Journal of Environmental Protection, 2010, 1, 251-260
doi:10.4236/jep.2010.13030 Published Online September 2010 (http://www.SciRP.org/journal/jep)

Earthworms: Charles Darwin's 'Unheralded Soldiers of Mankind': Protective & Productive for Man & Environment

Rajiv K. Sinha, Krunal Chauhan, Dalsukh Valani, Vinod Chandran, Brijal Kiran Soni, Vishal Patel

Griffith School of Engineering (Environment), Griffith University, Brisbane, Australia.
Email: Rajiv.Sinha@griffith.edu.au

Received April 15th, 2010; revised May 20th, 2010; accepted May 22nd, 2010.

ABSTRACT

Earthworms promises to provide cheaper solutions to several social, economic and environmental problems plaguing the human society. Earthworms can safely manage all municipal and industrial organic wastes including sewage sludge and divert them from ending up in the landfills. Their body work as a 'biofilter' and they can 'purify' and also 'disinfect' and 'detoxify' municipal and several industrial wastewater. They reduce the BOD & COD loads and the TDSS of wastewater significantly. They can even remove the EDCs (endocrine disrupting chemicals) from sewage which is not removed by the conventional sewage treatments plants. Earthworms can bio-accumulate and bio-transform many chemical contaminants including heavy metals and organic pollutants in soil and clean-up the contaminated lands for re-development. Earthworms restore & improve soil fertility by their secretions (growth hormones) and excreta (vermicast with beneficial soil microbes) & boost 'crop productivity'. They have potential to replace the environmentally destructive chemical fertilizers from farm production. The 'protein rich' earthworm biomass is being used for production of 'nutritive feed materials' for fishery, dairy & poultry industries. They are also being used as 'raw materials' for rubber, lubricant and detergent industries. The bioactive compounds isolated from earthworms are finding new uses in production of 'life saving medicines' for cardiovascular diseases and cancer cure.

Keywords: *Detoxifying, Disinfecting, Waste Degradation, Wastewater Purification, Soil Decontamination, Soil Fertility, Crop Production, Earthworms Medicines, Nutritive Feed*

1. Introduction

A revolution is unfolding in vermiculture studies for multiple uses in environmental protection and sustainable development. Earthworms have over 600 million years of experience as 'environmental managers' in the ecosystem. Vermiculture scientists all over the world knew about the role of earthworms as 'waste managers', as 'soil managers & fertility improvers' and 'plant growth promoters' for long time. But some comparatively 'new discoveries' about their role in 'treatment of municipal and industrial wastewaters', 'remediation of chemically contaminated soils' and 'development of life saving medicines', 'nutritive feed materials' for fishery & dairy industries and raw materials for 'rubber, lubricants, soaps & detergent industries' have revolutionized the studies into vermiculture.

Earthworms promises to provide cheaper solutions to several social, economic and environmental problems of human society. They are both 'protective' & 'productive' for environment and society. They protect the environment (by remedifying the contaminated soil, degrading the solid wastes and purifying wastewater) and also produce nutritive 'protein rich feed materials' for cattle and 'organic fertilizers' for the farmers to grow safe and chemical-free organic foods for society [1].

2. The Biology & Ecology of Earthworms

Earthworms are long, narrow, cylindrical, bilaterally symmetrical, segmented animals without bones. Usually the life span of an earthworm is about 3 to 7 years depending upon the type of species and the ecological situation. Earthworms harbor millions of 'nitrogen-fixing' and 'decomposer microbes' in their gut. They have 'chemoreceptors' which aid in search of food. Their body con-

tains 65% protein (70-80% high quality 'lysine rich protein' on a dry weight basis), 14% fats, 14% carbohydrates and 3% ash [2-4].

Earthworms occur in diverse habitats specially those which are dark and moist. They can tolerate a temperature range between 5℃ to 29℃. A temperature of 20℃ to 25℃ and a moisture of 60-75% is optimum for good worm function. Earthworms multiply very rapidly. Studies indicate that they double their number at least every 60-70 days. Given the optimal conditions of moisture, temperature and feeding materials earthworms can multiply by 2^8 *i.e.* 256 worms every 6 months from a single individual. Each of the 256 worms multiplies in the same proportion to produce a huge biomass of worms in a short time. The total life-cycle of the worms is about 220 days. They produce 300-400 young ones within this life period [5]. Earthworms continue to grow throughout their life.

3. Earthworms: The Protector of Human Environment

Earthworms are 'unheralded soldiers of mankind' created by Mother Nature. Although the great visionary scientist Sir Charles Darwin indicated about them long back but very few biologists really realized that. Now it is being realized and revived all over the world and services of earthworms are being utilized with a technological approach. Some of the virtues of earthworms given below

3.1. Tremendous Abilities & Ecological Adaptation for Survival in Harsh Environment

Earthworms can tolerate toxic chemicals in environment. 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 for the earthworms that were alone able to survive [6].

3.2. Tolerate and Bio-Accumulate Toxic Soil Chemicals & Contaminants from Environment

Several studies have found that earthworms effectively bio-accumulate or biodegrade several organic and inorganic chemicals including 'heavy metals', 'organochlorine pesticide' and micropollutants like 'polycyclic aromatic hydrocarbons' (PAHs) residues in the medium in which it inhabits [7,8]. Earthworms that survived in the 'Seveso Disaster' (1976) ingested TCDD contaminated soils. They were shown to bio-accumulate dioxin in their tissues and concentrate it on average 14.5 fold [6].

Earthworms have also been reported to bio-accumulate 'endocrine disrupting chemicals' (EDCs) from sewage. Significantly high concentrations of EDCs (dibutylphthalate, dioctylphthalate, bisphenol-A and 17 β-estrdiol) in tissues of earthworms (*E. fetida*) living in sewage percolating filter beds and also in garden soil [9].

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 [10,11]. Studies shows that earthworms can tolerate and bio-accumulate high concentrations of heavy metals like cadmium (Cd), mercury (Hg), lead (Pb) copper (Cu), manganese (Mn), calcium (Ca), iron (Fe) and zinc (Zn) in their tissues without affecting their physiology and this particularly when the metals are mostly non-bioavailable. The species *Lumbricus terrestris, L. rubellus* and *D. rubida* was found to bio-accumulate very high levels of lead (Pb) and Cadmium (Cd) in their tissues [7].

3.3. Destroy Pathogens and Disinfect the Environment

Earthworms routinely devour on the protozoa, bacteria and fungus as food in any waste materials or soil where they inhabit. They seem to realize instinctively that anaerobic bacteria and fungi are undesirable and so feed upon them preferentially, thus arresting their proliferation. More recently, Dr. Elaine Ingham has found in her research that worms living in pathogen-rich materials (e.g. sewage and sludge), when dissected, show no evidence of pathogens beyond 5 mm of their gut. This confirms that something inside the worms destroys the pathogens, and excreta (vermicast) becomes pathogen-free [5,6]. In the intestine of earthworms some bacteria & fungus (*Pencillium* and *Aspergillus*) have also been found [12]. The earthworms also release coelomic fluids that have anti-bacterial properties and destroy all pathogens in the waste biomass [13]. They produce 'antibiotics' and kills the pathogenic organisms in the waste and soil where they inhabit and render it virtually sterile. It was reported that the removal of pathogens, faecal coliforms (*E. coli*), *Salmonella* spp., enteric viruses and helminth ova from sewage and sludge appear to be much more rapid when they are processed by *E. fetida*. Of all *E. coli* and *Salmonella* are greatly reduced [14].

In another study the pathogen die-off in vermicomposting of sewage sludge spiked with *E. coli, S. typhimurium* and *E. faecalis* at the 1.6-5.4 × 10^6 CFU/g, 7.25 × 10^5 CFU/g and 3-4 × 10^4 CFU/g respectively. The composting was done with different bulking materials such as lawn clippings, sawdust, sand and sludge alone for a total period of 9 months to test the pathogen safety of the product for handling. It was observed that a safe product

was achieved in 4-5 months of vermicomposting and the product remained the same quality without much reappearance of pathogens after in the remaining months of the test [15]. Other studies also confirmed significant human pathogen reduction in biosolids vermicomposted by earthworms. Pathogens like enteric viruses, parasitic eggs and *E. coli* were reduced to safe levels in sludge vermicast [16-18]. Studies also revealed that the earthworms reduced the population of *Salmonella* spp. to less than 3 CFU/gm of vermicomposted sludge. There were no fecal coliforms and *Shigella* spp. and no eggs of helminths in the treated sludge. [16,19,20].

3.4. Low Greenhouse Gas (GHG) Emissions by Vermicomposting of Waste with Earthworms

Emission of greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in waste management programs of both garbage & sewage has become a major global issue today in the wake of increasing visible impacts of global warming. Biodegradation of organic waste either by composting or when disposed in landfills has long been known to generate methane (CH_4) and nitrous oxide (N_2O) resulting from the slow anaerobic decomposition of waste organics over several years [21]. Molecule to molecule, CH_4 is 20-22 times and N_2O is 296-310 times more powerful GHG than the CO_2. Studies have also indicated high emissions of nitrous oxide (N_2O) in proportion to the amount of food waste used, and methane (CH_4) is also emitted in high amounts if the composting piles contain cattle manure. [22-25].

Studies have established that vermicomposting of wastes by earthworms significantly reduce the total emissions of greenhouse gases in terms of CO_2 equivalent, especially the highly powerful GHG nitrous oxide (N_2O). Worms significantly increase the proportion of 'aerobic to anaerobic decomposition' in the compost pile by burrowing and aerating actions leaving very few anaerobic areas in the pile, and thus resulting in a significant decrease in methane (CH_4), nitrous oxide (N_2O) and also volatile sulfur compounds which are readily emitted from the conventional (microbial) composting process [26]. Analysis of vermicompost samples has shown generally higher levels of available nitrogen (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 nitrogen (N) rather than releasing it as N_2O.

Our studies also showed that on average, aerobic, anaerobic and vermicomposting systems emitted 504, 694 and 463 CO_2-e/m^2/hour respectively. This is significantly much less than the landfills emission which is 3640 CO_2-e/m^2/hour due to the extremely anaerobic conditions existing in the landfills. Vermicomposting emitted minimum of N_2O-1.17 mg/m^2/hour, as compared to Aerobic Composting (1.48 mg/m^2/hour) and Anaerobic Composting (1.59 mg/m^2/hour). Hence, earthworms can play a good part in the strategy of greenhouse gas reduction and mitigation in the disposal of global MSW [21,27].

3.5. Earthworms Combat Soil Salinity & Improve Fertility of Sodic Soils

Studies indicate that *Esinea fetida* can tolerate soils nearly half as salty as seawater *i.e.* 15 gm/kg of soil and also improve its biology and chemistry. (Average seawater salinity is around 35 g/L). Farmers at Phaltan in Satara district of Maharashtra, India, applied live earthworms to their sugarcane crop grown on saline soils irrigated by saline ground water. The yield was 125 tones/ hectare of sugarcane and there was marked improvement in soil chemistry. Within a year there was 37% more nitrogen, 66% more phosphates and 10% more potash. The chloride content was less by 46% [28,29]. In another study there was good production of potato (*Solanum tuberosum*) by application of vermicompost in a reclaimed sodic soil in India. The sodicity (ESP) of the soil was also reduced from initial 96.74 to 73.68 in just about 12 weeks. The average available nitrogen (N) content of the soil increased from initial 336.00 kg/ha to 829.33 kg/ha [30].

4. Role of Earthworms in Environmental Protection & Food Production

4.1. Safe Management of Municipal & Industrial Solid Wastes While Diverting them from Landfills & Converting into Valuable Resource (Nutritive Fertilizer)

We are facing the escalating economic and environmental cost of dealing with current and future generation of mounting municipal solid wastes. Millions of tons of MSW generated from the modern society are ending up in the landfills everyday, creating extraordinary economic and environmental problems for the local government to manage and monitor them for environmental safety (emission of greenhouse and toxic gases and leachate discharge threatening ground water contamination) [31]. Construction of secured engineered landfills incurs 20-25 million U.S. dollars before the first load of waste is dumped. According to Australian Bureau of Statistics over the past 5 years the cost of landfill disposal of waste has increased from AU $ 29 to AU $ 65 per ton of waste in Australia. During 2002-2003, waste management services within Australia cost AU $ 2458.2 millions. In 2002-03 Australians generated 32.3 million tonnes of

MSW of which 17.4 mt *i.e.* about 54% ended up in landfills [32].

A serious cause of concern today is the emission of powerful greenhouse gases (GHG) resulting from the disposal of MSW either in the landfills or from their management by composting [21]. The Australian Greenhouse Office reported that disposal of MSW (primarily in landfills) contributed 17 million tonnes CO_2-e of GHG in Australia in 2005, equivalent to the emissions from 4 millions cars or 2.6% of the national GHG emissions [33]. Vermicomposting of all biodegradable 'organic wastes' is emerging as a new tool in all developed world to divert large portion of community wastes (over 70%) from landfills and also reduce the GHG emissions significantly as discussed above [27].

Earthworms have real potential to both increase the rate of aerobic decomposition and composting of organic matter, and also to stabilize the organic residues in them. Earthworm participation enhances natural biodegradation and decomposition of organic waste from 60 to 80% over the conventional composting. Given the optimum conditions of temperature (20-30℃) and moisture (60-70%), about 5 kg of worms (numbering approx.10,000) can vermiprocess 1 ton of waste into vermi-compost in just 30 days [4].

4.1.1. Detoxified and Disinfected Nutritive End-Products (Vermicompost)

The earthworms ingest and bio-accumulate toxic materials, selectively devour on harmful microbes (pathogens) in the waste biomass. The end product is more homogenous, 'detoxified' and 'disinfected', richer in 'plant-available nutrients & humus' and significantly low contaminants.

4.1.2. Role of Earthworms in Safe Management of Environmentally Hazardous Wastes

Earthworms can degrade 'fly-ash' from the coal power plants which is considered as a 'hazardous waste' and poses serious disposal problem due to heavy metal contents. Earthworms ingest the heavy metals from the fly-ash while converting them into vermi-compost. It can even degrade 'human excreta' into odourless porous product with good texture and safe pathogen quality [15,34].

Worms can also vermicompost 'sewage sludge'—a great environmental hazard containing toxic chemicals and pathogens. In 12 weeks the black and brittle sludge became a homogenous and porous mass of brown vermicast with light texture. Foul odor disappeared by week 2. Upon chemical analysis, the vermicomposted sludge was over 80% free of heavy metals cadmium (Cd) and lead (Pb) and almost completely free of any pathogens [20].

4.2. Safe Management of Municipal and Industrial Wastewater without Formation of Sludge, their Purification, Detoxification & Disinfection for Reuse

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' and they have been found to remove the 5 days biological oxygen demand (BOD_5) by over 90%, chemical oxygen demand (COD) by 80-90%, total dissolved solids (TDS) by 90-92% and the total suspended solids (TSS) by 90-95% from wastewater by the general mechanism of 'ingestion' and biodegradation of organic wastes and also by their 'absorption' through body walls. Worms also remove chemicals including heavy metals and pathogens from treated wastewater. They have the capacity to bio-accumulate high concentrations of toxic chemicals in their tissues and kill any pathogen by discharge of anti-pathogenic 'coelomic fluid' and the resulting treated wastewater becomes almost free of chemicals and pathogens to be reused for non-potable purposes [13].

4.3. Cleaning Up of Chemically Contaminated Lands & Soils and Making them Productive: Converting the 'Wastelands into Wonderlands'

Large tract of arable land is 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 are free of toxic pesticides, mainly aldrin, chlordane, dieldrin, endrin, heptachlor, mirex and toxaphene. According to 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 cadmium (Cd), lead (Pb), mercury (Hg), zinc (Zn) etc. and chlorinated compounds like the PCBs and 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.

Earthworms have been found to bio-accumulate heavy

metals, pesticides and lipophilic organic micropollutants like the polycyclic aromatic hydrocarbons (PAH) from the soil. *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. [8,11,35,36].

Significantly, vermiremediation leads to total improvement in the quality of soil and land where the worms inhabit and make them highly productive. 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 percent 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 (nitrates, phosphates and potash), micronutrients and beneficial soil microbes including the 'nitrogen fixers' and 'mycorrhizal fungus'.

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. 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. A 'wasteland' is transformed into 'wonderland'. Earthworms are in fact regarded as 'biological indicator' of good fertile soil and land.

4.3.1. Mechanism of Worm Action in Remediation of Contaminated Soils

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. 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. Earthworms have also been found to biodegrade 'toxic organic contaminants' like phthalate, phenanthrene and fluoranthene in soil [7,37].

4.3.2. Role of Earthworms in Removing Chemical Contaminants from Soils

1) Removal of Heavy Metals

Earthworms can bio-accumulate high concentrations of heavy metals. They can particularly ingest and accumulate extremely high amounts of zinc (Zn), lead (Pb) and cadmium (Cd). Cadmium levels up to 100 mg per kg dry weight have been found in tissues. Earthworms species *Lumbricus terrestris* can bio-accumulate in their tissues 90-180 mg lead (Pb)/gm of dry weight, while *L. rubellus* and *D. rubida* it was 2600 mg /gm and 7600 mg /gm of dry weight respectively. Zinc (Zn), manganese (Mn), and iron (Fe) were shown to be excreted through the calciferous glands of earthworms [7,38].

2) Removal of Polycyclic Aromatic Hydrocarbons (PAH's)

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. Earthworm species *L. rubellus* degraded spiked PAHs phananthrene & fluoranthene (100 μg/kg of soil). Losses of both PAHs occurred at a faster rate in soils with earthworms, than the soil without worms. After 56 days 86% of the phenanthrene was removed. *E. fetida* was also found to degrade the PAHs. The concentration of anthracene decreased by 2-fold after addition of earthworms, benzo(a)pyrene decreased by 1.4-fold and phenanthrene was completely removed (100%) by earthworms [8,37].

We studied the remedial action of earthworms on PAHs contaminated soils obtained from a former gas works site in Brisbane, Australia 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. Worms removed nearly 80% of the PAHs as compared to just 47% where worms were not applied and only microbial degradation occurred. This was just in 12 weeks 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 few days and were more soft and porous in texture [39].

3) Removal of Petroleum and Crude Oil Hydrocarbons

Studies with earthworm species *Eisenia fetida* on oil contaminated soil revealed that worms significantly decreased oil contents in comparison to the control. It also successfully treated high molecular weight hydrocarbons 'asphaltens' from the Prestige Oil Spill. Earthworms mineralized the asphaltens thus eliminating it from the system. It also decontaminated complex hydrocarbons polluted soil [40-42].

4) Removal of Agrochemicals

There is no farmland in world which was not contaminated with agrochemicals in the wake of 'green revolution' of 1960s which unleashed heavy use of agrochemicals to boost farm production. 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 bio-accumulate or biodegrade 'organochlorine pesticide' and 'polycyclic aromatic hydrocarbons' (PAHs) residues in the medium in which it lives [7,43,44].

5) Removal of Polychlorinated Biphenyls (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 have serious adverse effects on the human health and the environment. PCB contaminated soil treated with earthworms resulted in significantly greater PCB losses (average 52%) when compared to the soil without earthworm [45].

4.3.3. Use of Earthworms in Soil Decontamination: Acquiring Global Agenda

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.

The greatest advantage of vermiremediation technology is that it is 'on-site' treatment and there is 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 per hectare of land as compared to $ 10,000-15,000 per hectare by mechanical excavation of contaminated soil & its landfill disposal.

Vermiremediation by commercial vermiculture in U.K. 'Land Reclamation and Improvements Programs' has become an established technology for long-term soil decontamination, improvement & maintenance, without earth-cutting, soil excavation and use of chemicals'. U.S., Australia and other developed nations are also following.

4.4. Restoration of Soil Fertility to Produce Safe, Chemical-Free Food for Society without Recourse to Environmentally Destructive Agrochemicals

Earthworms lead to total improvement in the physical (soil porosity & softness), chemical (good pH and essential plant nutrients) and biological (beneficial soil microbes & organisms) quality of the soil and land where they inhabit. They 'regenerate' even the compacted soil due to burrowing actions and make it productive. Such soils allow good aeration and water percolation [46]. They swallow large amount of soil with organics (microbes, plant & animal debris) and excrete them out as 'vermicasts' which are rich in NKP (nitrates, phosphates and potash), micronutrients and beneficial soil microbes. Even after single application of vermicompost the net overall efficiency of nitrogen (N) is considerably greater than that of chemical fertilizers.

4.4.1. Potential of Vermicompost to Replace the Environmentally Destructive Agro-Chemicals and Produce Chemical-Free Organic Foods

There have been several reports that earthworms and its vermicompost can induce excellent plant growth and promote good crop production without chemical fertilizers. Glasshouse studies made at CSIRO Australia found that the earthworms (*Aporrectodea trapezoids*) increased growth of wheat crops (*Triticum aestivum*) by 39%, grain yield by 35%, lifted protein value of the grain by 12% & also resisted crop diseases as compared to the control [47]. Studies on the agronomic impact of vermicompost on cherries found that it increased yield of 'cherries' for three (3) years after 'single application' inferring that the use of vermicompost in soil builds up fertility and restore its vitality for long time contrary to chemical fertilizers [48].

4.4.2. Earthworms Protects Plants against Pests and Diseases & Significantly Reduce Use of Environmentally Destructive Chemical Pesticides

Earthworms are both 'plant growth promoter and protec-

tor'. There has been considerable evidence in recent years regarding the ability of earthworms and its vermicompost to protect plants against various pests and diseases either by suppressing or repelling them or by inducing biological resistance in plants to fight them or by killing them through in-built pesticidal action [49-51]. Spray of chemical pesticides is significantly reduced by over 75% where earthworms and vermicompost are used in agriculture [29].

5. Role of Earthworms in Protection of Human Health

Traditional medicinemen in China and Philippines used earthworms in forkloric 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 [52]. The Chinese Materia Medica by Li Shizhen (1518-1593) listed 40 usage 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' [53].

5.1. Use of Earthworms in Development of Modern Medicine

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, Japan and other countries on the identification, isolation and synthesis of some 'bioactive compounds' from earthworms (*Lumbricus rubellus* & *Eisenia fetida*) with potential medicinal values have brought revolution in the vermiculture studies. Some of these compounds have been found to be enzymes exhibiting 'anti-blood clotting' effects [54].

5.2. Cure for Heart Diseases and Cancer

Lumbrokinase (LK) is a group of 6 'proteolytic enzymes' and recent researches suggest that it may be effective in treatment and prevention of 'ischemic heart disease' as well as 'myocardial infarction', 'thrombosis' of central vein of retina, 'embolism' of peripheral veins, and 'pulmonary embolism'. It is now being used in the treatment of 'cerebral infarction'. Japanese scientists also confirmed the curative effects of 'lumbrokinase' experimentally in the 1980s. [55]. Researches done at Ohio State University, USA, show that cancer cannot be induced in earthworms inferring that there are some bioactive compounds and 'genetic defense' mechanism that protects them. The group of enzymes lumbrokinase (LK) also promises to wage a 'war on cancer' [56].

5.3. Earthworms for Production of Antibiotics

The coelomic fluid of earthworms have been reported to have anti-pathogenic activities and are good biological compound for the production of 'antibiotics' [13].

5.4. Combating Stress & Increasing Human Longevity

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 to modify humans 'stress response system' in order to extend their life.

6. Role of Earthworms in Production of Materials for Consumer Industries

6.1. Raw Materials for Rubber, Lubricant, Detergent, Soaps and Cosmetics

Some biological compounds from earthworms are also finding industrial applications. Being 'biodegradable' they are environmentally friendly and sustainable. 'Stearic acid found in earthworms is a long chain saturated fatty acid and are widely used as 'lubricant' and as an 'additive' in industrial preparations. It is used in the manufacture of metallic stearates, pharmaceuticals soaps, cosmetics and 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 'softner' and in the manufacture of 'detergents' and 'insecticides'. Worms are also finding new uses as a source of 'collagen' for pharmaceutical industries [57,58].

6.2. Nutritive Feed Materials for Poultry, Dairy and Fishery Industries

Earthworms are rich in high quality protein (65%) and is 'complete protein' with all essential amino acids. There is 70-80% high quality 'lysine' and 'methionine'. Glumatic acid, leucine, lysine & arginine are higher than in fish 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 & B. There is 0.25 mg of Vitamin B_1 and 2.3 mg of Vitamin B_2 in each 100 gm of earthworms. Vitamin D accounts for 0.04-0.073% of earthworms wet weight. Thus worms are wonderful pro-

biotic feed for fish, cattle and poultry industry. They are being used as 'additives' to produce 'pellet feeds' in the USA, Canada and Japan [59,60].

As earthworm protein is complete with 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.

7. Conclusions & Remarks

Value of earthworms in sustainable development (converting waste into resource, improving soil fertility & boosting crop productivity by vermicompost and production of some valuable life saving medicines for mankind) and environmental protection (detoxification and disinfection of wastewater, decontamination of soils and land remediation and replacing the environmentally destructive agro-chemicals in food production) has grown considerably in recent years all over the world. It is like getting 'gold from garbage' (highly nutritive biofertilizer) by vermi-composting technology; 'silver from sewage' (disinfected & detoxified water for reuse in agriculture & industries) by vermi-filtration technology; 'converting a wasteland (chemically contaminated lands) into wonderland' (fertile land) by vermi-remediation technology; harvesting 'green gold' (food crops) by using 'black gold' (vermicompost) by agro-production technology; creating a 'worm factory' to produce medicines & materials for societal use. In India, the earthworms have enhanced the lives of poor and the unemployed. Educated unemployed have now taken to vermicomposting business on commercial scale. The three versatile species *E. fetida, E. euginae* and *P. excavatus* performing wide social, economic & environmental functions occur almost everywhere.

And if vermicompost can 'replace' the 'chemical fertilizers' for production of 'safe organic foods' which has now been proved worldwide, it will be a giant step towards achieving global 'social, economic & environmental sustainability'. Production of chemical fertilizers is 'environmentally damaging' (generating hazardous wastes & pollutants and greenhouse gases) in its entire life-cycle, since harnessing of raw materials from the earth crust, to their processing in factories and application in farms (polluting soil & killing beneficial organisms) with severe economic & environmental implications. Production and use of 1 kg of chemical nitrogen fertilizer emits 2,500 gm of CO_2, 10 gm N_2O & 1 gm CH_4. Molecule to molecule, N_2O and CH_4 are 310 & 22 times more powerful GHG than CO_2.

Earthworms are truly justifying the beliefs and fulfilling the dreams of Sir Charles Darwin who called earthworms as '*unheralded soldiers*' *of mankind*' and '*friends of farmers*'. Darwin wrote that '*no other creature on earth has done so much for mankind*' as the earthworms.

It is also justifying the beliefs of Dr. Anatoly Igonin one of the great contemporary vermiculture scientist from Russia who said '*Earthworms create soil & improve soil's fertility and provides critical biosphere's functions: disinfecting, neutralizing, protective and productive*'.

REFERENCES

[1] C. Lee, "Environment Protection, Biotechnology and Earthworms Used to Enrich Farmers for Organic Farming," Taihai Publishers, Beijing, 2003.

[2] C. A. Edwards and J. R. Lofty, "Biology of Earthworms," Chapman & Hall, London, 1972, p. 283.

[3] C. A. Edwards and P. J. Bohlen, "Biology and Ecology of Earthworms," 3rd Edition, Chapman and Hall, London, 1996.

[4] C. Visvanathan, J. Trankler, K. Jospeh and R. Nagendran, (Eds.) "Vermicomposting as an Eco-tool in Sustainable Solid Waste Management," Asian Institute of Technology, Anna University, India, 2005.

[5] P. Hand, "Earthworm Biotechnology," In: R. Greenshields, Ed., *Resources and Application of Biotechnology*: *The New Wave*, MacMillan Press Ltd., US, 1988.

[6] J. E. Satchell, "Earthworm Ecology—From Darwin to Vermiculture," Chapman and Hall Ltd., London, 1983, pp. 1-5.

[7] M. P. Ireland, "Heavy Metals Uptake in Earthworms," *Earthworm Ecology*, Chapman & Hall, London, 1983.

[8] S. M. Contreras-Ramos, S. Alvarez-Bernal and L. Dendooven, "*Eisenia fetida* Increased Removal of Polycyclic Aromatic Hydrocarbons (PAHs) from Soil," *Environmental Pollution*, Vol. 141, No. 3, 2006, pp. 396-401.

[9] S. Markman, A. I. Guschina, S. Barnsleya, L. K. Buchanan, D. Pascoe and C. T. Muller, "Endocrine Disrupting Chemicals Accumulate in Earthworms Exposed to Sewage Effluents," Cardiff School of Biosciences, Cardiff University, Cardiff, *Journal of Chemosphere*, Vol. 70, No. 1, 2007, pp. 119-125.

[10] OECD, "Guidelines for Testing Organic Chemicals; Proposal for New Guidelines: Earthworms Reproduction Tests (*E. fetida andrei*)," Organization for Economic Cooperation and Development, 2000.

[11] H. Safawat, S. Hanna and R. W. Weaver, "Earthworms Survival in Oil Contaminated Soil," *Journal of Plant and Soil*, Vol. 240, No. 1, 2002, pp. 127-132.

[12] D. R. Singleton, B. F. Hendrix, D. C. Coleman and W. B. Whitemann, "Identification of Uncultured Bacteria Tightly Associated with the Intestine of the Earthworms *Lumricus rubellus*," *Soil Biology and Biochemistry*, Vol. 35, 2003, pp. 1547-1555.

[13] V. Pierre, R. Phillip, L. Margnerite and C. Pierrette, "Anti-bacterial Activity of the Haemolytic System from the Earthworms *Eisinia foetida Andrei*," *Invertebrate*

Pathology, Vol. 40, No. 1, 1982, pp. 21-27.

[14] O. Bajsa, J. Nair, K. Mathew and G. E. Ho "Vermiculture as a Tool for Domestic Wastewater Management," *Water Science and Technology*, IWA Publishing, Vol. 48, No. 11-12, 2003, pp. 125-132.

[15] O. Bajsa, O. J. Nair, K. Mathew and G. E. Ho, "Pathogen Die-Off in Vermicomposting Process," Paper Presented at the International Conference on Small Water and Wastewater Treatment Systems, Perth, Australia, 2004.

[16] B. R. Eastman, "Achieving Pathogen Stabilization Using Vermicomposting," *Biocycle*, 1999, pp. 62-64. (Also on Worm World Inc. http://www.gnv.fdt.net/reference/index.html).

[17] B. R. Eastman, P. N. Kane, C. A. Edwards, L. Trytek, B. Gunadi and J. R. Mobley, "The Effectiveness of Vermiculture in Human Pathogen Reduction for USEPA Biosolids Stabilization," *Journal of Compost Science and Utilization*, Vol. 9, No. 1, 2001, pp. 38-41.

[18] M. Lotzof, "Vermiculture: An Australian Technology Success Story," *Waste Management Magazine*, February 2000.

[19] S. M. Contreras-Ramos, E. M. Escamilla-Silva and L. Dendooven, "Vermicomposting of Biosolids with Cow Manure and Wheat Straw," *Biological Fertility of Soils*, Vol. 41, No. 3, 2005, pp. 190-198.

[20] R. K. Sinha, S. Herat, G. Bharambe and A. Brahambhatt, "Vermistabilization of Sewage Sludge (Biosolids) by Earthworms: Converting a Potential Biohazard Destined for Landfill Disposal into a Pathogen Free, Nutritive & Safe Bio-fertilizer for Farms," *Journal of Waste Management & Research*, UK. http://www.sagepub.com

[21] X. F. Lou and J. Nair, "The Impact of Landfilling and Composting on Greenhouse Gas Emissions—A Review," *Journal of Bioresource Technology*, Vol. 100, No. 16, 2009, pp. 3792-3798.

[22] P. Toms, J. Leskiw and P. Hettiaratchi, "Greenhouse Gas Offsets: An Opportunity for Composting," Presentation at the 88th Annual Meeting and Exhibition, San Antonio, 8-12 June 1995, pp. 18-23.

[23] X. L. Wu, H. N. Kong, M. Mizuochi, Y. Inamori, X. Huang and Y. Qian, "Nitrous Oxide Emission from Microorganisms," *Japanese Journal of Treatment Biology*, Vol. 31, No. 3, 1995, pp. 151-160.

[24] Y. S. Wang, W. S. Odle, W. E. Eleazer and M. A. Baralaz, "Methane Potential of Food Waste and Anaerobic Toxicity of Leachate Produced during Food Waste Decomposition," *Journal of Waste Management and Research*, Vol. 15, No. 2, 1997, pp. 149-167.

[25] H. Yaowu, Y. Inamori, M. Mizuochi, H. Kong, N. Iwami and T. Sun, "Measurements of N_2O and CH_4 from Aerated Composting of Food Waste," *Journal of the Science of The Total Environment*, Elsevier, Vol. 254, No. 1, 2000, pp. 65-74.

[26] M. J. Mitchell, S. G. Horner and B. L. Abrams, "Decomposition of Sewerage Sludge in Drying Beds and the Potential Role of the Earthworm *Eisenia fetida*," *Journal of Environmental Quality*, Vol. 9, No. 3, 1980, pp. 373-378.

[27] R. K. Sinha and A. Chan, "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, 2009, Paper Communicatd to Journal of Waste Management & Research, U.K. http://www.sagepub.com

[28] R. K. Sinha, S. Herat, G. Bharambe, S. Patil, P. D. Bapat, K. Chauhan and D. Valani, "Vermiculture Biotechnology: The Emerging Cost-Effective and Sustainable Technology of the 21st Century for Multiple Uses from Waste & Land Management to Safe & Sustained Food Production," *Environmental Research Journal*, NOVA Science Publishers, NY, Vol. 3, No. 1, 2009, pp. 41-110.

[29] R. K. Sinha, S. Herat, D. Valani and K. Chauhan, "Vermiculture and Sustainable Agriculture," *American-Eurasian Journal of Agricultural and Environmental Sciences*, IDOSI Publication (Special Issue), Vol. 5(S), 2009, pp. 01-55.

[30] A. Ansari, "Effect of Vermicompost on the Productivity of Potato (*Solanum tuberosum)* Spinach (*Spinacia oleracea*) and Turnip (*Brassica campestris*)," *World Journal of Agricultural Sciences*, Vol. 4, No. 3, 2008, pp. 333-336.

[31] D. J. Lisk, "Environmental Effects of Landfills," *The Science of the Total Environment*, Vol. 100, 1991, pp. 415- 468.

[32] ABS, "Waste Management Services Australia-2002-03," Cat No. 8698.0, Australian Bureau of Statistics, Canberra, 2004.

[33] AGO, "National Greenhouse Gas Inventory 2005," Australian Greenhouse Office, 2007.

[34] M. Saxena, A. Chauhan and P. Asokan, "Flyash Vemicompost from Non-friendly Organic Wastes," *Pollution Research*, Vol. 17, No. 1, 1998, pp. 5-11.

[35] C. Coker, "Environmental Remediation by Composting," *Biocycle*, Vol. 47, No. 12, 2006, pp. 18-23.

[36] T. Lukkari, S. Teno, A. Vaisanen and J. Haimi, "Effect of Earthworms on Decomposition and Metal Availability in Contaminated Soil: Microcosm Studies of Populations with Different Exposure Histories," *Soil Biology & Biochemistry*, Vol. 38, No. 2, 2006, pp. 359-370.

[37] W. C. Ma, J. Imerzeel and J. Bodt, "Earthworm and Food Interactions on Bioaccumulation and Disappearance of PAHs: Studies on Phenanthrene and Flouranthene," *Journal of Ecotoxicology and Environmental Safety*, Vol. 32, No. 3, 1995, pp. 226-232.

[38] R. Hartenstein, E. F. Neuhauser and J. Collier, "Accumulation of Heavy Metals in the Earthworm *E. foetida*," *Journal of Environmental Quality*, Vol. 9, No. 1, 1980, pp. 23-26.

[39] R. K. Sinha, G. Bharambe and D. Ryan, "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*, Springer, Vol. 28, No. 4, 14 May 2008, pp. 466-475.

[40] Y. Tomoko, K. Toyota and S. Hiroaki, "Enhanced Bioremediation of Oil-Contaminated Soil by a Combination of the Earthworm (*Eisenia fetida*) and Tea Extraction Residue," *Edaphologia*, Vol. 77, 2005, pp. 1-9.

[41] J. Martin-Gil, L. M. Navas-Gracia, E. Gomez-Sobrino, A. Correa-Guimaraes, S. Hernandez-Navarro and M. Sanchez-Bascones, "Composting and Vermicomposting Experiences in the Treatments and Bioconversion of Asphaltens from the Prestige Oil Spill," *Bioresource Technology*, Vol. 99, No. 6, 2007, pp. 1821-1829.

[42] B. Ceccanti, G. Masciandaro, C. Garcia, C. Macci and S. Doni, "Soil Bioremediation: Combination of Earthworms and Compost for the Ecological Remediation of a Hydrocarbon Polluted Soil," *Journal of Water & Air Soil Pollution*, Vol. 177, No. 1-4, 2006, pp. 383-397.

[43] B. Davis, "Laboratory Studies on the Uptake of Dieldrin and DDT by Earthworms," *Soil Biology and Biochemistry*, Vol. 3, No. 3, 1971, pp. 221-223.

[44] J. Haimi, J. Salminen, V. Huhta, J. Knuutinen and H. Palm, "Bioaccumulation of Organochlorine Compounds in Earthworms," *Journal of Soil Biology & Biochemistry*, Vol. 24, No. 12, 1992, pp. 1699-1703.

[45] A. C. Singer, W. Jury, E. Leupromchai, C.-S. Yahng and D. E. Crowley, "Contribution of Earthworms to PCB Bioremediation," *Journal of Soil Biology & Biochemistry*, Vol. 33, No. 6, 2001, pp. 765-775.

[46] C. Yvan, S. Cadoux, B. Pierre, J. Roger-Estrade, G. Richard and H. Boizard, "Experimental Evidence for the Role of Earthworms in Compacted Soil Regeneration Based on Field Observations and Results from a Semi-field Experiment," *Soil Biology & Biochemistry*, Vol. 41, No. 4, 2009, pp. 711-717.

[47] G. H. Baker, P. M. Williams, P. J. Carter and N. R. Long, "Influence of Lumbricid Earthworms on Yield and Quality of Wheat and Clover in Glasshouse Trials," *Journal of Soil Biology and Biochemistry*, Vol. 29, No. 3-4, 1997, pp. 599-602.

[48] K. A. Webster, "Vermicompost Increases Yield of Cherries for Three Years after a Single Application," EcoResearch, South Australia, 2005. http:www.ecoresearch.com.au

[49] N. Q. Arancon, C. A. Edwards and S. Lee, "Management of Plant Parasitic Nematode Population by Use of Vermicomposts," *Proceedings of Brighton Crop Protection Conference-Pests and Diseases*, Vol. 8B-2, 2002, pp. 705-716.

[50] C. A. Edwards and N. Arancon, "Vermicompost Supress Plant Pests and Disease Attacks," In: REDNOVA NEWS, 2004. http://www.rednova.com/display/?id = 55938

[51] C. A. Edwards, N. Q. Arancon, E. Emerson and R. Pulliam, "Suppressing Plant Parasitic Nematodes and Arthropod Pests with Vermicompost Teas," *BioCycle*, Vol. 48, No. 12, 2007, pp. 38-39.

[52] C. Wengling and S. Jhenjun, "Pharmaceutical Value and Uses of Earthworms: Vermillenium Abstracts," Flowerfield Enterprizes, Kalamazoo, 2000.

[53] L. Kangmin and L. Peizhen, "Earthworms Helping Economy, Improving Ecology and Protecting Health," *International Journal of Environmental Engineering*, In: R. K. Sinha, *et al.*, Eds., *Special Issue on 'Vermiculture Technology for Environmental Management & Resource Development'*, Accepted for Publication, 2010.

[54] H. Mihara, M. Maruyama and M. Sumi, "Novel Thrombolytic Therapy Discovered in Oriental Medicine Using the earthworms," *Southeast Asian Journal of Tropical Medicine & Health*, Vol. 23, Suppl 2,1992, pp. 131-140.

[55] C. Qingsui, "A New Medicine for Heart Diseases Containing Enzyme Activator Extracted from Earthworms," In: Lopez & Alis, *The Utilization of Earthworms for Health Remedies*, 2003.

[56] R. Moss, "Of Enzymes, Worms and Cancer: The War on Cancer (Lumbrokinsae Enzyme from Earthworms)," *Worm Digest*, 2004.

[57] F. G. de Boer and O. Sova, "Vermicomposting as a Resource for Biodegradable Detergents," 4*th ZERI World Congress*, Windhoek, Namibia, 1998.

[58] L. Kangmin, "Earthworm Case," 4*th ZERI World Congress*, Windhoek, Namibia, 1998. (Also in Vermiculture Industry in Circular Economy, *Worm Digest*, 2005.) http://www.wormdigest.org/content/view/135/2/

[59] R. D. Guerrero, "Handbook of Vermicompost and Vermimeal Production and Utilization," *Aquatic Biosystems*, Laguna, Philippines, 2004.

[60] R. A. Dynes, "Earthworms; Technology Info to Enable the Development of Earthworm Production," Rural Industries Research and Development Corporation, Government of Australia, Canberra, 2003.

