/P ratio (50.46–66.90%) in different vermibeds introduced with *L. mauritii* and *P. ceylanensis*. Both the earthworm species can be used for vermicomposting different organic substrates; however, duration of vermicomposting with *P. ceylanensis* is not as much of *L. mauritii*. The use of *L. mauritii* for vermicomposting of other substrates has been well established by other workers also but standardization of *P. ceylanensis*, a locally available species, for vermicomposting of different organic substrates is a new finding and the species could be useful for vermiconversion of organic substrates under local conditions. The growth (avg. growth rate: 1.34–1.79 mg/worm/day), reproduction (0.85–0.94 cocoons/worm/day with the hatching success of 74.67–82.67%) and life cycle (±50 days) of *P. ceylanensis* seems to be on par with the vermicomposting worms like *P. excavatus* and *P. sansibaricus*. Since the duration of life-cycle and the period of incubation are lesser, *P. ceylanensis* exhibits favorable features for adoption as vermicomposting worm (Karmegam and Daniel 2009b).

Mechanism of worm action in vermicomposting

Earthworms promote the growth of beneficial decomposer aerobic bacteria in waste biomass and also act as an aerator, grinder, crusher, chemical degrader and a biological stimulator (Dash 1978; Binet *et al.* 1998).

a) Grinding action

The waste feed materials ingested is finely ground (with the aid of stones in their muscular gizzard) into small particles to a size of 2-4 μm and passed on to the intestine for enzymatic actions. The gizzard and the intestine work as a bioreactor.

b) Enzymatic action

The worms secrete enzymes proteases, lipases, amylases, cellulases and chitinases in their gizzard and intestine which bring about rapid biochemical conversion of the cellulosic and the proteinaceous materials in the waste organics (Dash 1978; Domínguez 2004; Pramanik 2007).

c) Worms reinforce decomposer microbes and act synergistically

Worms promotes the growth of beneficial decomposer microbes (bacteria, actinomycetes and fungi) in waste biomass. Earthworms host millions of decomposer (biodegrader) microbes in their gut which is described as little bacterial factory (Singleton *et al.* 2003). Edwards and Fletcher (1988) showed that the number of bacteria and actinomycetes contained in the ingested material increased up to 1000-fold while passing through the gut. A population of worms numbering about 15,000 will in turn foster a microbial population of billions of millions. Under favorable conditions, earthworms and microorganisms act symbiotically and synergistically to accelerate and enhance the decomposition of the organic matter in the waste. It is the microorganisms which break down the cellulose in the food waste, grass clippings and the leaves from garden wastes (Morgan and Burrows 1982).

d) Humification of degraded waste organics

The final process in vermi-processing and degradation of organic matter is the humification in which the large organic particles are converted into a complex amorphous colloid containing phenolic materials. Only about one-fourth of the organic matter is converted into humus (Domínguez 2004).

Advantages of vermi-composting over conventional technologies

a) Earthworms enrich composts by nutrients and make them bio-available

Earthworms induce several beneficial changes in the biochemical properties of the composting wastes. They mineralize the nitrogen (N), phosphorus (P), potassium (K) and all other nutrients in the waste organics to increase their value in the VC and also make them bio-available to plants (Buchanan *et al.* 1988). They ingest nitrogen from the waste and excrete it in the mineral form as nitrates, ammonium and muco-proteins. The nitrogenous waste excreted by the nephridia of the worms is mostly urea and ammonia and is plant-available.

b) Earthworms proliferate beneficial soil microbes in the compost

Worms have been found to proliferate *Actinomycetes*, *Azotobacter*, *Rhizobium*, *Nitrobacter* and phosphate solubilizing bacteria significantly in their end products. Our study also indicated higher values of *Azotobacter* (the nitrogen fixing bacteria) and the *Actinomycetes* (the bacteria that increase biological resistance in pants against pests and diseases) in VC as compared to the conventional aerobic and anaerobic composts (Singh 2009). Moreover, the survival rate of biofertilizer organisms, *Azospirllum brasilense*, *Azotobacter chroococcum*, *Bacillus megaterium* and *Rhizobium* *leguminosarum* in earthworm casts (*Eudrilus eugeniae*) showed increased viability when compared with lignite carrier material (Raja Sekar and Karmegam 2009b, 2010).

c) Earthworms destroy pathogens

The earthworms release coelomic fluids that have anti-bacterial properties and destroy pathogens in the waste biomass (Pierre *et al.* 1982). They also devour the harmful protozoa, bacteria and fungus as food. They seem to realize instinctively those anaerobic bacteria and fungi are undesirable and so feed upon them preferentially, thus arresting their proliferation. Monroy *et al.* (2009) in a subsequent feeding experiment in mesocosms, observed that the coliform population was reduced by 98% after passage through the earthworms' guts, which suggests that digestive processes in the gut of *E. fetida* are the main factors involved in the decrease in total coliforms observed in the low dose vermireactors. Decreases in total coliform numbers were not related to decreases in bacterial biomass, which indicates a specific negative effect of earthworms on the coliforms.

d) Low greenhouse gas (GHG) emissions by vermicomposting of waste

High volumes of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) is emitted from the conventional composting process especially in anaerobic conditions. CH_4 and N_2O are 21 and 310 times more powerful than CO_2 as GHG. Worms significantly increase the proportion of aerobic to anaerobic decomposition in the compost pile by burrowing and aerating action leaving very few anaerobic areas in the pile, and thus significantly reducing emission these gases and also volatile S compounds. Analysis of VC samples has shown generally higher levels of available N as compared to the conventional compost samples made from similar feedstock. This implies that the vermicomposting process by worms is more efficient at retaining N rather than releasing it as N_2O.

Our study found that on average the anaerobic composting systems emitted the highest amount of CO_2 (2950 $mg/m^2/h$) and CH_4 (9.54 $mg/m^2/h$), while the vermicomposting system with worms emitted the least amount of CO_2 (880 $mg/m^2/h$) and CH_4 (2.17 $mg/m^2/h$). Vermicomposting systems had the lowest emission of N_2O which is most powerful GHG (Sinha and Chan 2009; Chan *et al.* 2010).

e) No or low energy use in vermi-composting process

Normal microbial composting requires energy for aeration (constant turning of waste biomass and even for mechanical airflow) and sometimes for mechanical crushing of waste to achieve uniform particle size. Vermi-composting does not involve such use of energy. Earthworms aerate the system constantly by burrowing actions (Visvanathan *et al.* 2005).

f) Homogenous end-products

The greatest advantage over the conventional composting system is that the end product is more homogenous, richer in plant-available nutrients and humus and significantly low contaminants. They are soft, highly porous with greater water holding capacity (Edwards and Bohlen 1996).

g) Earthworms remove toxic chemicals from end-products

Several studies have found that earthworms effectively bio-accumulate or biodegrade several organic and inorganic chemicals including heavy metals, organochlorine pesticide and polycyclic aromatic hydrocarbons (PAHs) residues in the medium in which it feeds and detoxify the end-products (Hartenstein *et al.* 1980; Nelson *et al.* 1982; Ireland 1983; Sinha *et al.* 2008a).

h) Earthworm biomass comes as valuable by-product of waste vermicomposting

Huge population of earthworms results from vermicomposting of wastes (Domínguez 2004). Worms are finding new uses for production of some life-saving medicines and nutritive feed materials besides their traditional uses in farms for improving soil fertility and enhancing crop productivity.

Commercial vermiculture: A global movement and booming business

Although farmers have been practicing vermicomposting of farm wastes throughout the world for centuries large scale vermicomposting of MSW including the sewage sludge on commercial scale is a recent development to divert them from ending up in the landfills, and has become a global movement (Sherman 2000). First serious experiments for management of municipal/industrial organic wastes were established in Holland in 1970, and subsequently in England, and Canada. Later, vermiculture were followed in USA, Italy, Philippines, Thailand, China, Korea, China, Japan, Brazil, France, Australia, Israel and Russia.

1) USA: U.S. has some largest vermicomposting companies and plants in world and States are encouraging people for backyard vermicomposting to divert wastes from landfills (Bogdanov 1996, 2004). A farm in Los Angles rears 1,000,000 worms to treat 7.5 tons of garbage each month. Nearly 300 large-scale vermiculturist formed an International Worms Growers Association in 1997 and is having booming business. Vermicycle organics produced 7.5 million pounds of VC every year in high-tech greenhouses. Its sale of VC grew by 500% in 2005. Vermitechnology unlimited has doubled its business every year since 1991 (Li 1998). US scientists are also searching for life-saving vermi-medicines from the bioactive compounds in earthworms (Mihara *et al.* 1990). Cooper with his counterparts in India (Balamurugan et al. 2009) reported that the extract of the earthworm *Lampito mauritii* is having anti-inflammatory effect on rats.

2) Canada: Canada is also ahead in vermicomposting business on commercial scale for both VC and vermimeal production. Large-scale vermicomposting plants have been installed at several places to VC municipal and farm wastes and their use in agriculture (GEORG 2004). An Organic Agriculture Centre of Canada has been established whose objective is to replace Chemical Agriculture by Vermiculture (Munroe 2007).

3) UK: UK is also following US and Canada in promoting vermiculture mainly for waste management and to reduce the needs of waste landfills. 1000 metric ton vermi-composting plants have been erected in Wales to compost diverse organic wastes (Frederickson 2000).

4) France: France is also promoting vermiculture on commercial scale to manage all its MSW and reduce the needs of landfills. About 20 tons of mixed household wastes are being vermi-composted everyday using 1000 to 2000 million red tiger worms (*E. andrei*) (Visvanathan *et al.* 2005).

5) New Zealand: It is also a leading nation in vermiculture. The Envirofert Company of New Zealand is vermicomposting thousands of tons of green waste every year. They put the green waste first to a lengthy thermophilic cooking, and then to vermicomposting by worms after cooling. Cooking of green waste help destroy the weeds and pathogens which may come from the feces of pets in grasses. They claim that each worm eat the cooked green waste at least 8 times leaving an end product rich in key minerals, plant growth hormones, enzymes, and beneficial soil microbes. Envirofert is also planning to VC approximately 40,000 tones of food wastes from homes, restaurants and food processing industries every year (www.envirofert.co.nz) (Frederickson 2000; Gary 2009).

6) Australia: Vermicomposting is being done on large scale in Australia as a part of the Urban Agriculture Development Program utilizing the urban solid wastes (Sinha 2008c). The Sydney Waters in New South Wales have set up a vermiculture plant of 40 million worms to degrade up to 200 ton of urban wastes a week. The Gayndah Shire Council in Queensland, Australia, is vermi-composting over 600 tons of organic waste into valuable organic fertilizer (vermicompost) and selling to the local farmers. Vermicomposting of sludge from the sewage and water treatment plants is being increasingly practiced in Australia and as a result it is saving over 13,000 cum of landfill space every year in Australia (Komarowski 2001). The Hobart City Council in Tasmania, VC and stabilize about 66 cum of sewage sludge every week.

7) **India:** Importance of earthworms in India has been well recognized from ancient times. India also launched vermicomposting program of MSW in the 1990s and Bhawalkar Ecological Research Institute (BERI) in Pune were among the pioneer institutions. Tata Energy Research Institute (TERI) in Delhi is also doing commendable works. In recent years it is growing as a part of sustainable non-chemical agriculture program combined with poverty eradication program. Farmers are using VC on a large scale and a revolution is going on. Vermicomposting business has enhanced the lives of poor in India and generated self-employment opportunities for the unemployed. In several Indian villages NGO's are freely distributing cement tanks and 1000 worms and encouraging men and women to collect waste from villages and farmers, VC them and sell both worms and VC to the farmers. People are earning from Rupees 5 to 6 lakhs (approx. AU$ 15-20,000) every year from sale of both worms and their VC to the farmers. Mostly they use farm waste and also MSWs collected from streets and waste dumpsites (Bhawalkar 1995).

Bihar, Karnataka, Tamil Nadu, Gujarat and Maharashtra are leading states in vermiculture revolution. The Karnataka Compost Development Corporation established a first vermicomposting unit in the country to handle all municipal urban solid wastes and is producing 150 to 200 t of VC every day from city garbage (Kale 2006). She has listed several farmers whose life has been changed from a poor farm labourer to a rich farmer who embraced vermiculture.

8) Philippines: Vermiculture and vermicomposting were introduced in the Philippines in the 1970s. VC is being used by farmers on large scale replacing the chemical fertilizers. Recently, commercial production of vermimeal from earthworms' biomass has been started as a substitute to fishmeal for promoting fishery industries (Guerrero 2006).

9) Argentina: Vermiculture is an expanding business in Argentina especially for the development of country sides. Worms Argentina is a growing company which reports to be exporting composting worms on large scales to European, South American, Caribbean and Middle East nations. They are in high demands from Middle East countries for recycling of polluting dairy effluents (Pajon 2009).

10) China: Vermiculture is a fast growing industry in China for the development of rural communities. It is in fact revival of the traditional culture practiced by ancient medicine-men who used earthworms for treatment of several diseases. Earthworms are now being used for vermicomposting of waste, promoting organic farming and for the development of vermi-medicines and nutritive vermimeals. A dietary supplement in the name of PLASMIN is being marketed in China (Sun 2009).

11) Russia: Vermiculture is being promoted on large scale in Russia especially for the development of life-saving vermi-medicines for treatment of human diseases for which conventional medicine do not have an answer. Scientists have developed a special breed of the versatile species *E. fetida* which can tolerate and survive in cold climates (Titov and Anokhin 2006).

12) Japan: Japan is promoting vermiculture since 1970s mainly for production of vermi-medicines from the bioactive compounds isolated from earthworms (Hori *et al.* 1974; Tanaka and Nakata 1974; Wang 2000). According to Kale (1993), Japan had imported 3000 t of earthworms from the United States in 1985-1987 for cellulose waste vermicomposting at a large scale. Hiraishi (2002) reported vermicomposting of household biowaste using *E. fetida* and also evaluated waste reduction efficiency and coexistent microbial community structure. This clearly shows that vermiculture has been promoted in Japan for waste utilization and vermi-medicines. A study by Yoshida *et al.* (2005) gave an insight into the use of earthworms in radioecology and ecotoxicology studies. Their study concludes that multi-element analyses could provide much information on the concentration and transfer of elements for earthworms which are one candidate reference organism for environmental radiation protection studies. Recently, Ueda *et al.* (2008) reported a novel anti-plant viral protein from coelomic fluid of the earthworm *E. foetida* and it has been purified, characterized and identified as a serine protease. Very recently, Ueda *et al.* (2010) reported a novel cold-adapted cellulase complex from *E. foetida* with characterization of a multi-enzyme complex with carboxymethylcellulase, β-glucosidase, β-1,3 glucanase, and β-xylosidase.

VERMIFILTRATION TECHNOLOGY FOR WASTEWATER TREATMENT, PURIFICATION AND DISINFECTION

Vermifiltration of wastewater using waste eater earthworms is a newly conceived novel technology with several advantages over the conventional systems. Earthworms body work as a biofilter (Roots 1956) and they have been found to remove the 5 days biological oxygen demand (BOD_5), chemical oxygen demand (COD), total dissolved solids (TDS) and total suspended solid (TSS) by over 90, 80-90, 90-92 and 90-95%, respectively from wastewater by the general mechanism of ingestion and biodegradation of organic wastes and also by their absorption through body walls. Suspended solids are trapped on top of the vermifilter (VF) and processed by earthworms and fed to the soil microbes immobilized in the VF. Worms also remove chemicals including heavy metals and pathogens from treated wastewater (Komarowski 2001; Bajsa *et al*. 2003; Taylor *et al.* 2003; Xing *et al*. 2005; Yadav *et al.* 2010).

Earthworm species suitable for vermifiltration of wastewater

The same waste eater species of worm e.g. *E. fetida*, *P. excavatus*, *E. eugeniae* and *L. rubellus* that are suitable for composting solid wastes are also suited for vermifiltration of wastewater. *E. fetida* has been found to be more versatile (Soto and Toha 1998; Komarowski 2001; Sinha *et al.* 2008a).

Critical factors affecting vermifiltration of wastewater

a) Worm biomass

As the earthworms play the critical role in wastewater purification their number and population density (biomass) in soil, maturity and health are important factors. This may range from several thousands to millions. There are reports about 8-10,000 numbers of worms/m^2 of the worm bed and in biomass as 10 kg per cubic meter (cum) of soil for optimal function (Komarowski 2001).

b) Hydraulic retention time (HRT)

Hydraulic retention time is the time taken by the wastewater to flow through the soil profile (VF bed) in which earthworms inhabits. It is also very essential for the wastewater to remain in contact with the worms in the filter bed for certain period of time. This is called hydraulic retention time. HRT depends on the flow rate of wastewater to the vermifiltration unit, volume of soil profile and quality of soil used. HRT is very critical, because this is the actual time spent by earthworms with wastewater to retrieve organic mater from it as food. During this earthworms carry out the physical and biochemical process to remove nutrients, ultimately reducing BOD, COD and total dissolved and suspended solids (TDSS). The longer wastewater remains in the system in contact with earthworms, the greater will be the efficiency of vermi-processing and retention of nutrients. Maximum HRT can results from slower rate of wastewater discharge on the soil profile (VF bed) and hence slower percolation into the bed. Increasing the volume of soil profile can also increase the HRT. The number of live adult worms, functioning per unit area in the VF bed can also influence HRT. High hydraulic loading rate leads to reduced HRT in soil and could reduce the treatment efficiency (Komarowski 2001; Xing *et al*. 2005).

HRT of vermifiltration system can be calculated as:

$$HRT = (\rho \times V_s) / Q_{\text{wastewater}}$$

where HRT = theoretical hydraulic retention time (h); V_s = volume of the soil profile (VF bed), through which the wastewater flow and which have live earthworms (cum); ρ = porosity of the entire medium (gravel, sand and soil) through which wastewater flows; $Q_{\text{wastewater}}$ = flow rate of wastewater through the VF bed (cum/h).

Thus the HRT is directly proportion to the volume of soil profile and inversely proportion to the rate of flow of wastewater in the VF bed.

c) Hydraulic loading rate (HLR)

The volume and amount of wastewater that a given VF system (measured in area and depth of the soil medium in the VF bed in which the earthworms live) can reasonably treat in a given time is the hydraulic loading rate of the VF system. HLR can thus be defined as the volume of wastewater applied, per unit area of soil profile (VF bed) per unit time. It critically depends upon the number of live adult earthworms functioning per unit area in the VF bed. The size and health of the worms is also critical for determining the HLR (Xing *et al*. 2005; Hughes *et al*. 2007):

HLR of vermi-filtration system can be calculated as:

$$HLR = V_{\text{wastewater}} / (A \times t)$$

where HLR = hydraulic loading rate (m/h), $V_{\text{wastewater}}$ = volumetric flow rate of wastewater (cum), A = area of soil profile exposed (m^2), t = time taken by the wastewater to flow through the soil profile (h).

High HLR leads to reduced HRT in soil and could reduce the treatment efficiency. HLRs will vary from soil to soil. The infiltration rates depend upon the soil characteristics defining pore sizes and pore size distribution, soil morphological characteristics, including texture, structure, bulk density, and clay mineralogy (Sinha *et al.* 2008a).

d) Toxicity and pH of wastewater

The toxicity and pH of wastewater also influence vermifiltration by earthworms. Worms can, however, tolerate a wide range of pH between 4.5 and 9 and some species e.g. *E. fetida* can also resist toxicity to a greater extent (Komarowski 2001; Hughes *et al*. 2007).

Important studies on vermifiltration system

1) Hartenstein and Bisesi (1989) studied the use of earthworm for the management of effluents from intensively housed livestock which contain very heavy loads of BOD, total dissolved and suspended solids (TDSS) and nutrients, N and P. The worms produced clean effluents and also nutrient rich VC.

2) Taylor *et al*. (2003) studied the treatment of domestic wastewater using VF beds and concluded that worms can reduce BOD and COD loads as well as the TDSS significantly by more than 70-80%.

3) Soto and Toha (1998) studied the vermifiltration of municipal wastewater in a pilot plant for treating wastewater of 1000 inhabitants and found that the BOD load was removed by 99%, TSS by 95%, VSS (volatile suspended solids) by 96%, N by 89% and P by 70%. The VF bed was prepared of stones at the bottom and sawdust above with 20-30 cm humus at the top in which 5000-10,000 earthworms (*E. andrei*) per square meter was released. *E. coli* was removed by 1000-fold. Such systems allowed for treating 1000 L/m^2/wastewater/day. They have commercialized and patented the technology in Chile.

4) A pilot study on vermifiltration of sewage was made by Xing *et al*. (2005) at Shanghai Quyang Wastewater Treatment Facility in China. The earthworm bed which was 1 m (long) × 1 m (wide) × 1.6 m (high), was composed of granular materials and earthworms. The worm's number was kept at about 8000 worms/m^2. The average COD value of raw sewage used was 408.8 mg/L that of 5 days biological oxygen demand (BOD_5) was 297 mg/L that of suspended solids was 186.5 mg/L. The HRT varied from 6 to 9 hours and the hydraulic loading from 2.0 to 3.0 $m^3/(m^2.d)$ of sewage. The removal efficiency of COD ranged between 81-86%, the BOD_5 between 91-98%, and the suspended solids between 97-98%.

Our studies on vermifiltration of municipal and industrial wastewater

a) Sinha *et al*. (2007) studied the vermifiltration of brewery and milk dairy wastewaters which have very high BOD_5 and TSS loadings e.g. 6780 mg/L and 682 mg/L respectively from brewery and 139,200 and 36,000 mg/L, respectively from the dairy industry. Earthworms removed the high BOD_5 loads by 99% in both cases and TSS by over 98%. The HRTs in case of brewery wastewater was 3-4 h and 6-10 h for dairy wastewater.

b) Sinha *et al*. (2008a) studied the vermifiltration of sewage obtained from the Oxley Wastewater Treatment Plant in Brisbane, Australia.

Results showed that the earthworms removed BOD (BOD_5) loads of sewage by over 99% at HRT of 1-2 h. Average COD removed from the sewage by earthworms is over 50%. COD removal was not very significant, but at least much higher than the control. Earthworms also removed the TSS from the sewage by over 90% (**Table 4**).

The experiment was carried out in a 220 L capacity vermicomposting bin with provisions for dripping wastewater from the top and collecting the filtered water at bottom through an outlet. The VF bed was prepared by organizing pebbles at bottom of the bin and about 30 cm layer of soil on top in which worms were released. A control bin was also organized which had pebbles and soil bed but no earthworms. The pebbles and soil (with microbes) can also be expected to contribute in the filtration of wastewater.

An important observation was that although the BOD, COD and the TSS of wastewater were also considerably removed by the control system it never worked for longer time and frequently got choked. The organic solids in the wastewater accumulated as peat in the soil layer and also

Table 4 Removal of BOD, COD and TSS of municipal wastewater (sewage) treated by earthworms (vermifiltered) and without earthworms (in mg/L) (HRT: 1-2 hrs).

Parameters studied	Untreated raw sewage (mg/L)	Treated sewage reduction in values (mg/L)		% Reduction by earthworms (Vermifiltered)	% Reduction without earthworms (Control)
		With worms (Vermifiltered)	Without worms (Control)		
BOD_5	309	1.97	86.3	99.4	72.1
COD	293	132	245	54.9	16.4
TSS	438	22	184	94.97	57.99

Source: Sinha *et al.* 2008a

attracted heavy fungal infection. It became un-operational after sometimes. In the vermifiltration system the earthworms constantly fed upon the solids and the fungus and never allowed the system to be choked and become un-operational.

c) Chandran (2010) is currently studying the vermifiltration and vermiremediation of petroleum contaminated wastewater (and consequently the contaminated soil of VF bed) from automobile service industry in Brisbane. The wastewater contain fractions of aliphatic (e.g. cycloalkanes) and more toxic aromatic hydrocarbons (e.g. PAHs) and organochlorines originating from waste engine and gear oils, brake and transmission fluids, grease and coolants, petrol and diesel. The chemicals of concern are the total petroleum hydrocarbons (TPH), dichloromethane (DCM), dichloroethane (DCE) and *t*-butyl methyl ether (tBME). tBME is added to reduce the atmospheric concentration of CO in vehicle exhaust. This compound has raised global concern recently due to its high mobility and persistence in environment and possible carcinogenicity. Study is in progress. If successful (as the preliminary studies indicate) the combined vermifiltration and vermiremediation systems would be highly economical and also environmentally sound and sustainable method for treatment of contaminated wastewater and soils from all petroleum refineries and industries. The earthworms (*E. fetida*) not only tolerated and survived the toxic petro-chemicals for several hours but also bio-filtered and bio-remediated the dark brown pungent wastewater to pale yellow and odorless water significantly removing the chemicals. The soil in the VF bed also became completely odorless after 2-3 days indicating that the worms have bio-accumulated, biodegraded and bio-transformed all the volatile chemicals. The soil in the control system (without worms) continued to emit pungent smell of petroleum products for several days.

The mechanism of worm action in vermifiltration

The twin processes of microbial stimulation and biodegradation, and the enzymatic degradation of waste solids by worms simultaneously work in the vermifiltration system. VFs provide a high specific area – up to 800 m^2/g and discharge up to 60%. Suspended solids are trapped on top of the VF and processed by earthworms and fed to the soil microbes immobilized in the VF. Intensification of soil processes and aeration by the earthworms enable the soil stabilization and filtration system to become effective and smalller in size (Bhawalkar 1995; Komarowski 2001; Hughes *et al.* 2007).

1) Earthworms intensify the organic loadings of wastewater in the VF soil bed by the fact that it granulates the clay particles thus increasing the hydraulic conductivity of the system. They also grind the silt and sand particles, thus giving high total specific surface area, which enhances the ability to adsorb the organics and inorganic from the wastewater passing through it (Komarowski 2001).

2) The granular vermicast produced on the soil bed due to worm's feeding and excretion activities also offers excellent hydraulic conductivity of sand (being porous like sand) and a very high adsorption site and power of clay to adsorb the suspended solids and heavy metals from the wastewater (Taylor *et al.* 2003; Urdaneta *et al.* 2008).

3) Earthworms also graze on the surplus harmful and ineffective microbes in the wastewater selectively and maintain a culture of effective biodegrader microbes to function (Xing *et al.* 2005).

Advantages of vermifiltration over conventional wastewater treatment systems

Vermi-filtration of wastewater is low energy and efficient system and has distinct advantage over all the conventional wastewater treatment systems – the activated sludge process, trickling filters and rotating biological contactors which are highly energy intensive, costly to install and operate and do not generate any income.

1) No sludge formation: Since the conventional technologies are mostly the flow-processes and have finite HRT it always results into a residual stream of complex organics and heavy metals in the form of sludge. This plagues most municipal councils in world as the sludge is a biohazard and requires safe landfill disposal at high cost. The greatest advantage of vermifiltration system is that there is no formation of sewage sludge. The worms decompose the organics in the wastewater and also devour the solids (which form the sludge) synchronously (Sinha *et al.* 2008a).

In all developed nations a worm farm has become a necessity in all wastewater and water treatment plants to resolve sludge problems. Earthworms feed readily upon the sludge components, rapidly convert them into VC, reduce the pathogens to safe levels and ingest the heavy metals (Komarowski 2001).

2) No foul odor: There is no foul odor as the earthworms arrest rotting and decay of all putrescible matters in the wastewater and the sludge (Sinha *et al.* 2008a).

3) Vermifiltered water is free of pathogens and toxic chemicals and suitable for reuse in agriculture and industries: Vermifiltered wastewater is free of pathogens and toxic chemicals (heavy metals and endocrine disrupting chemicals).The worms devour on all the pathogens (bacteria, fungus, protozoa and nematodes) in the medium in which they inhabit. They have the capacity to bio-accumulate high concentrations of toxic chemicals in their tissues and the resulting wastewater becomes almost chemical-free. Earthworms have also been reported to bio-accumulate endocrine disrupting chemicals (EDCs) from sewage which otherwise is not removed by our conventional sewage treatment plants (STPs). Markman *et al.* (2007) reported significantly high concentrations of EDCs (dibutylphthalate, dioctylphthalate, bisphenol-A and 17 β-estradiol) in tissues of earthworms (*E. fetida*) living in sewage percolating filter beds and also in garden soil.

Vermifiltered wastewater also becomes nutritive as the worms release considerable amounts of essential nutrients like NKP from their metabolic activities into the bio-filtered water. It is very suitable for park and farm irrigation (Sinha *et al.* 2008a).

4) Highly cost-effective: In the VF process there is 100% capture of organic materials, the capital and operating costs are less as it is significantly low energy consuming system, and there is high value added end products such as nutritive

VC and vermifiltered water for farms and earthworms biomass for industrial uses (Sinha *et al.* 2008a).

For decentralized sewage treatment at source of generation (homes)

If a VF bed of 0.3 cm soil is prepared with approximately 5000 worms (over 2.5 kg) to start with, it can easily treat 950-1000 L of domestic wastewater or sewage generated by (on an average) a family of 4 people with average BOD value ranging between 300-400 mg/L, COD 100-300 mg/L, TSS, 300-350 mg/L everyday with HRT of the wastewater in the VF bed being approximately 1-2 h. Given that the worms multiply and double their number at least every 60 days under ideal conditions of temperature and moisture, even starting with this number of earthworms a huge population (biomass) of worms with robust vermifiltration system can be established quickly within a few months which will be able to treat greater amount of wastewater generated in the family. An important consideration is the peak hour wastewater generation which is usually very high and may not comply with the required HRT (1-2 h) which is very critical for sewage treatment by vermifiltration system. To allow 1-2 h HRT in the VF bed an onsite domestic wastewater storage facility will be required from where the discharge of wastewater to the VF tank can be slowly regulated through flow control.

Vermifiltration: Destined to become a global movement

Due to its simplicity and cost-effectiveness vermifiltration of both municipal and industrial wastewater is destined to become a global movement especially in the developing countries who cannot afford to construct and maintain the costly energy consuming conventional STPs. In Chile, over 100 STPs of different sizes, going from individual houses to plants for 12,000 persons and bigger plants for industries are already working. It has been introduced on a commercial scale in Mexico and Venezuela (Soto and Toha 1998). India, Argentina, Philippines and Brazil are also introducing the technology on a commercial scale. Some companies in Pune (India) have already started pilot plants. Middle East countries are reported to be using earthworms for treating the polluting livestock and dairy effluents (Pajon 2009).

VERMIREMEDIATION FOR CLEANUP OF CHEMICALLY CONTAMINATED LANDS WITH SOIL IMPROVEMENT

Large tracts of arable land are being chemically contaminated due to mining activities, heavy use of agro-chemicals in farmlands, landfill disposal of toxic wastes and other developmental activities like oil and gas drilling. No farmland of world especially in the developing nations is free of toxic pesticides, mainly aldrin, chlordane, dieldrin, endrin, heptachlor, mirex and toxaphene. According to the National Environment Protection Council there are over 80,000 contaminated sites in Australia. There are 40,000 contaminated sites in US; 55,000 in just six European countries and 7,800 in New Zealand. There are about 3 million contaminated sites in the Asia-Pacific. These also include the abandoned mine sites along with the closed landfills. The contaminated sites mostly contain heavy metals Cd, Pb, Hg, Zn, etc. and chlorinated compounds like the polychlorinated biphenyls (PCBs) and dichloro-diphenyl-trichloroethane (DDT). Cleaning them up mechanically by excavating the huge mass of contaminated soils and disposing them in secured landfills will require billions of dollars. There is also great risk of their leaching underground (aggravated by heavy rains) and contaminating the groundwater. Contaminated soils and waters pose major environmental, agricultural and human health problems worldwide (UNEP 1996; Eswaran *et al.* 2001). Sterilized and unsterilized soil was contaminated with PAHs, added with *E. fetida* and biosolid or VC and incubated aerobically for 70 days, while dynamics of inorganic N were monitored by Contreras-Ramos *et al.* (2007). Their study showed that the addition of *E. fetida* to sterilized soil increased concentration of NH_4^+ 100 > mg N kg^{-1}, while concentrations in unsterilized remained < 60 mg N kg^{-1} except for soil amended with biosolid plus PAHs where it increased to > 80 mg kg^{-1}. Addition of PAHs had no significant effect on concentration of NH_4^+ compared to the unamended soil, except in the soil added with biosolid. Addition of *E. fetida* to sterilized soil increased concentration of NO_2^- 15 > mg N kg^{-1} while concentrations in unsterilized soil remained < 7.5 mg N kg^{-1} except for soil amended with biosolid where it increased to > 20 mg kg^{-1}. Addition of biosolid and VC increased concentration of NO_3^-, while addition of *E. fetida* decreased concentration of NO_3^- in biosolid amended soil. In another study, Contreras-Ramos *et al.* (2006) reported that the earthworm, *E. fetida* increased the reduction of PAHs in soil. The ability of *E. fetida* in the removal of PAHs in soil can be utilized for reclamation of soils contaminated with PAHs.

Traditionally, remediation of chemically contaminated soils involves off-site management by excavating and subsequent disposal by burial in secured landfills. This method of remediation is very costly affair and merely shifts the contamination problem elsewhere. Additionally, this involves great risk of environmental hazard while the contaminated soils are being transported and migration of contaminants from landfills into adjacent lands and water bodies by leaching. Soil washing for removing inorganic contaminants from soil is another alternative to landfill burial, but this technique produce a residue with very high metal contents which requires further treatment or burial (Baker and Herson 1994; Schaffner 2004).

Since the late 1980s, after the chemical and mechanical treatments of lands and water bodies and thermal treatment (incineration) of hazardous wastes proved economically and environmentally unsustainable, focus shifted towards the biological methods which are cost-effective as well as environmentally sustainable and also socially acceptable (BIOWISE 2000; Schaffner 2004).

Vermiremediation (using chemical tolerant earthworm species) is emerging as a low-cost and convenient technology for cleaning up the chemically polluted or contaminated sites. Earthworms in general, especially *E. fetida* are highly resistant to many chemical contaminants, including heavy metals and organic pollutants in soil, and have been reported to bio-accumulate them in their tissues. Earthworms have been used for land recovery, reclamation and rehabilitation of sub-optimal soils such as poor mineral soils, polder soils, open cast mining sites, closed landfill sites and cutover peat (Butt *et al.* 2004). Within the soil environment, an earthworm's sphere of influence is known as the drilosphere system. This incorporates the burrow systems, surface and belowground earthworm casts, internal earthworm gut and process, the earthworm surface in contact with the soil, and associated biological, chemical and physical interactions, in addition to the soil microorganisms (Brown and Doube 2004).

Earthworms in general are highly resistant to many chemical contaminants including heavy metals and organic pollutants in soil and have been reported to bio-accumulate them in their tissues. After the Seveso chemical plant explosion in 1976 in Italy, when vast inhabited area was contaminated with certain chemicals including the extremely toxic TCDD (2,3,7,8-tetrachlorodibenzo-*p*-dioxin) several fauna perished but the earthworms were able to survive. Earthworms which ingested TCDD-contaminated soils were shown to bio-accumulate dioxin in their tissues and concentrate it on average 14.5-fold (Satchell 1983).

Interestingly, the study conducted by Suthar *et al.* (2008) clearly indicates that earthworms have efficient potentials for bioaccumulation of metals in their tissues which can be used as an ecological indicator of soil contaminations. A species-specific metal accumulation pattern was observed by them in the earthworms, *Metaphire posthuma* (endogeic) and *L. mauritii* (anecic). Comparatively, endogeic showed the higher metal contents in their tissues than anecic (t-test: $P < 0.05$); collected form different habitats studied. Data suggested that species-specific feeding behaviour, earthworm niche structure, ecological category of inhabiting earthworm and even horizontal distribution of contaminants in soil layers are some major determinant for metal accumulation patterns in soil dwelling earthworms. The difference in burrowing patterns can influence the patterns of metal bioaccumulations between endogeic and anecic, although other factors are also contributory.

It is possible to generate an earthworm population of 0.2-1.0 million/ha of land within a short period of 3 months for vermiremediation (Bhawalkar 1995). Given the optimal conditions of moisture, temperature and feeding materials earthworms can multiply rapidly to produce a huge number of worms in a short time.

Earthworm species suitable for land remediation (soil decontamination)

Certain species of earthworms such as *Aporrectodea tuberculata*, *A. giardi*, *E. fetida*, *Lumbricus terrestris*, *L. rubellus*, *Dendrobaena rubida*, *D. veneta*, *Eiseniella tetraedra*, and *Allolobophora chlorotica* have been found to tolerate and remove a wide range of chemicals from soil (Satchell 1983; Schaefer *et al*. 2005; Alekseeva 2006). Our study also indicates that *E. fetida* is the most versatile chemical bioaccumulator (Sinha *et al.* 2008b). Earthworms have been tested and found to bioaccumulate heavy metals, pesticides and lipophilic organic micropollutants like PAHs from the soil (OECD 2000; Contreras-Ramos *et al*. 2006). *E. fetida* was used as the test organisms for different soil contaminants and several reports indicated that *E. fetida* tolerated 1.5% crude oil (containing several toxic organic pollutants) and survived in this environment (Tomoko *et al*. 2005).

Factors affecting vermiremediation

Same climatic factors of temperature, moisture and pH that are critical to the survival and function of earthworms during vermicomposting and vermifiltration of wastes, and wastewaters also effects vermiremediation of contaminated soils by worms (Sinha *et al*. 2008b).

Important studies on vermiremediation system

1. Studies on removal of heavy metals

Hartenstein *et al*. (1980), studied that earthworms can bioaccumulate high concentrations of heavy metals like Cd, Hg, Pb, Cu, Mn, Ca, Fe and Zn in their tissues without affecting their physiology and this particularly when the metals are mostly non-bioavailable. They can particularly ingest and accumulate extremely high amounts of Zn, Pb and Cd. Cadmium levels up to 100 mg/kg dry weight (dw) have been found in tissues. Ireland (1983) reported that *L. terrestris* can bio-accumulate in their tissues 90-80 mg Pb/g dw, while *L. rubellus* and *D. rubida* it was 2600 and 7600 mg/g dw, respectively. Zn, Mn and Fe were shown to be excreted through the calciferous glands of earthworms. Contreras-Ramos *et al*. (2005) also confirmed that earthworms, *E. fetida* reduced the concentrations of Cr, Cu, Zn and Pb in the vermicomposted sludge below the limits 1200, 1500, 2800 and 300 mg/kg respectively, set by the USEPA compost standards (US Composting Council 1997) in 60 days.

2. Studies on removal of PAHs

PAHs are priority pollutants and cause great concern with respect to human health and environment. They are inherently recalcitrant hydrocarbons, and the higher molecular weight PAHs are very difficult to remediate. Ma *et al*. (1995) studied the influence of *L. rubellus* on the disappearance of spiked PAHs phenanthrene and fluoranthene (100 µg/kg of soil) and found that the losses of both PAHs occurred at a faster rate in soils with earthworms than soil without. After 56 days, 86% of phenanthrene was removed. Eijsackers *et al*. (2001) reported that the concentration of phenanthrene decreased steadily when the worms are added. After 50 days, only very low concentration of phenanthrene was detected (<0.5 mg/kg of soil). And after 11 weeks no phenanthrene was detected as it was <0.03 mg/kg of soil. Contreras-Ramos *et al*. (2006) studied the uptake of three PAHs *viz.* phenanthrene, anthracene and benzo(a)pyrene at different concentrations by *E. fetida* and measured the PAHs concentrations in the soil and in the tissues of earthworms exposed to the PAHs for 11 weeks. Ten earthworms per 50 g of soil (equivalent to 200 worms/kg of soil) were added and sufficient moisture was maintained. The concentration of anthracene decreased by 2-fold after addition of earthworms and the average removal was 51% which was only 23% by microbes alone when the earthworms were not added to the soil. On an average the concentration of benzo(a)pyrene decreased by 1.4-fold and the average removal was 47% which was only 13% by microbes when earthworms were not present. Phenanthrene was completely removed by earthworms when the amount of the chemical was <100 mg/kg of soil, while only 77% was removed by microbes in the absence of earthworms.

3. Studies on removal of petroleum and crude oil hydrocarbons

Schaefer (2005) studied that increased microbial catabolic activity due to the presence of *E. fetida* was responsible for the loss of 91% (1074 mg/kg of soil to 96 mg/kg) of crude oil contamination in 56 days of treatment. Tomoko *et al*. (2005) added earthworm species, *E. fetida* with varying organic wastes to an oil contaminated soil and found that worms significantly decreased oil contents in comparison to the control. Martin-Gil *et al*. (2007) also studied the use of *E. fetida* and vermicomposting in the treatment of high molecular weight hydrocarbons asphaltens from the Prestige Oil Spill. About 80% vegetable waste (potato peelings, etc.) was added to 20% heavily fuel oil contaminated soil and then vermicomposted in treatment vessel. Earthworms were added at the density of 330 g/m^2 of treatment vessel for 6 months. Earthworms mineralized the asphaltens thus eliminating it from the system. Further, their results reveal that by using microorganisms living in either earthworm intestines (*Stenotrophomonas maltophilia*) or vermiculture substrates (*Scedosporium apiospermium*), it is possible to degrade and to eliminate the polycyclic asphaltens into CO_2 and H_2O, helped by evaporation, dissolution and/or photooxidation processes.

4. Studies on removal of agrochemicals

Several studies have found definite relationship between organochlorine pesticide residues in the soil and their amount in earthworms, with an average concentration factor (in earthworm tissues) of about 9 for all compounds and doses tested. Studies indicated that the earthworms bioaccumulate or biodegrade organochlorine pesticide and PAHs residues in the medium in which it lives (Davis 1971; Ireland 1983; Haimi *et al*. 1992). Ramteke and Hans (1992) isolated microbes from the gut of earthworm *Pheretima posthuma* treated with hexachlorocyclohexane (HCH) and noted significant subsequent HCH degradation. The HCH degrader microorganisms in the worms gut gradually increased over a 5 week period, replacing other gut microflora, indicating the potential for specialized gut growth by earthworms in order to degrade organic chemicals. Bolan and Baskaran (1996) studied the effect of *L. rubellus* and *A. caliginosa* vermicasts on the sorption and movement of herbicides C^{14}-metsulforon methyl, C^{14}–atrazine and C^{14}-2,4-dichlorophenoxyacetic acid (2,4-D) in soil. Worm vermicasts sorbet higher amount of herbicides from the contaminated soil than the control soil due to the higher levels

Table 5 Percent removal of some PAH compounds from contaminated soil by earthworms in a 12-week period.

Extracted PAH compounds	**T1** **Soil + worms + cow dung**	**T2** **Soil + worms + food wastes**	**T3** **Soil + compost (no worms)**
1. Benzo (a) anthracene	76% (58%)	71% (56%)	37% (6%)
2. Chrysene	67% (49%)	83% (68%)	41% (12%)
3. Benzo (b) flouranthene	90% (72%)	97% (82%)	65% (47%)
4. Benzo (k) flouranthene	90% (72%)	80% (65%)	40% (10%)
5. Benzo (a) pyrene	89% (71%)	78% (63%)	49% (24%)
6. Dibenzo (a,h) pyrene and Benzo (g,h,i) pyrene	83% (65%)	54% (39%)	54% (30%)
Average =	79% (61%)	80% (65%)	47.5% (21%)

Values within bracket are those after taking the dilution factor into consideration due to mixing of feed materials into soil.
Source: Sinha *et al.* 2008b

of organic C and more fine size of fractions in worm worked contaminated soils. Gevao *et al.* (2001) applied earthworms (*A. longa*) at 5 worms/2 kg of soil contaminated with non-extractable pesticides (C^{14}-isoproturon, C^{14}-dicamba and C^{14}-atrazine) residues in soil for 28 days. They found that due to earthworm burrowing actions, a greater degree of bound pesticides residues in soil was released as compared to those without worms. When the study was applied to freshly added pesticides in soil, the non-extractable residues of C^{14}-isoproturon, C^{14}-dicamba and C^{14}-atrazine were higher by a factor of 2, 2, and 4, respectively in the soil without worms. Thus, not only the earthworms restricted the formation of bound fraction of pesticides, but also enhanced the release and mineralization of bound pesticides residues.

5. Studies on removal of PCBs

PCBs are a group of oily, colorless, organic fluids belonging to the same chemical family as the pesticide DDT. They constitute a family of chemicals with over 200 types, and are used in transformers and power capacitors, electrical insulators, as hydraulic fluids and diffusion pump oil, in heat transfer applications, as plasticizers for many products. PCBs are categorized as unusually toxic and persistent organic pollutant (POPs). They were produced at about 100 million pounds per year during the 1960s and 70s but now severely curtailed due to its potential adverse effects on the human health and the environment. Singer *et al.* (2001) studied the role of *Pherertima hawayana* in mixing and distribution of PCB-degrader microorganisms when added to Aroclor 1242 contaminated soil (100 mg/kg of soil) over an 18-week period. Ten earthworms/0.6 kg of contaminated soil were added. The contaminated soil treated with earthworms resulted in significantly greater PCB losses (average 52%) when compared to the soil without earthworm treatment, which was 41%. The authors concluded that PCB losses from contaminated soils were partly due to burrowing activities of worms, thus allowing more infiltration of microorganisms and about 10-fold greater gas exchange and diffusion. Also, the deposition of nutrient-rich vermicast in the burrows maintained a more metabolically active degrader microbial community.

Our studies on vermiremediation of PAHs contaminated soil

Sinha *et al.* (2008b) studied the remedial action of earthworms on PAH (benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)flouranthene, benzo(a)pyrene, dibenzo(a,h)pyrene and benzo(g,h,i)pyrene)-contaminated soils obtained from a former gas works site in Brisbane where gas was being produced from coal. The initial concentration of total PAHs compounds in the soil at site was greater than 11,820 mg/kg of soil. The legislative requirements for PAHs concentration in soil in Australia is only 100 mg/kg for industrial sites and 20 mg/kg for residential sites. 10 kg each of PAHs contaminated soil was subjected to three treatments and studied for 12 weeks. In treatment 1 (T1- soil + worms + cow dung) and treatment 2 (T2- soil + worms + food wastes), 500 earthworms (mixed species of *E. fetida*, *E. eugeniae* and *P. excavatus*) were added to the soil with 5 kg each of feed materials (semi-dried cow dung and food wastes). The treatment 3 (T3- soil + compost and no worms were added) was kept as control in which only 5 kg of conventional compost was added. Compost provided the necessary degrader microbes for PAH degradation and hence that could determine the precise role of earthworms in PAH removal as earthworms also proliferate degrader microbes in any system and act synergistically. Soils were kept moist (about 60-70% moisture content) by regular sprinkling of water (**Table 5**). The worms could remove nearly 80% of the PAHs (or above 60% after taking the dilution factors into consideration) as compared to just 47 and 21% where it was not applied and only microbial degradation occurred. This was just in a 12-week study period. It could have removed by 100% in another few weeks. More significant was that the worm-added soil became odor-free of chemicals in a few days and was softer and more porous.

Mechanism of worm action in vermiremediation

Earthworms have both abiotic and biotic effects on contaminated soils in the remediation process. Abiotic effects are burrowing actions and the resulting burrows acts as inputs points and preferred pathways for water and particle movement, nutrient flow and aeration. This also results into mechanical breakdown of soil particles exposing greater surface areas for biotic action (Brown and Doube 2004).

Earthworms uptake chemicals from the soil through passive absorption of the dissolved fraction, through the moist 'body wall' in the interstitial water and also by mouth and intestinal uptake while the soil passes through the gut. The passive diffusion is driven by the difference between the pore water in soil and within the earthworm's tissues (Jager *et al.* 2003).

Hydrophobic organic contaminants are taken up by the earthworms in two ways:

1) By passive diffusion from the soil solution through the worms outer membrane;

2) By intestinal re-sorption of the compounds from the soil while it passes through the gut (by digestion) and then their degradation by enzymatic activity called Cytochrome P450 system. This enzymatic activity has been found to operate particularly in *E. fetida* which survives the benzo(a)pyrene concentration of 1,008 mg/kg of soil (Achazi *et al.* 1998).

Earthworms apparently possess a number of mechanisms for uptake, immobilization and excretion of heavy metals and other chemicals. They either bio-transform or biodegrade the chemical contaminants rendering them harmless in their bodies. Some metals are bound by a protein called metallothioneins found in earthworms which has very high capacity to bind metals. The chloragogen cells in earthworms appear to mainly accumulate heavy metals absorbed by the gut and their immobilization in the small spheroidal chloragosomes and debris vesicles that the cells contain (Ireland 1983). Ma *et al.* (1995) found that earthworms biodegrade organic contaminants like phthalate, phenanthrene and fluoranthene. In a study by McKelvie *et al.* (2010), the earthworms (*E. fetida*) were exposed to phenanthrene for thirty days to compare hydroxypropylb-cyclodextrin (HPCD) extraction of soil and ^{1}H NMR earthworm metabolomics as indicators of bioavailability. The initial phenanthrene concentration was 319 mg/kg, which biodegraded to 16 mg/kg within 15 days, at which time HPCD extraction suggested that phenanthrene was no longer bioavailable. Multivariate statistical analysis of ^{1}H NMR spectra for *E. fetida* tissue extracts indicated that phenanthrene exposed and control earthworms differed throughout the 30 day experiment despite the low phenanthrene concentrations present after 15 days. This metabolic response was better correlated to total phenanthrene concentrations than HPCD-extractable phenanthrene concentrations suggesting that ^{1}H NMR metabolomics offers considerable promise as a novel, molecular level method to directly monitor the bioavailability of contaminants to earthworms in the environment.

Advantages of vermiremediation over mechanical and chemical treatment of contaminated sites

There are several advantages in using earthworms for bioremediation of chemically contaminated soils. They have been shown to both retard the binding of chemical compounds with soil particles and also increase compound availability for microbial action while also enhancing the population of degrader microbes within the system. Earthworms have the potential to be employed not only in the recovery of contaminated soils, but also as a part of bioremediation strategy and in the subsequent improvement of that soil and the land as a whole, for other beneficial uses (Brown and Doube 2004).

1) On-site treatment: The greatest advantage of vermiremediation is that it is on-site treatment and there are no additional problems of earth-cutting, excavation and transportation of contaminated soils to the landfills or to the treatment sites incurring additional economic and environmental cost. Vermiremediation would cost about \$500-1000/ha of land as compared to \$10,000-15,000/ha by mechanical excavation of contaminated soil and its landfill disposal (Brown and Doube 2004).

2) Simultaneously reuse and recycles organic wastes: Of considerable economic and environmental significance is that the worm feed used in vermiremediation process is necessarily an organic waste product. This means that it would also lead to reuse and recycling of vast amount of organic wastes which otherwise end up in landfills for disposal at high cost. Kaur *et al.* (2010) conducted an experiment to envisage for fast bioremediation of toxic paper mill sludge into a soil ameliorating agent by co-composting with and without *E. fetida*. They observed that mixing cattle dung with the sludge improved physico–chemical characteristics (with transition metals in the permissible range for manures) of the products of both the processes and enhanced its acceptability for worms. Higher decline in organic carbon and higher content of nitrogen and phosphorous along with lower electrical conductivity and higher pH of the products of vermicomposting indicated that *E. fetida* helped in fast conversion of toxic paper mill sludge into a soil conditioner in 100 days.

3) Improves total quality of land and soil: Significantly, vermiremediation leads to total improvement in the quality of soil and land where the worms inhabit. Earthworms significantly contribute as soil conditioner to improve the physical, chemical as well as the biological properties of the soil and its nutritive value. They swallow large amount of soil everyday, grind them in their gizzard and digest them in their intestine with aid of enzymes. Only 5-10% of the digested and ingested material is absorbed into the body and the rest is excreted out in soil in the form of fine mucus coated granular aggregates called vermicastings which are rich in NKP, micronutrients and beneficial soil microbes including the N-fixers and mycorrhizal fungus (Bhawalkar 1995; Butt 1999).

And what is of still greater economic and environmental significance is that the polluted land is not only cleaned-up but also improved in quality. The soil becomes lighter and porous-rich in biological activities and the productivity is increased to several times. During the vermi-remediation process of soil, the population of earthworms increases significantly benefiting the soil in several ways. Earthworms are in fact regarded as biological indicator of good fertile soil and land (Brown and Doube 2004; Sinha *et al.* 2008b).

Vermiremediation destined to become a global movement

Vermiremediation by commercial vermiculture in U.K. Land Reclamation and Improvements Programs has become an established technology for long-term soil decontamination, improvement and maintenance, without earth-cutting, soil excavation and use of chemicals (Butt 1999; Butt *et al.* 2004). U.S., Australia and other developed nations are also using vermiculture for clean-up of contaminated lands at mine sites, oil-drilling sites and landfills (Bogdanov 1996; Dynes 2003). Tetra-Tech Company working for EPA in USA is examining the feasibility of using vermiremediation technology to remediate urban lands around Great Lakes in California. They are using the information from our paper (Sinha *et al.* 2008) and have requested for more relevant matters on the subject (Rich Poruban and Kevin Kratt, pers. comm.).

VERMI-AGRO-PRODUCTION TECHNOLOGY FOR SUSTAINABLE FOOD PRODUCTION WITH FARM PROTECTION

Vermi-agroproduction promises to usher in the Second Green Revolution by completely replacing the destructive agro-chemicals which did more harm than good to both the farmers and their farmland during the First Green Revolution of the 1950-60's. (Sinha *et al.* 2010b). Earthworms restore and improve soil fertility and boost crop productivity by the use of their metabolic product – vermicast. They excrete beneficial soil microbes, and secrete polysaccharides, proteins and other nitrogenous compounds into the soil. They promote soil fragmentation and aeration, and bring about soil turning and dispersion in farmlands. Worm activity can increase air-soil volume from 8-30%. One acre of land can contain up to 3 million earthworms the activities of which can bring up to 8-10 tons of top soil to the surface (in the form of vermicast) every year (Barley and Jennings 1959; Syers and Springett 1984; Singh 1993; Bhat and Khambata 1994; Brown 1995; Tomati and Galli 1995; Ghabbour 1996). The presence of worms improves water penetration in compacted soils by 50%. A U.S. study indicated that 10,000 worms in a farm plot provides the same benefit as three farmers working 8 hours in shift all year round with 10 tons of manure applied in the plot (Li 1998). Indian study showed that an earthworm population of 0.2-1.0 million/ha of farmlands can be established within a short period of 3 months. On an average 12 t/ha/year of soil or organic matter is ingested by earthworms, leading to upturning of 18 tons of soil/year, and the world over at this rate it may mean a 5.08 cm (2 inches) of fertile humus layer over the globe (Bhawalkar 1995).

Vermicompost: A nutritive bio-fertilizer and growth promoter

VC is a nutritive plant food rich in NKP, macro- and micronutrients, beneficial soil microbes like N-fixing bacteria and mycorrhizal fungi and are excellent growth promoters (Krishnamoorthy and Vajranabhaiah 1986; Edwards and Burrows 1988; Buckerfield *et al.* 1999; NIIR 2004). It contains K, S, Mg, Mn, Cu, Co, Bo, Fe and carbon. The UK Ministry of Agriculture reported 93 mg/L nitrate, 387 mg/L K, 53 mg/L P and 167 mg/L Mg in pure vermicasts (Li 1998). Neilson (1965) and Tomati *et al.* (1987) reported the presence of plant growth hormones (auxins, gibberellins and cytokinins) in VC. Moreover, VC contains enzymes like amylase, lipase, cellulase and chitinase, which continue to break down organic matter in the soil (to release the nutrients and make it available to the plant roots) even after they have been excreted (Chaoui *et al.* 2003). Muscolo *et al.* (1999) also found an auxin-like effect of earthworm-worked humic substances on cell growth and nitrogen metabolism in *Daucus carota*. Atiyeh *et al.* (2002) evaluated the effects of HAs, formed during the breakdown of organic wastes by earthworms (vermicomposting), on plant growth. In the first experiment, HAs were extracted from pig manure VC using the classic alkali/acid fractionation procedure and mixed with a soilless container medium (Metro-Mix 360), to provide a range of 0, 50, 100, 150, 200, 250, 500, 1000, 2000, and 4000 mg of humate per kg of dry weight of container medium, and tomato seedlings were grown in the mixtures. In the second experiment, humates extracted from pig manure and food wastes VCs were mixed with vermiculite to provide a range of 0, 50, 125, 250, 500, 1000, and 4000 mg of humate per kg of dry weight of the container medium, and cucumber seedlings were grown in the mixtures. Both tomato and cucumber seedlings were watered daily with a solution containing all nutrients required to ensure that any differences in growth responses were not nutrient-mediated. The incorporation of both types of VC derived HAs, into either type of soilless plant growth media, increased the growth of tomato and cucumber plants significantly, in terms of plant heights, leaf areas, shoot and root dry weights. Plant growth increased with increasing concentrations of HAs incorporated into the medium up to a certain proportion, but this differed according to the plant species, the source of the VC, and the nature of the container medium. Plant growth tended to be increased by treatments of the plants with 50–500 mg/kg HAs, but often decreased significantly when the concentrations of HAs derived in the container medium exceeded 500–1000 mg/kg. These growth responses were most probably due to hormone-like activity of HAs from the VCs or could have been due to plant growth hormones adsorbed onto the humates. In a similar study, Arancon *et al.* (2006) reported that the peppers treated with HAs extracted from food waste VCs produced significantly more fruits and flowers than those treated with commercially-produced HAs. As has been reported by Singh *et al.* (2008), the VC substitution was found to influence growth, physiological disorders, fruit yield and quality of strawberry (*Fragaria* x *ananassa*).

Atiyeh *et al.* (2000) found that VC tended to be higher in nitrates, which is the more bio-available form of N for plants. Suhane (2007) found that exchangeable K was over 95% higher in VC and a good amount of Ca and Zn. Suhane (2007) also studied the beneficial and biologically active soil microorganisms in VC and found that the total bacterial count was more than 10^{10}/g of VC. It included *Actinomycetes*, *Azotobacter*, *Rhizobium*, *Nitrobacter* and P-solubilizing bacteria ranging from 10^2-10^6/g of VC.

Most significant is that earthworm VC contains humus which is not found in any other fertilizer – organic or inorganic. It is formed from the organic matters in soil over a long period of time. Without HAs contained within the humus, plants cannot grow and survive. HA enables the plant to extract nutrients from the soil, stimulates and increases root growth, helps the plants to overcome stress, helps dissolve unresolved minerals to make organic matter ready for plants to use (Li 1998; Canellas *et al.* 2002). Romero *et al.* (2007) reported that the HA-like fractions in raw and vermicomposted winery and distillery wastes using the earthworm *E. andrei* for 8 months. From the study, it was concluded that after vermicomposting, the chemical and structural characteristics of the HA-like fractions approach those typical of soil HA. In particular, a loss of aliphatic structures and polypeptidic and carbohydrate components, and an increase in oxygenated and acidic functional groups occur in the HAL fractions of VCs.

VC has also been found to reduce the incidence of pest and disease attacks on crops besides promoting good growth. Edwards *et al.* (2010a, 2010b) reported the suppressive effect of aqueous extracts from VC on cucumber beetles (*Acalymna vittatum*), tobacco hornworm (*Manduca sexta*), green peach aphid (*Myzus persicae*), citrus mealybug (*Planococcus citri*), and two spotted spider mite (*Tetranychus urticae*) attacks on tomatoes and cucumbers. Even a foliar spray of VC solution on crop plants induces excellent impacts on growth and quality of fruits and disease suppression (Zaller 2006). Utkhede and Koch (2004) also used concentrated VC tea against plant pathogens and found that the concentrated VC tea had the ability to prevent the incidence of bacterial canker of tomato plants caused by *Clavibacter species* under greenhouse conditions.

Important studies on vermi-agroproduction system

1) Edwards and Burrows (1988) studied the agronomic impacts of VC and found that it consistently improved seed germination, enhanced seedling growth and development, and increased plant productivity much more than would be possible from the mere conversion of mineral nutrients into plant-available forms. The growth responses of plants from VC appears more like hormone-induced activity associated with the high levels of nutrients, HAs and humates in VC rather than boosted by high levels of plant-available nutrients.

2) Studies made by Baker and Barrett (1994) at CSIRO Australia found that earthworms can increase growth of wheat crops by 39%, grain yield by 35%, lift protein value of the grain by 12% and fight crop diseases. Palainswamy (1996) also studied that earthworms and its vermicast improve the growth and yield of wheat by more than 40%.

3) Bhawalkar (1995) studied the agronomic impacts of VC on farm soil and found that if 100 kg of organic waste with say, 2 kg of plant nutrients (NPK) are processed through the earthworms in farm soil, there is a production of about 300 kg of fresh living soil with 6% of NPK and several trace elements. This magnification of plant nutrients is done from grinding rock particles with organics and by enhancing atmospheric N fixation. Earthworms activate this ground mix in a short time of just 1 h.

4) Arancon *et al.* (2004) studied the agronomic impacts of VC and inorganic (chemical) fertilizers on strawberries when applied separately and also in combination. VC was applied at 10 tons/ha while the inorganic fertilizers (NPK) at 85 (N): 155 (P): 125 (K) kg/ha. While there was not much difference in the dry shoot weight of strawberries, the yield of marketable strawberries and the weight of the largest fruit was greater on plants in plots grown on VC as compared to inorganic fertilizers in 220 days after transplanting. Also there were more runners and flowers on plants grown on VC. Also, farm soils applied with VC had significantly greater 'microbial biomass' than the one applied with inorganic fertilizers.

5) Webster (2005) studied the agronomic impact of VC on cherries and found that it increased yield of cherries for three (3) years after single application inferring that use of VC in soil builds up fertility and restore its vitality for long time and its further use can be reduced to a minimum after some years of application in farms.

6) Buckerfield and Webster (1998) found that worm-worked waste (VC) boosted grape yield by two-fold as compared to chemical fertilizers.

Table 6 Growth of egg plants promoted by vermicompost, worms with vermicompost and chemical fertilizer.

Treatments	Av. growth (in inches)	Av. No. of fruits/ plant	Av. weight of fruits/plant	Total No. of fruits	Max. weight of one fruit
1. Earthworms (50) + VC * (250 g)	28	20	675 g	100	900 g
2. Vermicompost (250 g)	23	15	525 g	75	700 g
3. Chemical fertilizer (NPK) (full dose)	18	14	500 g	70	625 g
4. Control	16	10	425 g	50	550 g

Source: Sinha *et al.* 2009b

Table 7 Growth of okra plants promoted by vermicompost, worms with vermicompost and chemical fertilizer.

Treatment	Av. growth (in inches)	Av. No. of fruits/ plant	Av. weight of fruits/plant	Total No. of fruits	Max. weight of one fruit
1. Earthworms (50) + VC (250 g)	39.4	45	48 g	225	70 g
2. Vermicompost (250 g)	29.6	36	42 g	180	62 g
3. Chemical fertilizer (NPK) (full dose)	29.1	24	40 g	125	48 g
4. Control	25.6	22	32 g	110	43 g

Source: Sinha *et al.* 2009b

7) Jordão *et al.* (2007) used the VC for lettuce (*Lactuca sativa* L.) cultivation. The Cu concentrations in lettuce leaves from the treatment with VC enriched with this metal were below the range of critical toxicity level to plants, i.e., from 20 to 100 mg L^{-1}. However, the estimated Cu concentrations in the roots from the treatment with VC enriched with Cu were much larger than that of the treatment with the natural VC, reaching 246.3 mg L^{-1}. The Ni and Zn concentrations in lettuce leaves from the treatments, with VCs enriched with the respective metals, were above the range of critical toxicity levels to plants, i.e., from 10 to 50 mg kg^{-1} and from 15 to 30 mg kg^{-1}, respectively. However, no symptom of toxicity was found visually. Larger accumulations of Cu, Ni and Zn were found in the lettuce leaves than in the roots after the treatments with the uncontaminated VC. A greater absorption of Cu and Ni by roots was found in treatments with VC enriched with these elements, whereas Zn was found preferentially in the leaves.

8) Fernández-Luqueño *et al.* (2010) investigated the effect of different forms of N fertilizer on common bean plant characteristics and yield in a Typic Fragiudepts (sandy loam) soil under greenhouse conditions. Common bean (*Phaseolus vulgaris* L.) was fertilized with wastewater sludge, or wastewater sludge VC, or urea, or grown in unamended soil, while plant characteristics and yield were monitored (the unamended soil had no fertilization). Yields of common bean plants cultivated in unamended soil or soil amended with urea were lower than those cultivated in wastewater sludge-amended soil. Application of VC further improved plant development and increased yield compared with beans cultivated in wastewater amended soil. It was found that application of organic waste products improved growth and yield of bean plants compared to those amended with inorganic fertilizer.

9) Roy *et al.* (2010) studied the effect of different amendments to soil on the plant growth and productivity. The paddy straw and Ageratum conyzoides residues were used as direct mulch, compost, and VC in different plots planted with *Zea mays*, *Phaseolus vulgaris* and *Abelmoschus esculentus*, separately in three experimental plots. The different treatments affected the seed germination of the three test crops significantly. Plant height, basal area, productivity and biomass allocation in above ground parts were highest in VC treated plots and lowest either in control or in mulched plots. Further, the study revealed that different amendments affected crops differently and the pre-treatment of crop/plant residues like vermicomposting are invariably beneficial and contributed to crop growth and available N in soil.

Our studies on growth impacts of worms and vermicompost on crop plants

a) Sinha *et al.* (2009b) studied the growth impacts of earthworms and their VC on potted egg and okra plants. There were three (3) treatments with a control (**Tables 6, 7**). Eggplants (Brinjal, *Solanum melongena*) grown on VC with live worms in soil bored on average 20 fruits/plant with average weight being 675 g. Those grown on chemical fertilizers (NPK) bored only 14 fruits/plant with average weight being only 500 g. Total numbers of fruits obtained from VC (with worms) applied plants were 100 with maximum weight being 900 g while those on chemicals were 70 fruits and 625 g as maximum weight of a fruit. Okra plants (*Ablemoschus esculentus*) grown on VC with live worms in soil bored on average 45 fruits/plant with average weight being 48 g. Those grown on chemical fertilizers (NPK) bored only 24 fruits/plant with average weight being only 40 g. Total numbers of fruits obtained from VC (with worms) applied plants were 225 with maximum weight being 70 g while those on chemicals were 125 fruits and 48 g as maximum weight of a fruit. Presence of live worms with VC in soil made significant difference in total growth promotion (height of plants; number, size and weight of fruits) of both vegetable crops.

b) Sinha *et al.* (2009b) studied the growth impacts of earthworms and their VC on potted corn plants (*Zea mays*) and compared with chemical fertilizers (NPK + Mg + S + Fe + B+ Zn). There were two treatments with two replicas of each and a control. VC with earthworms in soil achieved excellent growth over chemical fertilizers. While the plants on chemicals grew only 5 cm (87 to 92 cm) in 7 weeks (week 7-19), those on VC with worms grew by 15 cm (90 to 105 cm) within the same period. Corn plants with worms and VC also attained maturity (appearance of male and female reproductive organs) very fast. Plants with worms only although did not achieve good growth in height, but also matured faster than the control group and the male reproductive organs appeared. Another significant finding was that plants on VC demanded less water for irrigation.

c) Sinha *et al.* (2009b) studied the growth impacts of earthworms with VC on potted wheat plants (*Triticum aestivum*) and compared with chemical fertilizers (NPK + Mg + S + Fe + B + Zn) and conventional compost (cow manure). It had three treatments with two replicas of each and a control. Wheat crops on VC with worms maintained very good growth from the very beginning and achieved maturity very fast. The striking rates of seed germination were very high, nearly 48 hours (2 days) ahead of others and the numbers of seed germinated were also high by nearly 20%. Plants were greener and healthier over others, with large numbers of tillers and long seed ears at maturity. Seeds were healthy and nearly 35-40% more as compared to plants on chemical

Table 8 Growth and yield of farmed wheat crops promoted by vermicompost, cattle dung, compost and chemical fertilizers.

Treatments	**Input/ha**	**Yield/ ha**
1. Control	No input	15.2 Q / ha
2. Vemicompost (VC)	25 Quintal VC / ha	40.1 Q / ha
3. Cattle dung compost (CDC)	100 Quintal CDC / ha	33.2 Q / ha
4. Chemical fertilizers (CF)	NPK (120: 60: 40) kg / ha	34.2 Q / ha
5. CF + VC	NPK (120: 60: 40) kg / ha + 25 Q VC / ha	43.8 Q / ha
6. CF + CDC	NPK (120: 60: 40) kg / ha + 100 Q CDC / ha	41.3 Q / ha

Keys: N = urea; P = single super phosphate; K = mureate of potash (in Kg/ha)
Source: Sinha *et al.* (2009 b)

Table 9 Growth and yield of farmed wheat crops upon successive applications of vermicompost over 1-4 years compared with chemical fertilizers.

Treatments	**Input/ha**	**Yield/ha**
1. Control	(No Input)	15.8 Q / ha
2. Vemicompost	20 Q / ha (1st Year Farming by VC)	35.3 Q / ha
3. Vemicompost	20 Q / ha (2nd Year Farming by VC)	36.2 Q / ha
4. Vemicompost	20 Q / ha (3rd Year Farming by VC)	37.3 Q / ha
5. Vemicompost	20 Q / ha (4th Year Farming by VC)	38.8 Q / ha
6. Chemical fertilizers	NPK (120:60:40) kg / ha	35.4 Q / ha

Keys: VC = vermicompost; N = urea; P = single super phosphate; K = mureate of potash
Source: Sinha *et al.* 2009b

fertilizers. What they achieved in just 5 weeks, was achieved by others in 10 weeks. More signifi-cant was that the pot soil with VC was very soft and porous and retained more moisture. Pot soil with chemicals was hard and demanded more water frequently.

d) Sinha *et al.* (2009b) also studied the growth impacts of VC on wheat crops in farms in India and compared it with conventional cattle dung compost and chemical fertilizers. VC supported yield better than chemical fertilizers. And when same amount of agrochemicals were supplemented with VC at 25 quintal (Q, One quintal = 100 kg)/ha the yield increased to about 44 Q/ha which is over 28% and nearly 3 times over control. On cattle dung compost applied at 100 Q/ha (4 times of VC) the yield was just over 33 Q/ha. Application of VC had other agronomic benefits. It significantly reduced the demand for irrigation by nearly 30-40%. Test results indicated better availability of essential micronutrients and useful microbes in VC applied soils. Most remarkable observation was significantly less incidence of pests and disease attacks in VC applied crops which reduced use of chemical pesticides by over 75% (**Table 8**).

We also studied that when VC was applied in the 2nd, 3rd and 4th successive years on the same farm plot, the growth and yield of wheat crops increased gradually over the years even at the same amount of VC applied i.e. at 20 Q/ha. In the plot with 1st year of farming by VC (after a changeover from chemical fertilizers) the yield (35.3 Q/ha) was comparable to those on chemical fertilizers (35.4 Q/ha). In the farm plot with 4th year of farming by VC the yield was 38.8 Q/ha which was close to previous study (40.1 Q/ha) where VC was used at 25 Q/ha (**Table 9**).

e) The field trial carried out by Karmegam and Daniel (2008) with a vegetable crop, *Lablab purpureus* for 180 days has shown that VC either alone or in combination with 50% of the recommended dose of chemical fertilizer is able to produce results constantly equal to exclusive application of chemical fertilizer as observed through certain growth parameters. The nutrient uptake (NPK) by plants and fruit yield was higher with VC application and equivalent to chemical fertilizer application. The highest fruit yield (fresh weight) of 108.77 tonnes ha^{-1} was recorded in the treatment which received 2.5 tonnes of VC (*R. exaltata* and cowdung in 1:1 ratio prepared using *P. ceylanensis*) + ½ dose of recommended NPK ha^{-1}, while it was 61.87 tonnes ha^{-1} in T_0 (control plots without VC and/or chemical fertilizer). The good evidence produced through plant growth experiments carried out in this study shows that, VC can promote plant growth and retain major nutrients in soil. The study clearly indicates that the VC in respect of organic wastes and earthworm species utilized, had equal effects with that of chemical fertilizer alone or partially substituted with VC.

f) Karmegam and Daniel (2009c) studied the effect of vermicasts (VmC) on the growth performances of an ornamental plant, *Codiaeum variegatum* (L.) Bl. var. *pictum* (Lodd.) Muell. Arg. in layering experiments was studied in comparison with peat moss. The VmCs were collected from the vermibeds of *L. mauritii* Kinb. and of *P. ceylanensis* Mich. cultured in three kinds of organic substrates i.e., leaf litter of *P. longifolia* (LP), *P. typhoides* cobs (PT) and a weed *R. exaltata* (RE) in combination with cowdung (1:1). The VmCs recovered from each vermibed were used alone and in combination with peat moss (PM; 1:1) as layering media for *C. variegatum* and the results were compared with PM. Root initiation, root length, total number of roots developed, fresh and dry weight of the roots were higher in the layering experiments with VmC and VmC + PM than that of PM which served as control. All these parameters showed significant differences between VmC and PM (control).

Advantages of vermiculture agriculture over chemical agriculture

1) Safe food for society: The biggest advantage of great social significance is that the food produced is completely organic when the VC application in soil along with other organic farming practices.

2) Highly nutritive crop fertilizer with bio-available nutrients: Studies indicate that VC is at least 4 times more nutritive than the conventional composts and gives 30-40% higher yield of crops over chemical fertilizers. In Argentina, farmers consider it to be seven (7) times richer than conventional composts in nutrients and growth promoting values (Pajon – Quoted in Munroe 2007). The HA in VC stimulates plant growth even in small amount (Canellas *et al.* 2002). VC retains nutrients for a longer time than the conventional compost and while the latter fails to deliver the required amount of macro and micronutrients to plants in shorter time, the VC does. Of greater agronomic significance is that the minerals in the VC are readily and immediately bio-available to plants (Arancon and Edwards 2006). Chemical fertilizers (and also manures) have to be broken down in the soil before the plants can absorb.

3) Reduces water for crop irrigation: VC has very high porosity, aeration, drainage and water holding capacity than the conventional compost (Nighawan and Kanwar 1952). Hence, the use of VC reduces the requirement of water for

Table 10 Economics of vermicompost production per year derived by assessing at farmers production level in India.

Method:	**VAT METHOD**		**HEAP METHOD**	
Size:	60 ft × 5 ft × 1.5 ft		8 ft × 4 ft × 1.5 ft	
COST PARTICULARS				
Variable costs	**Costs (in Indian Rupees)**	**Percent**	**Costs (in Indian Rupees)**	**Percent**
Vermicompost production costs (for 6 cycles)	64444.00	88.45	20292.00	87.23
Interest on vermicompost production costs at 10%	6444.40	8.84	2029.20	8.72
Total variable cost (1 + 2)	70888.40	97.29	22321.20	95.95
FIXED COSTS				
Amortized cost of investment on production facility at 10% cost	1972.06	2.71	941.00	4.05
Total fixed costs	1972.06	2.71	941.00	4.05
Total costs	72860.46	100.00	23262.20	100.00
OUTPUT PARTICULARS				
Number of harvests per cycle	One		One	
Yield per harvest	6.23 tons		1.74 tones	
Number of cycles per year	6 (cycle duration 2 months)		6	
Earthworm yield per year	500 kg		70 kg	
Total vermicompost yield per year	37.38 tons		10.44 tons	
PROFITABILITY OF VERMICOMPOST PRODUCTION		**Amount in Indian Rupees (Rs.)**		
Average cost of production/ton of vermicompost		1949.18		2517.55
Total cost per year in vermicompost production		72860.46		23262.20
Incomes from vermicompost at Rs. 3,200/ton		119619		33408.00
Income from worms at Rs. 200/kg		10000.00		2000.00
Total income from vermicompost		129619.00		35408.00
Net cash income		65179.00		15116.00
Net income		56758.54		12145.80
Rate of return (similar to Benefit-Cost Ratio)		1.78		1.52

Source: Reddy *et al.* 2009

irrigation by about 30%-40%. On the contrary, use of chemical fertilizers require high amount of water for irrigation.

4) Benefits economy and ecology of nations: Another big advantage of great economic and environmental significance is that productions of VC locally (on farm) from MSW (which constitute about 75% organic components) divert a large volume of MSW from landfills which are proving to be an economic and environmental burden on human societies. Its production is also significantly cheaper than the chemical fertilizers which are produced in factories from vanishing petroleum products generating huge waste and pollution. Reddy *et al.* (2009) from the Department of Agricultural Economics, University of Agricultural Sciences, Bangalore, India studied the economic impact and production efficiency of VC use in agriculture through methodological approaches as summarized below. Using the approach ‘with and without’, impact of VC is assessed based on sample farmers who use VC and control farmers (without VC use). For assessing the economics and profitability of VC use, typical economic measures need to be estimated. Production costs including that of VC are categorized as variable costs and fixed costs. Variable costs are those which vary with the level of output. They include expenditure on seed, fertilizer, labour, FYM, pesticides, interest on working capital, etc. Total income from crop production is derived by multiplying output with market prices. Gross profit is computed as total income minus variable costs and net income (profit) is derived by deducting total costs from total income. Using the approach of partial budgeting method, profitability of VC use in crop production can be estimated. The economics of VC production per year in Indian conditions are given in **Table 10**.

5) Regenerate farm soil and reduces use of fertilizers: Over successive years of application, VC build-up the soils natural fertility improving its total physical (porous), chemical (rich in nutrients) and biological (beneficial soil microbes) properties. It also regenerates a rich population of worms in the farm soil from the cocoons which further help improve soil fertility and subsequently lesser amount of VC is required to maintain a good yield and productivity (Bhawalkar 1995; Chaoui *et al*. 2003; Sinha *et al*. 2009b). On the contrary, with the continued application of chemical fertilizers over the years the natural fertility of soil is destroyed and it becomes addict. Subsequently greater amount of chemicals are required to maintain the same yield and productivity of previous years.

There is also significant loss of chemical fertilizer from the farm soil due to oxidation in sunlight. Study reveal that upon application of 100 kg urea (N) in farm soil, 40-50 kg gets oxidised and escapes as ammonia (NH_3) into the air, about 20-25 kg leaches underground polluting the groundwater, while only 20-25 kg is available to plants (Suhane 2007).

6) Protects crops and reduces use of chemical pesticides: Another advantage of great environmental significance is that VC repels and also suppresses plant pests and diseasees in crops and inhibits soil-borne fungal diseases. In field trials with pepper, tomatoes, strawberries and grapes significant suppression of plant-parasitic nematodes has been found. There is also significant decrease in arthropods (aphid- *M. persicae*, mealy bug- *P. citri*, and spider mite- *T. urticae*) populations with addition of 20 and 40% VC in soil (Edwards *et al.* 2007). Humus in vermicast extracts toxins, harmful fungi and bacteria from soil and protects plants. Actinomycetes in vermicast induce biological resistance in plants against pests and diseases (Suhane 2007). As such use of VC significantly reduces the need for chemical pesticides. Our studies indicated over 75% reduction.

The global movement for ecological agriculture by vermiculture to replace chemical agriculture

Worldwide farmers are desperate to get rid of the vicious circle of the use of chemical fertilizers as their cost have been constantly rising and also the amount of chemicals used per hectare has been steadily increasing over the years to maintain the yield and productivity of previous years. Nearly 3-4 times of agro-chemicals are now being used per hectare what was used in the 1960s (Suhane 2007). In Australia, the cost of monoammonium phosphate (MAP) fertilizer has risen from AU$ 530.00 to 1500.00/t since 2006 (Sinha *et al.* 2009b). Farmers urgently need a sustainable alternative which is both economical and also productive while also maintaining soil health and fertility. The new concept is Ecological Agriculture which is by definition different from Organic Farming that was focused mainly on production of chemical-free foods. Ecological agriculture emphasize on total protection of food, farm and human ecosystems while improving soil fertility and development of secondary source of income for the farmers. UN has also endorsed it. Vermiculture provides the best answer for ecological agriculture which is synonymous with sustainable agriculture (Sinha *et al*. 2009b, 2010b).

Australian and Canadian farmers have taken initiatives to VC all their farms wastes and supplement them with reduced doses of chemical fertilizers. Municipal councils and composting companies are also participating in vermicomposting business, composting all types of organic wastes on commercial scale and selling them to the farmers. This has dual benefits. Cutting cost on landfill disposal of waste while earning revenues from sale of worms and VC (Munroe 2007; Sinha *et al*. 2009b).

In India also, the farmers are being motivated to embrace vermiculture. A number of villages in the districts of Samastipur, Hazipur and Nalanda in State of Bihar have been designated as bio-village where the farmers have switched over to organic farming by VC and have completely given up the use of chemical fertilizers for the last four years since 2005. The author, Dr. Rajiv K. Sinha, is also involved in spearheading this movement in Bihar in collaboration with agricultural scientists from Rajendra Agriculture University, Pusa (Suhane 2007; Sinha *et al.* 2009b). In the state of Karnataka in India, a vermiculture revolution is going on under the guidance of Prof. Radha D. Kale since the 1990s (Kale 2006). More than 50% of farmers in the State have switched over to vermiculture in farming and given up chemical agriculture.

VERMI-PROTECTION TO PREVENT, CURE DISEASES AND PROTECT HUMAN HEALTH

Use of earthworms in traditional medicine

Researches reveal that traditional medicinemen in China and Philippines used earthworms in folkloric healings of many sickness such as to cure fever, inflammation of different parts of the body, stomach-aches and toothaches, rheumatism and arthritis, to cure mumps and measles and even to make child delivery easier by faster contraction of the uterus and reducing labour pains. China has been using earthworms in traditional healing for 2,300 years (Sun 2009). The Chinese *Materia Medica* by Li Shizhen (1518-1593) listed 40 uses of earthworms in traditional medicine such as hemiplegia (a condition where half of the body is paralysed) dilating blood vessels, lowering blood pressure, smoothing asthma, alleviating pains, relieving impotence, promoting lactation, protecting the skin, as anti-bacterial, anti-convulsions and as a tonic (Li 1998). They used 8-10 earthworms thoroughly washed and then cooked to dark brown. The cooked worms were ground and mixed with freshly boiled water (about 1 litre) and cooled. The clear liquid was given to patients to drink or applied topically on the afflicted area.

1. Thinning of blood by worm extracts

The traditional medicine practitioners of China even used the worms for thinning the blood in the older people. For this the extract from mashed earthworms was mixed with water and boiled for about 10 min and then cooled to prepare a tonic (Ang-Lopeź and Alis 2006). Several of the above medicinal properties of earthworms have now been scientifically verified.

2. Prolonged blood clotting time by worm extracts

A test was carried out on the blood clotting effects of earthworms extracts. The species used *E. eugeniae*. 5 ml of crude extracts of worms were mixed with human blood and time taken in the formation of fibrin (clotting time) was noted. Normal blood clotting time ranged from 4 to 6 min but when mixed with worm extracts it prolonged by up to more than an hour. Worm enzymes have been known to have anti-coagulating and fibrinolytic properties for long (Ang-Lopeź and Alis 2006).

Use of earthworms in modern medicine

The great news for the world of vermitech scientists appeared in Philippines *News Today* on November 25, 2005 telling *Earthworms can help dissolve blood clots for stroke patients* (Cordero 2005). In the last 10 years, a number of earthworm's clot-dissolving, lytic and immune boosting compounds have been isolated and tested clinically. Current researches made in Canada, China, Philippines, Japan and other countries on the identification, isolation and synthesis of some bioactive compounds from earthworms (*L. rubellus* and *E. fetida*) with potential medicinal values have brought revolution in the vermiculture studies (Wang 2000). Some of these compounds have been found to be enzymes exhibiting anti-blood clotting effects.

Oral administration of earthworms' powder and enzymes were found to be effective in treating thrombotic diseases, arthritis, diabetes mellitus, pulmonary heart disease, lowering blood pressure, epilepsy, schizophrenia, mumps, exzema, chronic lumbago, anemia, vertigo and digestive ulcer (Mihara *et al*. 1990; Ang-Lopeź and Alis 2006). Scientists have also isolated bronchial dilating substance from earthworms. Mihara *et al*. (1983, 1992) also extracted enzymes lumbritin, lumbrofebrin and terrestrolumbrolysin and lumbrokinase (LK) enzymes from *L. rubellus* useful in thrombolytic therapy.

1. Cure for heart diseases

LK is a group of 6 proteolytic enzymes now being used in the treatment of cerebral infarction (Jin *et al*. 2000). The enzymes also show some potential in prosthetic care of patients who have received prosthetic vascular grafts (Hwang *et al.* 2002).

Fibrinolysin and fibrinokinase are other novel fibrinolytic enzymes extracted from earthworms which have high cellulolytic activity as well as proteolytic activity. They can reduce the viscosity of blood and apparently has beneficial effects on paralysis of limbs or aphasia caused by cerebrovascular disease (Mihara *et al*. 1991; Wang *et al*. 2003). Collagenase was another valuable enzyme extracted from earthworms which can cure thrombus type diseases. It can cleave peptide bonds in timeworn, triple-helical collagen. Because of its unique ability to hydrolyze timeworn collagen it can be used to cut the strong outer cover of an old thrombus (blood clot). This enables the other two enzymes – fibrinolysin and fibrinokinase to enter into the thrombus and dissolve it thus opening the blood vessel and restoring oxygen supply (Li 1998).

The potential use of fibrinolytic enzymes in the prevention and treatment of serious cardiac and cerebro-vascular diseases has been very attractive in medicine and pharmacology. Besides therapeutic uses, fibrinolytic enzymes could be also used in degradation of organic waste products from the food and livestock industry (Nakajima *et al*. 2000)

Some fatty acids found in earthworms are of great value in modern medicine. The oleic acid which is an Omega-9 mono unsaturated fatty acids has great medicinal value in lowering the risks of heart attack and arteriosclerosis and in the prevention of cancer. Linoleic acid found in earthworms is also of great medicinal value. In the human body it is converted into gamma linoleic acid (GLA) and ultimately to prostaglandins, hormone like molecules that help regulate inflammation and blood pressure as well as heart, gastrointestinal and kidney functions (Li 1995; Ang-Lopeź and Alis 2006).

2. Cure for cancer from earthworms

Cooper (2009) reported that he was never been able to induce cancer in earthworms despite irritating them. That was very remarkable and inspired him to probe further. He found that earthworm leukocytes can recognize human cancer cells as foreign and can kill them. Electron microscopy showed an astonishing cinematography of earthworm cells becoming incredibly active, throwing out pseudopodia, and literally tearing apart cancer cell membranes from a human cell cancer line named K 562.

3. Anti-microbial products from earthworms for production of antibiotics

The coelomic fluid of earthworms has been reported to have anti-pathogenic activities and is good biological compound for the production of antibiotics (Pierre *et al.* 1982). Several fatty acids have been isolated from earthworms. Important among them are lauric acid which are known for its anti-microbial properties. It is a precursor to monolaurin which is a more powerful anti-microbial agent that has potential to fight lipid-coated RNA and DNA viruses, several pathogenic Gram-positive bacteria, yeasts and various pathogenic protozoa (Ang-Lopeź and Alis 2006).

In order to investigate the activity of peptides in earthworm tissue and coelomic fluid, Wang *et al.* (2007) established the peptide separation and purification method by which six antimicrobial peptides were isolated and purified from earthworm tissue liquid homogenate and coelomic fluid, which contained 5-50 amino acid (AA) residues with the same or similar sequence of Ala-Met-Val-Ser-Gly, and named the antibacterial vermipeptides family (AVPF) according to their structure and antibacterial characteristics. Wang and co-workers introduced a general protocol of AVPF peptide preparation methods from earthworms, including crude peptide preparation and purification by ultrafiltration, ion-exchange chromatography, gel-filtration and HPLC chromatography. The AVPF includes a wide antibacterial spectrum and speciality, performs antimicrobial activities not only to Gram-positive and Gram negative bacteria but also to fungi. The earthworm peptide (EP), EP5 caused apoptosis of HeLa cell and the threshold value of EP3 that causes apoptosis of HeLa cells was 0.75 mg/mL with an apoptotic rate of 48.12%. Short peptides with 5-7 amino acid residues formed multimers in the PB buffer, a more likely explanation for the antibacterial mechanism of short peptides that causes MGC803 cells to break. The antiviral effect of antimicrobial peptides (EP5) on the pseudorabies virus (PRV) was analyzed using the cytopathic effect (CPE) inhibition test. Results showed that EP5 inhibited the CPE by PRVon BHK cells. The mechanism of antiviral activity of EP5 may be explained by inhibiting the duplication of viral DNA.

4. Study of curative properties of 'vermivit' from earthworms on some human afflictions

The preparation of "Vermivit" is an alcoholic extract from the tissue of the earthworm *E. fetida* after a special treatment, with a density 0.939, protein concentration of 8 g/l, amino acids concentration of 1.7 g/l, 17 microelements, vitamins and essential amino acids (Titov and Anokhin 2006). Titov and Anokhin (2006) studied the health impacts of a medicine vermivit on 31 patients (another 25 as control group) suffering from shotty breast (11/10), malignant swellings of the 4th clinical group (5/5), adiposity (3/5), osteochondrosis (9/3), psora (2/2) and other diseases (1/0). The treatment with vermivit lasted from 1 to 3 months for 15 patients, up to 1 year for 14 and up to 3 years for 2. The results of 4 years of follow-up observations revealed the recovery of 9/0, improvement in 17/7, without effect in 2/15, and death of 3/3 of progressive tumoral process. No pathological changes were seen in patients who had taken the earthworm extract over a long period of time. There is no medicine to cure shotty breast except surgical operation.

5. Combating stress and increasing human longevity by studies on earthworms

Scientists in the University of Colorado, U.S. believe that researches into earthworms may provide an insight into increasing the longevity of humans up to around 120 years. By exposing the earthworms to stress they identified the genes (biomarker of ageing) which may allow modifying humans stress response system in order to extend their life (Li 1998).

6. Fibrinolytic enzymes from earthworms and their applications

An extensive review on earthworm fibrinolytic enzymes has been reported by Grdiša *et al.* (2009). The fibrinolytic system is responsible for the proteolytic degradation of fibrin and therefore plays a role in homeostasis and thrombosis. Intravascular thrombosis, a consequence of fibrin aggregation in the arteries, is one of the main causes of cardiovascular disease. Fibrin is the primary protein component of blood clots, which are formed from fibrinogen by thrombin. Formation of fibrin clot and fibrinolysis are normally well balanced in biological systems. However, if fibrin is not hydrolyzed due to some disorder, thrombosis can occur. The most common consequence of such thrombosis is myocardial infarction. Fibrinolytic enzymes are agents which dissolve fibrin clot. Today available agents are mostly plasminogen activator (t-PA), urokinase and streptokinase, which exhibit low specificity for fibrin, have undesired side effect and are also relatively expensive. Therefore, the search for other fibrinolytic agent from various sources continues. The presence of fibrinolytic activity in ceolomic fluid or tissue homogenate from earthworm has been reported previously. Because of that, earthworm tissue homogenate is an attractive source of various physiologically active compounds. Wang *et al.* (2003) have made extensive studies on different fibrinolytic enzymes from the earthworm, *E. fetida*. They purified seven fibrinolytic enzymes (EFE-a, b, c, d, e, f, g). All enzymes were very similar in size (23–29.7 kDa) with the isoelectric points in acidic pH range (3.46–3.94). Fibrinolytic activity of each enzyme on fibrin plates was different. The enzymes EFE-b, EFE-c and EFE-g showed relatively higher activity in comparison with the enzymes EFE-d and EFE-e. Relatively lower fibrinolytic activity was shown with EFE-a and EFE-f. There also has been some indication that EFE-a, besides fibrinolytic activity, exhibited plasminogen-activating activity. The other enzymes only have fibrinolytic activity. According to substrate specificity, the enzymes EFE-b, EFE-c, EFE-g represent trypsin-like enzymes, and EFE-d, EFE-e, EFE-f a group of chymotrypsin-like enzymes. It seems that EFE-a do not belong to trypsin-like or chymotrypsin-like enzymes, nor to the elastases. The optimal substrate for EFE-a has not been found yet. The activity of specific substrates for human plasmin and t-PA showed that EFE-b, EFE-c and EFE-g exhibited strong hydrolytic activity. However, EFE-a, EFE-d and EFE-e had very weak hydrolytic activity.

VERMI-PRODUCTION FOR PROMOTING CONSUMER INDUSTRIES

Raw materials for rubber, lubricant, detergent, soaps and cosmetic industries

Some biological compounds from earthworms are also finding industrial applications for resource recovery and sustainable development (Sabine 1981). Being biodegradable they are environmentally friendly and sustainable. Stearic acid found in earthworms is a long chain saturated fatty acid and is widely used as lubricant and as an additive in industrial preparations. It is used in the manufacture of metallic stearates, pharmaceuticals soaps, cosmetics and

Table 11 Comparison of the amino acid contents of vermimeal with fish meal and meat meal.

Amino acids (g/100 g of protein)	**Vermimeal**	**Fish meal**	**Meat meal**
Arginine	6.1	3.9	3.4
Cystine	1.6	0.8	1.0
Glutamic acid	13.8	8.4	*
Histidine	2.6	1.5	0.97
Isoleucine	4.5	3.6	1.33
Leucine	7.9	5.1	3.5
Lysine	7.1	6.4	3.0
Methionine	2.0	1.8	1.4
Phenylanine	4.1	2.6	2.1
Threonine	4.8	2.8	1.7
Tyrosine	3.4	1.8	1.2
Valine	5.0	3.5	2.2
Crude protein	61.0%	60.9%	51.0%

Source: Guerrero 2004; Guerrero and Guerrero 2006; * data not available

food packaging. It is also used as a softner, accelerator activator and dispersing agents in rubbers. Industrial applications of lauric acid and its derivatives are as alkyd resins, wetting agents, a rubber accelerator and softener and in the manufacture of detergents and insecticides (Li 1998; Ang-Lopeź and Alis 2006). Worms are also finding new uses as a source of collagen for pharmaceutical industries.

Nutritive feed materials (vermimeal) for poultry, dairy and fishery industries

Earthworms provide a valuable source of nutritive food for many mammals, reptiles and fishes in the wild. They are complete food rich in proteins, minerals, vitamins and roughage. They are rich in high quality protein (65%) and are complete protein with all essential amino acids. There is 70-80% high quality lysine and methionine. glumatic acid, leucine, lysine and arginine are higher than in fish meals and meat meals. Tryptophan is 4 times higher than in blood powder and 7 times higher than in cow liver. Worms are also rich in Vitamins A and B and minerals. There is 0.25 mg of Vitamin B_1 and 2.3 mg of Vitamin B_2 in each 100 g of earthworms. It is particularly high in Vitamin B_3 (Niacin). Vitamin D accounts for 0.04-0.073% of earthworms' wet weight. Worms are rich in phosphorus (8 g/kg) and calcium. Fe content is 14 times higher than fish meal (Sabine 1978; Guerrero 2006) (**Table 11**).

Thus, worms are wonderful pro-biotic feed for fish, cattle and poultry industry (Barcelo 1988; Fisher 1988; Dynes 2003). They are being used as additives to produce pellet feeds in the USA, Canada and Japan (Li 1998). Fish, shrimp and poultry fed on earthworms, grows at a much faster rate than those fed with many other commercial feeds. Barcelo (1988) reported that the gain in weight of broilers chicken fed with 14% vermimeal (produced from *E. eugeniae*) in diet was comparable with that of birds fed with commercial feeds, the cost of production of which are much higher. Guerrero (2006) reported that the growth of fishes in ponds were significantly greater with a diet of 15% vermimeal (produced from *P. excavatus*) and 10% fish meal as compared to those fed with only 25% fish meal. Pigs fed with fresh worms at 150 g/head/day gained weight by 34.6% as compared to those fed normally (Sabine 1981; Guerrero 2006). Worldwide, vermimeal is being recommended as a very high energy supplement for feeds because it contains absorbable amino acids which provides muscular growth rather than fat mass of growth. Since earthworms have a dry matter content of 18%, it will take 5.5 kg of fresh worms to produce 1 kg of vermimeal (Guerrero 2004).

Dietary food supplement from earthworms for human consumption

Because earthworm's proteins have 8-9 essential amino acids especially with the tasty glutamic acid it can be used for human beings as well. Worm protein is higher than in any meat products with about 2% lower fats than in meats and ideal for human consumption (Edwards and Niederer 1988; Sun 2009). Compared to meat meal, the amino acid composition of vermimeal is of much higher quality. A commercial product marketed as a dietary supplement is now produced in China and Canada with brand names PLASMIN and BOLOUAKE (Elicano 2004; Guerrero and Guerrero 2006). EUGETON is the brand name of earthworm-based food supplement developed by Aquatic Biosystems with support from the Philippine Council for Aquatic and Marine Research and Development, Laguna, Philippines. A comparative fibrinolytic activity test of PLASMIN and EUGETON capsules showed more or less similar activity of 0.0193 and 0.0195 units/mg respectively (Guerrero and Guerrero 2006).

CONCLUDING REMARKS

Vermiculture technologies for waste and land management and for improving soil fertility to promote crop productivity and production of valuable biological compounds has grown considerably in recent years all over the world and is being scientifically improved (UNSW, ROU 2002; NIIR 2004).

Vermi-composting and vermi-agro-production can use food wastes which are of negative economic and environmental value for society to produce food which has positive socio-economic value for society while also protecting farm soil and improving its fertility. And if VC can replace chemical fertilizers for production of safe organic foods, it will be a giant step towards achieving global, social, economic and environmental sustainability. With the growing global popularity of organic foods which became a US$ 6.5 billion business every year by 2000, there will be great demand for VC in the future. US Department of Agriculture estimated that 25% of Americans purchased organically grown foods at least once a week (Li 1998).

A serious cause of concern today is the emission of powerful GHGs, CH_4 and N_2O resulting from the disposal of MSW either in the landfills or from their management by composting (Lou and Nair 2009). Studies indicate high emissions of CH_4 and N_2O in proportion to the amount of food waste used (He *et al.* 2000). AGO (2007) reported that disposal of MSW (primarily in landfills) contributed 17 million t CO_2-equivalent of GHG in Australia in 2005, equivalent to the emissions from 4 million cars or 2.6% of the national GHG emissions. As anaerobic composting systems emits the highest amount of CO_2, CH_4 and N_2O and vermicomposting system emits lowest amounts of all these GHGs and since the global warming potential of CH_4 and N_2O is approximately 21 times and 310 times that of CO_2, respectively, therefore on the basis of CO_2-equivalent, due to the extreme anaerobic conditions prevailing in closed MSW landfills where all wastes are compacted and covered by soil everyday during filling they would emit highest amount of GHGs (3640 mg CO_2-e/m^2/h). As more than 70% of the MSW is disposed off in landfills in Australia and in all developed nations, commercial vermicomposting of MSW can play a good part in the strategy of greenhouse gas reduction and mitigation in the disposal of global MSW (Toms *et al.* 1995; Sinha *et al.* 2009a).

In any vermiculture practice, whether done for solid waste management or wastewater treatment or soil and land remediation, worm biomass comes as a valuable by-product. Worms are finding new uses and applications in modern medicine and in several consumer industries for sustainable production of essential goods for societal use and consumption (Li 1998; Wang 2000; Dynes 2003). And for production of worms for medicinal and industrial uses, it inevitably leads to utilization of a variety of organic wastes diverting them from landfills. The wastes are converted into VC – a nutritive biofertilizer, comes as a by-product. On a commercial scale, tons of worm biomass can result every year as under favorable conditions worms double their number at least every 60–70 days.

Earthworms are truly justifying the beliefs and fulfilling the dreams of Sir Charles Darwin who called them as '*unheralded soldiers of mankind*' and '*friends of farmers*' and wrote that '*there may not be any other creature in world that has played so important a role in the history of life on earth*' (Bogdanov 1996).

It is also justifying the beliefs of Great Russian scientist Dr. Anatoly Igonin who said '*Nobody and nothing can be compared with earthworms and their positive influence on the whole living Nature. They create soil and improve soil's fertility and provide critical biosphere's functions: disinfecting, neutralizing, protective and productive*' (Bogdanov 2004). Future of mankind on earth beholds with the earthworms and our relationship must be maintained.

REFERENCES

Achazi RK, Fleener C, Livingstone DR, Peters LD, Schaub K, Schiwe E (1998) Cytochrome P 450 and dependent activity in unexposed and PAH-exposed terrestrial annelids. *Journal of Comparative Biochemistry and Physiology*, Part C, **121**, 339-350

Alekseeva T, Besse P, Binet F, Delort AM, Forano C, Josselin N (2006) Effect of earthworm activity (*Aporrectodea giardi*) on atrazine adsorption and biodegradation. *European Journal of Soil Science* **57**, 295-307

Ang-Lopeź MJ, Alis R (2006) Indigenous uses of earthworms for health in the Philippines. In: Guerrero RD, Guerrero-del Castillo MRA (Eds) *Proceedings of the International Symposium Workshop on Vermi Technologies for Developing Countries*, Philippine Fisheries Association Inc., Laguna, Philippines, pp 135-144

Arancon NQ, Edwards CA (2006) Effects of vermicompost on plant growth. In: Guerrero RD, Guerrero-del Castillo MRA (Eds) *Proceedings of the International Symposium Workshop on Vermi Technologies for Developing Countries*, Philippine Fisheries Association Inc., Laguna, Philippines, pp 32-65

Arancon NQ, Edwards CA, Lee S, Byrne R (2006) Effects of humic acids from vermicomposts on plant growth. *European Journal of Soil Biology* **42**, S65-S69

Arancon NQ, Edwards CA, Bierman P, Welch C, Metzger JD (2004) Influences of vermicomposts on field strawberries 1. Effects on growth and yields. *Bioresource Technology* **93**, 145-153

Atiyeh RM, Lee S, Edwards CA, Arancon, NQ, Metzger JD (2002) The influence of humic acids derived from earthworm-processed organic wastes on plant growth. *Bioresource Technology* **84**, 7-14

Atiyeh RM, Subler S, Edwards CA, Bachman G, Metzger JD, Shuster W (2000) Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedobiologia* **44**, 579-590

AGO (2007) *National Greenhouse Gas Inventory 2005*, Australian Greenhouse Office, Canberra, ACT

Bajsa O, Nair J, Mathew K, Ho GE (2003) Vermiculture as a tool for domestic wastewater management. *Water Science and Technology* **48 (11–12)**, 125-132

Baker KH, Herson DS (1994) *Bioremediation*, McGraw Hill, Inc., New York, 929 pp

Baker GH, Barrett VJ (1994) *Earthworm Identifier*, CSIRO Publishing, Melbourne, Victoria, Australia, 24 pp

Balamurugan M, Parthasarathi K, Cooper EL, Ranganathan LS (2009) Curative effect of earthworm extract, *Lampito mauritii* (Kinberg) on inflammation, oxidation and blood profiles in rats. In: Karmegam N (Ed) *Vermitechnology I. Dynamic Soil, Dynamic Plant* **3 (Special Issue 2)**, 69-72

Barcelo PM (1988) Production and utilization of earthworms as feeds for broilers in the Philippines. *Journal of Tropicultura* **6 (1)**, 21-24

Barley, KP Jennings AC (1959) Earthworms and soil fertility III; The influence of earthworms on the availability of nitrogen. *Australian Journal of Agricultural Research* **10**, 364-370

Beetz A (1999) *Worms for Composting (Vermicomposting)*. ATTRA-National Sustainable Agriculture Information Service, Livestock Technical Note, June 1999, 8 pp

Binet F, Fayolle L, Pussard M (1998) Significance of earthworms in stimulating soil microbial activity. *Biology and Fertility of Soils* **27**, 79-84

Bhat JV, Khambata P (1994) Role of earthworms in agriculture. Indian Council of Agriculture Research (ICAR), New Delhi, India, Series No. 22, 36 pp

Bhawalkar US (1995) *Vermiculture Ecotechnology*, Publication of Bhawalkar Earthworm Research Institute (BERI), Pune, India, 330 pp

BIO-WISE (2000) *Contaminated Land Remediation: A Review of Biological Technology*, CIRIA Publications, London, DTI, 6 pp

Bogdanov P (1996) *Commercial Vermiculture: How to Build a Thriving Business in Redworms*, VermiCo Press, Oregon, 83 pp

Bogdanov P (2004) The single largest producer of vermicompost in world; In: Bogdanov P (Ed) *Casting Call* (Vol 9 (3)), October 2004. Available online: http://www.vermico.com

Bolan NS, Baskaran S (1996) Characteristics of earthworm casts affecting herbicide sorption and movement. *Biology and Fertility of Soils* **22**, 367-372

Brown GG (1995) How do earthworms affect microfloral and faunal community diversity? *Plant and Soil* **170**, 209-231

Brown GB, Doube BM (2004) On earthworms assisted bioremediation. In: Edward CA (Ed) *Earthworm Ecology* (2^{nd} Ed), CRC Press, Boca Raton, FL, pp 213-239

Buckerfield JC, Flavel TC, Lee KE, Webster KA (1999) Vermicompost in solid and liquid forms as a plant-growth promoter. *Pedobiologia* **43**, 753-759

Buckerfield JC, Webster KA (1998) Worm-worked waste boost grape yield: prospects for vermicompost use in vineyards. *The Australian and New Zealand Wine Industry Journal* **13**, 73-76

Buchanan MA, Russell E, Block SD (1988) Chemical characterization and nitrogen mineralization potentials of vermicomposts derived from different organic wastes. In: Edwards CA, Neuhauser EF (Eds) *Earthworms in Environmental and Waste Management*, SPB Academic Publisher, The Hague, The Netherlands, pp 231-239

Butt KR (1999) Inoculation of earthworms into reclaimed soils: the UK experience. *Land Degradation and Development* **10**, 565-575

Butt KR, Lowe CN, Frederickson J, Moffat AJ (2004) The development of sustainable earthworm populations at Calvert landfill site, UK. *Land Degradation and Development* **15**, 27-36

Canellas LP, Olivares FL, Okorokova AL, Façanha RA (2002) Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma membrane H^+-ATPase activity in maize roots. *Plant Physiology* **130**, 1951-1957

Chaoui HI, Zibilske LM, Ohno T (2003) Effects of earthworms casts and compost on soil microbial activity and plant nutrient availability. *Soil Biology and Biochemistry* **35 (2)**, 295-302

Chauhan K (2009) *A Comprehensive Study of Vermiculture Technology*, Report of 40 CP Honours Project for the Partial Fulfillment of Master of Environmental Engineering Degree; Griffith University, Australia (Principal Supervisor: Dr. Rajiv K. Sinha; Co-supervisor Dr. Sunil Herat), 80 pp

Chan YC, Sinha RK, Wang WJ (2010) Emission of greenhouse gases from home aerobic composting, anaerobic digestion and vermicomposting of household wastes in Brisbane (Australia). *Journal of Waste Management and Research* (in press)

Chandran V (2010) Study of vermifiltration and vermiremediation of some industrial wastewater and the soil contaminated by toxic wastewater using earthworms (*Eisenia fetida*). 40 CP Research Project, Griffith University, Brisbane, Australia (Supervisors: Dr. Rajiv K. Sinha & Dr. Sunil Herat), 80 pp

Contreras-Ramos SM, Álvarez-Bernal D, Dendooven L (2007) Dynamics of nitrogen in a PAHs contaminated soil amended with biosolid or vermicompost in the presence of earthworms. *Chemosphere* **67**, 2072-2081

Contreras-Ramos SM, Álvarez-Bernal D, Dendooven L (2006) *Eisenia fetida* increased removal of polycyclic aromatic hydrocarbons (PAHs) from soil. *Environmental Pollution* **141**, 396-401

Contreras-Ramos SM, Escamilla-Silva EM, Dendooven L (2005) Vermicomposting of biosolids with cow manure and oat straw. *Biology and Fertility of Soils* **41**, 190-198

Cooper E (2009) New enzymes isolated from earthworms is potent fibrinolytic. ACAM Integrative Medicine Blog. Oxford University Press Journal (UK). Available online: http://acam.typepad.com/blog/2009/04/index.html

Cordero CH (2005) Earthworms can help dissolve blood clots for stroke patients. Available online: http://www.thenewstoday.info/20051125/earthworms.can.help.dissolve.blood.clots.for.stroke.patients.html

Daniel T, Karmegam N (1999) Bio-conversion of selected leaf litters using an African epigeic earthworm, *Eudrilus eugeniae*. *Ecology, Environment and Conservation* **5 (3)**, 271-275

Dash MC (1978) Role of earthworms in the decomposer system. In: Singh JS, Gopal B (Eds) *Glimpses of Ecology*, India International Scientific Publication, New Delhi, pp 399-406

Datar MT, Rao MN, Reddy S (1997) Vermicomposting: a technological option for solid waste management. *Solid Waste Technology and Management* **24 (2)**, 89-93

Davis B (1971) Laboratory studies on the uptake of dieldrin and DDT by earthworms. *Soil Biology and Biochemistry* **3**, 221-223

Domínguez J (2004) State of the art and new perspectives on vermicomposting research. In: Edwards CA (Ed) *Earthworm Ecology*, CRC Press, Boca Raton, FL, pp 401-424

Domínguez J, Edwards CA (1997) Effects of stocking rate and moisture content on the growth and maturation of *Eisenia andrei* (Oligochaeta) in pig manure. *Soil Biology and Biochemistry* **29 (3–4)**, 743-746

Dynes RA (2003) Earthworms: Technology information to enable the development of earthworm production: A report for the Rural Industries Research and Development Corporation (RIRDC), Govt. of Australia, Canberra, ACT, Project No CSA-6A, p 33

Eastman BR, Kane PN, Edwards CA, Trytek L, Gunadi B, Mobley JR (2001) The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. *Journal of Compost Science and Utilization* **9 (1)**, 38-41

Edwards CA (1988) Breakdown of animal, vegetable and industrial organic wastes by earthworms. In: Edwards CA, Neuhauser EF (Eds) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, The Netherlands, pp 21-32

Edwards CA (1998) The use of earthworms in the breakdown and management of organic wastes. In: Edwards CA (Ed) *Earthworm Ecology*, CRC Press, Boca Raton, FL, pp 327-354

Edwards CA, Arancon N (2004) The use of earthworms in the breakdown of organic wastes to produce vermicomposts and animal feed protein. In: Edwards CA (Ed) *Earthworm Ecology*, CRC Press, Boca Raton, FL, pp 345-379

Edwards CA, Bohlen PJ (1996) *Biology and Ecology of Earthworms* (3rd Edn), Chapman and Hall, London, UK, 426 pp

Edwards CA, Burrows I (1988) The potential of earthworms composts as plant growth media. In: Edward CA, Neuhauser EF (Eds) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, The Netherlands, pp 21-32

Edwards CA, Fletcher KE (1988) Interaction between earthworms and microorganisms in organic matter breakdown. *Agriculture, Ecosystems and Environment* **24**, 235-247

Edwards CA, Niederer A (1988) The production and processing of earthworms protein. In: Edwards CA, Neuhauser EF (Eds) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, The Netherlands, pp 169-179

Edwards CA, Arancon NQ, Vasko-Bennett M, Askar A, Keeney G, Little B (2010a) Suppression of green peach aphid (*Myzus persicae*) (Sulz.), citrus mealybug (*Planococcus citri*) (Risso), and two spotted spider mite (*Tetranychus urticae*) (Koch.) attacks on tomatoes and cucumbers by aqueous extracts from vermicomposts. *Crop Protection* **29**, 80-93

Edwards CA, Arancon NQ, Vasko-Bennett M, Askar A, Keeney G (2010b) Effect of aqueous extracts from vermicomposts on attacks by cucumber beetles (*Acalymna vittatum*) (Fabr.)on cucumbers and tobacco hornworm (*Manduca sexta*) (L.) on tomatoes. *Pedobiologia* **53**, 141-148

Edwards CA, Arancon NQ, Emerson E, Pulliam R (2007) Suppression of plant parasitic nematodes and arthropod pests with vermicompost teas. *Biocycle* December 2007, pp 38-39

Eijsackers H, Van Gestel CAM, De Jonge S, Muijs B, Slijkerman D (2001) PAH – polluted dredged peat sediments and earthworms: a mutual inference. *Ecotoxicology* **10**, 35-50

Elicano T (2004) Novel thrombolytic therapy. Philippine Star, June 13, 2004, p 16

Elvira C, Sampedro L, Benitez E, Nogales R (1998) Vermicomposting from sludges from paper mills and dairy industries with *Elsenia andrei*: A pilot scale study. *Bioresource Technology* **63**, 205-211

Eswaran H, Lal R, Reich P (2001) Land degradation: an overview. In: Bridges EM, Hannam ID, Oldeman LR, Penning de Vries FWT, Scherr SJ, Sombatpanit S (Eds) *Response to Land Degradation*, Science Publishers, USA, pp 20-35

Fernández-Luqueño F, Reyes-Varela V, Martínez-Suárez C, Salomón-Hernández G, Yáñez-Meneses J, Ceballos-Ramírez JM, Dendooven L (2010) Effect of different nitrogen sources on plant characteristics and yield of common bean (*Phaseolus vulgaris* L.). *Bioresource Technology* **101**, 396-403

Fisher C (1988) The nutritional value of earthworm meal for poultry. In: Edwards CA, Neuhauser EF (Eds) *Earthworms in Waste and Environmental Management*, SPB Academic Publishing, The Hague, The Netherlands, pp 181-192

Fraser-Quick G (2002) Vermiculture – a sustainable total waste management solution. *What's New in Waste Management*? **4 (6)**, 13-16

Frederickson J (2000) The worm's turn. *Waste Management Magazine*. August, UK, 12 pp

Garg VK, Kaushik P (2005) Vermistabilization of textile mill sludge spiked with poultry droppings by an epigeic earthworm *Eisenia foetida*. *Bioresource Technology* **96**, 1189-1193

Garg VK, Kaushik P, Dilbaghi N (2006) Vermiconversion of wastewater sludge from textile mill spiked with anaerobically digested biogas plant slurry employing *Eisenia foetida*. *Ecotoxicology and Environmental Safety* **65**, 412-419

GEORG (2004) Feasibility of developing the organic and transitional farm market for processing municipal and farm organic wastes using large–scale vermicomposting. Publication of Good Earth Organic Resources Group, Halifax, Nova Scotia, Canada. Available online: http://www.alternativeorganic.com

Gevao B, Mordaunt C, Semple KT, Piearce TG, Jones KC (2001) Bioavailability of nonextractable (bound) pesticide residues to earthworms. *Environmental Science and Technology* **35**, 501-507

Ghabbour SI (1996) Earthworm in agriculture: a modern evaluation. *Indian Review of Ecological and Biological Society* **111 (2)**, 259-271

Giraddi RS, Lingaraju BS, Umapathy PN, Swamy AC, Megalamani BR (2008) Vermitechnology for successful management of muncipal wastes – A joint effort in South India. *Karnataka Journal of Agricultural Sciences* **21 (2)**, 284-286

Graff O (1981) Preliminary experiment of vermicomposting of different waste materials using *Eudrilus eugeniae* Kingberg. In: Appelhof M (Ed) *Proceedings of the Workshop on Role of Earthworms in the Stabilization of Organic Residues*, Malanazoo Publications, Michigan, USA, pp 179-191

Grdiša M, Mikecin A, Knežević N (2009) Fibrinolytic enzymes from earthworm. In: Karmegam N (Ed) Vermitechnology I. *Dynamic Soil, Dynamic Plant* **3 (Special Issue 2)**, 61-63

Guerrero RD (2004) *Handbook of Vermicompost and Vermimeal Production and Utilization*, Aquatic Biosystems, Laguna, The Philippines, 42 pp

Guerrero RD (2006) Commercial vermimeal production: is it feasible? In: Guerrero RD, Guerrero-del Castillo MRA (Eds) *Proceedings of the International Symposium Workshop on Vermi Technologies for Developing Countries*, Philippine Fisheries Association Inc., Laguna, Philippines, pp 112-120

Gunathilagraj K, Ravignanam T (1996) Vermicomposting of sericultural wastes. *Madras Agricultural Journal* **83**, 455-457

Haimi J, Salminen J, Huhta V, Knuutinen J, Palm H (1992) Bioaccumulation of organochlorine compounds in earthworms. *Soil Biology and Biochemistry* **24 (12)**, 1699-1703

Hartenstein R, Neuhauser EF, Collier J (1980) Accumulation of heavy metals in the earthworm *E. foetida*. *Environmental Quality* **9**, 23-26

Hartenstein R, Bisesi MS (1989) Use of earthworm biotechnology for the management of effluents from intensively housed livestock. *Outlook Agriculture USA* **18**, 72-76

He Y, Inamori Y, Mizuochi M, Kong H, Iwami N, Sun T (2000) Measurements of N_2O and CH_4 from aerated composting of food waste. *Journal of the Science of the Total Environment* **254**, 65-74

Hiraishi A (2002) Vermicomposting of household biowaste using *Eisenia fetida*: evaluation of waste reduction efficiency and coexistent microbial community structure. *Seibutsu-kogaku* **80**, 283-290

Hori M, Kondon K, Yoshida T, Konishi E, Minami S (1974) Studies of antipyretic components in the Japanese earthworm. *Biochemistry and Pharmacology* **23**, 1582-1590

Hughes R, Nair J, Mathew K, Ho G (2007) Toxicity of domestic wastewater pH to key earthworm species within an innovative decentralised vermifiltration system. *Water Science and Technology* **55 (7)**, 211-218

Hwang CM, Kim Di, Huh SH (2002) *In vivo* evaluation of lumbrokinase extracted from earthworms *Lumbricus rubellus* in a prosthetic vascular graft. *Cardiovascular Surgery* **43**, 891-894

Ireland MP (1983) Heavy metals uptake in earthworms. In: Satchel JE (Ed) *Earthworm Ecology: From Darwin to Vermiculture*, Chapman and Hall, London, pp 247-265

Jager T, Baerselman R, Dukeman E, De Groot AC, Hogendoorn EA, Jong AD, Kruitbosch J, Peijn W (2003) Availability of PAH to earthworms (*Eisenia andrei*) in field polluted soil and soil-sediment mixtures. *Journal of Environmental Toxicology and Chemistry* **22 (4)**, 767-775

Jayakumar M, Karthikeyan V, Karmegam N (2009) Comparative studies on physico-chemical, microbiological and enzymatic activities of vermicasts of the earthworms, *Eudrilus eugeniae*, *Lampito mauritii* and *Perionyx ceylanensis* cultured in pressmud. *International Journal of Applied Agricultural Research* **4 (1)**, 75-85

Jin L, Jin H, Zhang G, Xu G (2000) Changes in coagulation and tissue plasminogen activator after the treatment of cerebral infarction with lumbrokinsae (from earthworms). *Clinical Hemorheol Microcirca* **23**, 213-218

Jordão CP, Fialho LL, Neves JCL, Cecon PR, Mendonc ES, Fontes RLF (2007) Reduction of heavy metal contents in liquid effluents by vermicomposts and the use of the metal-enriched vermicomposts in lettuce cultivation. *Bioresource Technology* **98**, 2800-2813

Kalamdhad AS, Singh YK, Ali M, Khwairakpam M, Kazmi AA (2009) Rotary drum composting of vegetable waste and tree leaves. *Bioresource Technology* **100**, 6442-6450

Kale RD (2006) The role of earthworms and research on vermiculture in India. In: Guerrero RD, Guerrero-del Castillo MRA (Eds) *Proceedings of the International Symposium Workshop on Vermi Technologies for Developing Countries*, Philippine Fisheries Association Inc., Laguna, Philippines, pp 66-88

Kale RD (1998) Earthworms: nature's gift for utilization of organic wastes. In: Edward CA (Ed) *Earthworm Ecology*, St. Lucie Press, NY, pp 355-373

Kale RD (1993) Vermiculture: scope for new biotechnology. In: Ghosh AK (Ed) *Earthworm Resources and Vermiculture*, Zoological Survey of India, Calcutta, pp 105-108

Kale RD, Karmegam N (2010) The role of earthworms in tropics with emphasis on Indian ecosystems. *Applied and Environmental Soil Science* **2010**, Article ID 414356, 16 pp

Kale RD, Sunitha NS (1995) Efficiency of earthworms (*Eudrilus eugeniae*) in converting the solid waste from aromatic oil extraction industry into vermicompost. *Journal of IAEM* **22 (1)**, 267-269

Karmegam N, Daniel T (2009a) Investigating efficiency of *Lampito mauritii* (Kinberg) and *Perionyx ceylanensis* Michaelsen for vermicomposting of different types of organic substrates. *The Environmentalist* **29**, 287-300

Karmegam N, Daniel T (2009b) Growth, reproductive biology and life cycle of the vermicomposting earthworm, *Perionyx ceylanensis* Mich. (Oligochaeta: Megascolecidae). *Bioresource Technology* **100**, 4790-4796

Karmegam N, Daniel T (2009c) Effect of application of vermicasts as layering media for an ornamental plant, *Codiaeum variegatum* (L.) Bl. In Karmegam N (Ed) *Vermitechnology I. Dynamic Soil, Dynamic Plant* **3 (Special Issue 2)**, pp 100-104

Karmegam N, Daniel T (2008) Effect of vermicompost and chemical fertilizer on growth and yield of hyacinth bean, *Lablab purpureus* (L.) Sweet. *Dynamic Soil, Dynamic Plant* **2**, 77-81

Karmegam N, Daniel T (2000a) Decomposition of leaf litters using the compost worm, *Eisenia fetida*. *Indian Journal of Environment and Ecoplanning* **3 (1)**, 111-116

Karmegam N, Daniel T (2000b) Utilization of some weeds as substrates for vermicompost preparation using an epigeic earthworm, *Eudrilus eugeniae*. *Asian Journal of Microbiology, Biotechnology and Environmental Science* **2 (1-2)**, 63-66

Karmegam N, Alagumalai K, Daniel T (1999) Effect of vermicompost on the growth and yield of green gram (*Phaseolus aureus* Roxb.) *Tropical Agriculture* **76 (2)**, 143-146

Kaur A, Singh J, Vig AP, Dhaliwal SS, Rup PJ (2010) Cocomposting with and without *Eisenia fetida* for conversion of toxic paper mill sludge to a soil conditioner. *Bioresource Technology* **101**, 8192-8198

Khwairakpam M, Bhargava R (2009) Bioconversion of filter mud using vermicomposting employing two exotic and one local earthworm species. *Bioresource Technology* **100**, 5846-5852

Komarowski S (2001) Vermiculture for sewage and water treatment sludges, *WATER*, Publication of Australian Water and Wastewater Association, July, pp 39-43

Krishnamoorthy RV, Vajranabhaiah SN (1986) Biological activity of earthworm casts: an assessment of plant growth promoter levels in the casts. *Proceedings of Indian Academy of Sciences (Animal Science)* **95**, 341-351

Kristiana R, Nair J, Anda M, Mathew K (2005) Monitoring of the process of composting of kitchen waste in an institutional scale worm farm. *Water Science and Technology* **51 (10)**, 171-177

Lakshmi BL, Vijayalakshmi GS (2000) Vermicomposting of sugar factory filter pressmud using African earthworm species (*Eudrilus eugeniae*). *Pollution Research* **19 (3)**, 481-483

Li K-M (1998) Vermiculture Industry in Circular Economy, *Worm Digest* 16 October 2005. Available online:
http://www.wormdigest.org/content/view/135/2/

Li SL (1995) Research on *di long's* (earthworms) effect in lowering blood pressure. *Journal of Information* **12 (3)**, 22-24

Loehr RC, Martin JH, Neuhauser EF, Malecki MR (1984) Waste management using earthworms – engineering and scientific relationships. Final Project submitted to National Science Foundation, Department of Agriculture Engineering, Cornell University, New York, p 118

Lou XF, Nair J (2009) The impact of landfilling and composting on greenhouse gas emissions – a review. *Bioresource Technology* **100**, 3792-3798

Ma WC, Imerzeel J, Bodt J (1995) Earthworm and food interactions on bioaccumulation and disappearance of PAHs: studies on phenanthrene and flouranthene. *Ecotoxicology and Environmental Safety* **32**, 226-232

Mainoo NOK, Barrington S, Whalen JK, Sampedro L (2009) Pilot-scale vermicomposting of pineapple wastes with earthworms native to Accra, Ghana. *Bioresource Technology* **100**, 5872-5875

Markman SI, Guschina A, Barnsleya S, Buchanan KL, Bascoe D, Muller CT (2007) Endocrine disrupting chemicals accumulate in earthworms exposed to sewage effluents. *Chemosphere* **70 (1)**, 119-125

Martin-Gil J, Navas-Gracia LM, Gomez-Sobrino E, Correa-Guimarães A, Hernandez-Navarro S, Sanchez-Bascones M (2007) Composting and vermicomposting experiences in the treatments and bioconversion of asphaltens from the *Prestige* oil spill. *Bioresource Technology* **99**, 1821-1829

McKelvie JR, Wolfe DM, Celejewski M, Simpson AJ, Simpson MJ (2010) Correlations of *Eisenia fetida* metabolic responses to extractable phenanthrene concentrations through time. *Environmental Pollution* **158**, 2150-2157

Mihara H, Sumi H, Akazawa K, Yoneta T, Mizumoto H, Yoneta T (1983) Fibrinolytic enzymes extracted from the earthworms. *Journal of Thrombosis and Haemostasis* **50**, 258

Mihara H, Sumi H, Mizumoto H, Yoneta T, Ikeda R, Maruyama M (1990) Oral administration of earthworm powder as possible thrombolytic therapy. Recent Advances in Thrombosis and Fibrinolysis, Academic Press, New York, pp 287-298

Mihara H, Sumi H, Mizumoto H, Yoneta T, Ikeda R, Maruyama M (1991) A novel fibrinolytic enzyme extracted from the earthworm *Lumbricus rubellus*. *Japanese Journal of Physiology* **41**, 461-472

Mihara H, Maruyama M, Sumi H (1992) Novel thrombolytic therapy discovered in oriental medicine using the earthworms. *South East Asian Journal of Tropical Medicine and Health* **23**, 131-140

Monroy F, Aira M, Domínguez J (2009) Reduction of total coliform numbers during vermicomposting is caused by short-term direct effects of earthworms on microorganisms and depends on the dose of application of pig slurry. *Science of the Total Environment* **407**, 5411-5416

Munroe G (2007) Manual of on-farm vermicomposting and vermiculture. Publication of Organic Agriculture Centre of Canada, 40 pp. Available online: http://www.oacc.info/DOCs/Vermiculture_FarmersManual_gm.pdf

Muscolo A, Bovalo F, Gionfriddo F, Nardi S (1999) Earthworm humic matter produces auxin-like effects on *Daucus carota* cell growth and nitrate metabolism. *Soil Biology and Biochemistry* **31**, 1303-1311

Nakajima N, Sugimoto M, Ishihara K (2000) Stable earthworm serine proteases: application of the protease function and usefulness of the earthworm autholysate. *Biotechnology and Bioengineering* **90**, 174-179

Ndegwa PM, Thompson SA (2001) Integrating composting and vermicomposting in the treatment and bioconversion of biosolids. *Bioresource Technology* **76 (2)**, 107-112

Nelson BW, Chaney RL, Mulhern B (1982) Heavy metals concentrations in earthworms from soil amended with sewage sludge. *Journal of Environmental Quality* **11 (3)**, 382-385

Nighawan SD, Kanwar JS (1952) Physico-chemical properties of earthworm castings. *Indian Journal of Agricultural Sciences* **22**, 357-375

NIIR (2004) *The Complete Technology Book on Vermiculture and Vermicompost*, National Institute of Industrial Research, Delhi, 346 pp

OECD (2000) Guidelines for testing organic chemicals and proposal for new guidelines: Earthworms reproduction tests (*E. fetida andrei*). Organization for Economic Co-operation and Development (www.oecd.org)

Pajon S (Undated): *The Worms Turn – Argentina*, Intermediate Technology Development Group; Case Study Series 4; (Quoted in Munroe 2007)

Pajon S (2009) The Worm's Turn – Argentina". Intermediate Technology Development Group (ITDG), Case Study Series 4

Parthasarathi K (2007) Influence of moisture on the activity of *Perionyx excavatus* (Perrier) and microbial–nutrient dynamics of pressmud vermicompost. *Iranian Journal of Environmental Health Science and Engineering* **4 (3)**, 147-156

Patil S (2005) *Vermicomposting of fast food waste*. 20 CP Project submitted for the partial fulfilment of the degree of Master in Environmental Engineering, Griffith University, Australia (Supervisor: Dr. Rajiv K. Sinha), 80 pp

Pattnaik S, Reddy MV (2009) Bioconversion of municipal (organic) solid waste into nutrient-rich vermicompost by earthworms (*Eisenia fetida, Eudrilus eugeniae* and *Perionyx excavatus*). In: Karmegam N (Ed), *Vermitechnology I. Dynamic Soil, Dynamic Plant* **3 (Special Issue 2)**, pp 122-128

Pierre V, Phillip R, Margnerite L, Pierrette C (1982) Anti-bacterial activity of the haemolytic system from the earthworms *Eisenia foetida andrei*. *Invertebrate Pathology* **40**, 21-27

Prakash M, Jayakumar M, Karmegam N (2008) Physico-chemical characteristics and fungal flora in the casts of the earthworm, *Perionyx ceylanensis* Mich. Reared in *Polyalthia longifolia* leaf litter. *Journal of Applied Sciences Research* **4 (1)**, 53-57

Prakash M, Karmegam N (2010) Vermistabilization of pressmud using *Perionyx ceylanensis* Mich. *Bioresource Technology* **101**, 8464-8468

Pramanik P, Ghosh GK, Ghosal PK, Banik P (2007) Changes in organic-C, N, P and K and enzyme activities in vermicompost of biodegradable organic wastes under liming and microbial inoculants. *Bioresource Technology* **98**, 2485-2494

Raja Sekar K, Karmegam N (2009a) Efficiency of the earthworm, *Eisenia fetida* (Sav.) in vermistabilization of silkworm litter mixed with leaf litter. *International Journal of Applied Environmental Sciences* **4 (4)**, 481-486

Raja Sekar K, Karmegam N (2009b) Suitability of vermicasts as carrier material for a biofertilizer, *Azospirillum brasilense* (MTCC 4036). In: Karmegam N (Ed) *Vermitechnology I. Dynamic Soil, Dynamic Plant* **3 (Special Issue 2)**, 143-146

Raja Sekar K, Karmegam N (2010) Earthworm casts as an alternate carrier material for biofertilizers: Assessment of endurance and viability of *Azotobacter chroococcum*, *Bacillus megaterium* and *Rhizobium leguminosarum*. *Scientia Horticulturae* **124**, 286-289

Ramteke PW, Hans RK (1992) Isolation of hexachlorocyclohexane (HCH) degrading microorganisms from earthworm gut. *Environmental Science and Health* **27 (8)**, 2113-2122

Reddy BVC, Subba Reddy PN, Kale RD (2009) Economic impact and production efficiency of vermicompost use in agriculture: methodological approaches. In: Edwards CA, Jayaraaj R, Jayaraaj IA (Eds) *Proceedings of Indo-US Workshop on Vermitechnology in Human Welfare*, Rohini Achagam, Coimbatore, pp 164-186

Reinecke AJ, Viljoen SA, Saayman RJ (1992) The suitability of *Eudrilus eugeniae*, *Perionyx excavatus* and *Eisenia fetida* for vermicomposting in Southern Africa in terms of their temperature requirements. *Soil Biology and Biochemistry* **24**, 1295-1307

Romero E, Plaza C, Senesi N, Nogales R, Polo A (2007) Humic acid-like fractions in raw and vermicomposted winery and distillery wastes. *Geoderma* **139**, 397-406

Roots BI (1956) The water relation of earthworms II. Resistance to desiccation and emersion and behavior when submerged and when allowed a choice of environment. *Journal of Experimental Biology* **33**, 29-44

Roy S, Arunachalam K, Dutta BK, Arunachalam A (2010) Effect of organic amendments of soil on growth and productivity of three common crops viz. *Zea mays*, *Phaseolus vulgaris* and *Abelmoschus esculentus*. *Applied Soil Ecology* **45**, 78-84

Sabine JR (1978) The nutritive value of earthworm meal. In: Hartenstein R (Ed) *Proceedings of the Conference on Utilization of Soil Organisms in Sludge Management*, Syracuse, New York, pp 122-130

Sabine JR (1981) Vermiculture as an option for resources recovery in the intensive animal industries. In: Appelhof M (Compiled) *Proceedings of Workshop on the Role of Earthworms in the Stabilization of Organic Residues*, Kalamazoo, Michigan, pp 243-252

Safawat H, Hanna S, Weaver RW (2002) Earthworms survival in oil contaminated soil. *Plant and Soil* **240**, 127-132

Sangwan P, Kaushik CP, Garg VK (2010) Vermicomposting of sugar industry waste (press mud) mixed with cow dung employing an epigeic earthworm *Eisenia fetida*. *Waste Management Research* **28**, 71-75

Satchell JE (1983) *Earthworm Ecology – From Darwin to Vermiculture*, Chapman and Hall Ltd., London, pp 1-5

Saxena M, Chauhan A, Asokan P (1998) Flyash vemicompost from non-friendly organic wastes. *Pollution Research* **17 (1)**, 5-11

Schaefer M (2005) Earthworms in crude oil contaminated soils: toxicity tests and effects on crude oil degradation. *Contaminated Soil Sediment and Water* **35**, 7-8

Schaefer M, Petersen S, Filser J (2005) Effects of *Lumbricus* dynamics in oil-contaminated soil. *Soil Biology and Biochemistry* **37**, 2065-2076

Schaffner R (2004) Bioremediation offers an effective, ethical and economical alternative to standard cleanups. *Journal of AWWA,* January 2004

Seenappa SN, Rao J, Kale RD (1995) Conversion of distillery wastes into organic manure by earthworm *Eudrilus eugeniae. Journal of IAEM* **22**, 244-246

Sherman R (2000) Commercial systems latest development in mid-to-large scale vermicomposting. *Biocycle* November 2000, 51 pp

Singleton DR, Hendrix BF, Coleman DC, Whitemann WB (2003) Identification of uncultured bacteria tightly associated with the intestine of the earthworms *Lumbricus rubellus. Soil Biology and Biochemistry* **35**, 1547-1555

Sinha RK, Valani D (2011) *Vermiculture Revolution: The Technological Revival of Charles Darwin's Unheralded Soldiers of Mankind*, NOVA Science Publishers, New York

Sinha RK, Agarwal S, Chauhan K, Chandran V, Soni BK (2010a) Vermiculture Technology: Reviving the dreams of Sir Charles Darwin for scientific use of earthworms in sustainable development programs. *Journal of Technology and Investment* **1**, 155-172

Sinha RK, Agarwal S, Chauhan K, Valani D (2010b) The wonders of earthworms and its vermicompost in farm production: Charles Darwin's 'Friends of Farmers', with potential to replace destructive chemical fertilizers from agriculture. *Journal of Agricultural Sciences* **1 (2)**, 76-94

Sinha RK, Herat S, Bharambe G, Brahambhatt A (2010c) Vermistabilization of sewage sludge (biosolids) by earthworms: converting a potential biohazard destined for landfill disposal into a pathogen free, nutritive and safe bio-fertilizer for farms. *Waste Management Research* **28 (10)**, 872-881

Sinha RK (2009) Earthworms: the miracle of nature (Charles Darwin's 'unheralded soldiers of mankind and farmer's friends'). *The Environmentalist* **29 (4)**, 339-340

Sinha RK, Chan A (2009) Study of emission of greenhouse gases by Brisbane households practicing different methods of composting of food & garden wastes: aerobic, anaerobic and vermicomposting; NRMA – Griffith University Project (Report Submitted to Griffith University & NRMA, Australia), 10 pp

Sinha RK, Herat S, Bharambe G, Patil S, Bapat PD, Chauhan K, Valani D (2009a) Vermiculture biotechnology: the emerging cost-effective and sustainable technology of the 21st century for multiple uses from waste and land management to safe and sustained food production. *Environmental Research Journal* **3 (1)**, 41-110

Sinha RK, Herat S, Valani D, Chauhan K (2009b) Vermiculture and sustainable agriculture. *American-Eurasian Journal of Agricultural and Environmental Sciences* **5 (S)**, 01-55

Sinha RK, Bharambe G, Chaudhari U (2008a) Sewage treatment by vermi-filtration with synchronous treatment of sludge by earthworms: a low-cost sustainable technology over conventional systems with potential for decentralization. *The Environmentalist* **28**, 409-420

Sinha RK, Bharambe G, Ryan D (2008b) Converting wasteland into wonderland by earthworms: a low-cost nature's technology for soil remediation: a case study of vermiremediation of PAH contaminated soil. *The Environmentalist* **28**, 466-475

Sinha RK, Nair J, Bharambe G, Patil S, Bapat PD (2008c) Vermiculture Revolution: A low-cost and sustainable technology for management of municipal and industrial organic wastes (solid and liquid) by earthworms with significantly low greenhouse gas emissions. In: James I Daven, Robert N Klein (Eds) *Progress in Waste Management Research*, NOVA Science Publishers, New York, USA, pp 159-227

Sinha RK, Bharambe G, Bapat PD (2007) Removal of high BOD and COD loadings of primary liquid waste products from dairy industry by vermi-filtration technology using earthworms. *Indian Journal of Environmental Protection* **27 (6)**, 486-501

Sinha RK, Herat S, Bapat PD, Desai C, Panchi A, Patil S (2005) Domestic waste – the problem that piles up for the society: vermiculture the solution. *Proceedings of International Conference on Waste-The Social Context*, May 11-14, 2005, Edmonton, Alberta, Canada, pp 55-62

Sinha RK, Herat S, Agarwal S, Asadi R, Carretero E (2002) Vermiculture technology for environmental management: study of action of earthworms *Eisenia foetida*, *Eudrilus eugeniae* and *Perionyx excavatus* on biodegradation of some community wastes in India and Australia. *The Environmentalist* **22 (2)**, 261-268

Singh RD (1993) *Harnessing the Earthworms for Sustainable Agriculture*, Institute of National Organic Agriculture, Pune, India, pp 1-16

Singh K (2009) Microbial and nutritional analysis of vermicompost, aerobic and anaerobic compost. Report of 40 CP Honours Project for Partial Fulfilment of Master in Environmental Engineering, Griffith University, Australia (Principal Supervisor: Dr. Rajiv K. Sinha; Co-supervisor Dr. Sunil Herat), 80 pp

Singh J, Kaur A, Vig AP, Rup PJ (2010) Role of *Eisenia fetida* in rapid recycling of nutrients from biosludge of beverage industry. *Ecotoxicology and Environmental Safety* **73**, 430-435

Singh R, Sharma RR, Kumar S, Gupta RK, Patil RT (2008) Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry (*Fragaria* x *ananassa* Duch.). *Bioresource Technology* **99**, 8507-8511

Singer AC, Jury W, Leupromchai E, Yahng C-S, Crowley DE (2001) Contribution of earthworms to PCB bioremediation. *Journal of Soil Biology and Biochemistry* **33**, 765-775

Soto MA, Toha J (1998) Ecological wastewater treatment advanced wastewater treatment, recycling and reuse. AWT 98, Milan, September 14-16, 2008

Suhane RK (2007) *Vermicompost*, Publication of Rajendra Agriculture University, Pusa, Bihar, 88 pp

Sun Z (2009) The pharmaceutical and clinical uses of earthworms in China. In: Edwards CA, Jayaraaj R, Jayaraaj IA (Eds) *Proceedings of Indo-US Workshop on Vermitechnology in Human Welfare*, Rohini Achagam, Coimbatore, pp 148-163

Suthar S (2009) Vermistabilization of municipal sewage sludge amended with sugarcane trash using epigeic *Eisenia fetida* (Oligochaeta). *Journal of Hazardous Materials* **163**, 199-206

Suthar S (2008) Development of a novel polyculture vermireactor for efficient treatment of municipal sewage water sludge. *International Journal of Environment and Waste Management* **2 (1/2)**, 84-101

Suthar S (2007a) Production of vermifertilizer from gaur gum industrial waste by using composting earthworms *Perionyx sansibaricus* (P). *The Environmentalist* **7 (1)**, 329-335

Suthar S (2007b) Vermicomposting potential of *Perionyx sansibaricus* (Perrier) in different waste materials. *Bioresource Technology* **98**, 1231-1237

Suthar S, Singh S, Dhawan S (2008) Earthworms as bioindicator of metals (Zn, Fe, Mn, Cu, Pb and Cd) in soils: Is metal bioaccumulation affected by their ecological category? *Ecological Engineering* **32**, 99-107

Syers JK, Springett JA (1984) Earthworm and soil fertility. *Plant and Soil* **76**, 93-104

Tanaka B, Nakata S (1974) Studies of antipyretic components from the Japanese earthworm. *Tokyo Igaku Zasshi* **29**, 67-97

Taylor M, Clarke WP, Greenfield PF (2003) The treatment of domestic wastewater using small-scale vermicompost filter beds. *Ecological Engineering* **21**, 197-203

Tomati V, Grappelli A, Galli E (1987) The presence of growth regulators in earthworm-worked wastes. In: *Proceedings of an International Symposium on Earthworms*, 31st March-5th April 1985, Italy, pp 423-436

Tomati V, Galli E (1995) Earthworms, soil fertility and plant productivity. *Acta Zoologica Fennica* **196**, 11-14

Tomoko Y, Koki T, Hiroaki S (2005) Enhanced bioremediation of oil-contaminated soil by a combination of the earthworm (*Eisenia fetida*) and tea extraction residue. *Edaphologia* **77**, 1-9

Toms P, Leskiw J, Hettiaratchi P (1995) Greenhouse gas offsets: an opportunity for composting. *Presentation at the 88th Annual Meeting and Exhibition*, June 8-12, 1995, San Antonio, Texas, USA, pp 18-23

Titov IN, Anokhin BM (2006) The ten-year results of treatment with the extract of earthworm tissues; Innovation Centre, Moscow, Russia. In: Guerrero RD, Guerrero-del Castillo MRA (Eds) *Proceedings of the International Symposium Workshop on Vermi Technologies for Developing Countries*, Philippine Fisheries Association Inc., Laguna, Philippines, pp 148-149

Ueda M, Goto T, Nakazawa M, Miyatake K, Sakaguchi M, Inouye K (2010) A novel cold-adapted cellulase complex from *Eisenia foetida*: Characterization of a multienzyme complex with carboxymethylcellulase, β-glucosidase, β-1,3 glucanase, and β-xylosidase. *Comparative Biochemistry and Physiology* **Part B: 157**, 26-32

Ueda M, Noda K, Nakazawa M, Miyatake K, Ohki S, Sakaguchi M, Inouye K (2008) A novel anti-plant viral protein from coelomic fluid of the earthworm *Eisenia foetida*: purification, characterization and its identification as a serine protease. *Comparative Biochemistry and Physiology* **Part B: 151**, 381-385

UNSW, ROU (2002) *Best Practice Guidelines to Managing On-Site Vermiculture Technologies*, University of New South Wales Recycling Organics Unit, Sydney, NSW, Australia. Available online: www.resource.nsw.gov.au/data/Vermiculture%20BPG.pdf

UNEP (1996) *Our Planet*, Publication of United Nations Environment Program, Nairobi, Kenya, Vol 8, p 35

Urdaneta C, Marco Parra LM, Matute S, Garaboto MA, Barros H, Vazquez C (2008) Evaluation of vermicompost as bioadsorbent substrate of Pb, Ni. V and Cr for wastewaters remediation using Total Reflection X-ray Fluorescence. *Spectrochimica Acta Part B* **63**, 1455-1460

US Composting Council (1997) Test methods for the examination of composting and compost (Interim Draft), Bethesda, Maryland, Sec 7, 71 pp

Utkhede R, Koch C (2004) Biological treatments to control bacterial canker of greenhouse tomatoes. *BioControl* **49**, 305-313

Valani D (2009) *Study of aerobic, anaerobic and vermicomposting systems for food and garden wastes and the agronomic impacts of composts on corn and wheat crops;* Report of 40 CP Honours Project for the Partial Fulfillment of Master of Environmental Engineering Degree; Griffith University, Australia (Principal Supervisor: Dr. Rajiv K. Sinha; Co-supervisor Dr. Sunil Herat), 80 pp

Venkatesh RM, Eevera T (2008) Mass reduction and recovery of nutrients through vermicomposting of fly ash. *Applied Ecology and Environmental Research* **6 (1)**, 77-84

Visvanathan C, Trankler J, Jospeh K, Nagendran R (2005) *Vermicomposting as an Eco-tool in Sustainable Solid Waste Management*, Asian Institute of Technology, Anna University, Chennai, India, 40 pp

Wang ZW (2000) Research advances in earthworms bioengineering technology. *Medica* **31 (5)**, 386-389

Wang F, Wang C, Li M, Gui L, Zhang J, Chang W (2003) Purification, characterization and crystallization of a group of earthworms fibrinolytic enzymes from *Eisenia fetida. Biotechnology Letters* **25 (13)**, 1105-1109

Wang C, Sun Z, Liu Y, Zhang X, Xu G (2007) A novel antimicrobial vermipeptide family from earthworm *Eisenia fetida. European Journal of Soil Biology* **43**, S127-S134

Xing M, Yang J, Lu Z (2005) Microorganism-earthworm integrated biological treatment process – a sewage treatment option for rural settlements. ICID 21st European Regional Conference, 15-19 May 2005, Frankfurt (Oder), Germany, and Słubice, Poland

Yadav A, Garg VK (2009) Feasibility of nutrient recovery from industrial sludge by vermicomposting technology. *Journal of Hazardous Materials* **168**, 262-268

Yoshida S, Muramatsu Y, Peijnenburg WJGM (2005) Multi-element analyses of earthworms for radioecology and ecotoxicology. *Radioprotection* **40**, S491-S495

Zaller JG (2006) Foliar spraying of vermicompost extracts: effects on fruit quality and indications of late-blight suppression of field-grown tomatoes. *Biological Agriculture and Horticulture* **24**, 165-180

Vermiculture websites

http://www.alternativeorganic.com (Good Earth People, Canada)

http://www.rirdc.gov.au (Australian Govt. Pub. On EARTHWORMS)

http://www.vermitech.com (Australian Company in Vermiculture Business)

http://www.vermitechnology.com (U.S. Company in Vermiculture Business)

http://www.wormwoman.com (Mary Appelhof: Classic Book 'Worms Eat My Garbage')

http://www.wormdigest.org ('Worm Digest'-A Quarterly Magazine)

http://www.wormresearchcentre.co.uk (Earthworm Research Center in UK)

http://www.wormdigest.org/content/view/355/2/ (Modern Medicines from Earthworms)

http://www.NIIR.org (On Vermiculture Technology by National Institute of Industrial Research, New Delhi, India)