Chapter 10
Fly Ash Management Through Vermiremediation

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Abstract Fly ash (FA) is an inevitable byproduct from the coal-fired thermal power plants that need timely, effective and safe disposal in many developing countries. It is an amorphous ferro-alumino silicate material similar to soil having practically all the elements except organic carbon, nitrogen and phosphorous. Although in many developed countries its use has reached saturation but technologically-starved poor countries are still lagging far behind in its resourceful use. Its use in cement-concrete, and land and mine filling have been widely accepted but in agriculture, this chemically heterogeneous material deserves cautious consideration. At low concentration, FA alters soil physicochemical properties and thus, acts as soil ameliorant or conditioner. However, its use at higher rate is restricted due to presence of heavy metals that affect soil biosphere and limits plant growth. Hence, remediation of toxic metal ions for sustainable agricultural intervention is a prerequisite in FA-contaminated soils or dumpsites. Like phytoremediation, earthworms with unique accumulation, extraction, transformation, conversion, degradation and stimulation properties could also be engaged in remediation of FA. In this chapter, attempts have been made to elucidate various mechanisms and processes involved in vermiremediation, and the advantages, disadvantages and future prospects of this innovative technology.

Keywords Amendment · Bioaccumulation · Earthworm · Fly ash · Heavy metal · Vermiremediation

10.1 Introduction

With the burgeoning global population, the demands for food have increased tremendously over last few decades beyond the yielding ability of many crops. Increase in

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the current global food production for feeding the teaming millions is the greatest challenge before us (Dwibedi 2018). The pressure on land for higher productivity per unit area and time is increasing day by day, resulting in more dependence on chemical fertilizers, synthetic pesticides, hormones and probiotics at the cost of environmental health and sustainability. The land is degrading and becoming less productive which needs bio-physical amelioration for bringing back to its pristine conditions. Furthermore, the greed for energy, under the veil of pseudo civilization, prosperity and economic development, has been driving us towards peril (Dwibedi and Sahoo 2017).

Although the global primary energy consumption in 2018 recorded sharp decline in coal share (27%), it still ranks next to petroleum oil (34%) (International Energy Agency 2020). However, other alternative energy sources such as nuclear and hydrothermal power require sophisticated technologies and huge initial investments that are beyond the reach of many developing countries. Therefore, production of ash (bottom and fly ash), is an inevitable byproduct from the coal-fired thermal power plants that need safe, timely and effective disposal. Combustion of pulverized sub-bituminous coal (lignite) in thermal power plants results in generation of this end-residue (Basu et al. 2009). Fly ash (FA) is an amorphous ferro-alumino silicate material similar to soil with all the elements except organic carbon, P and N (Tripathy and Sahu 1997; Pandey and Singh 2010; Pandey 2020a, b, c, d). It has been categorized 'under high volume low effect waste under Hazardous Waste (Management and Handling and Trans-boundary Movement) Rules, 2008' (Parab et al. 2012). Its production along with power generation in thermal power plants over decades of economic developments, both by developed and developing countries has been a necessary evil. This problematic 'solid waste' across the globe has now acquired the status of 'resource material' due to innovative uses in cement-concrete, land and mine filling, agriculture, etc. Its utilization in European countries is almost 100% while in developing countries like India lower percentage is being utilized in spite of its higher production (Dwibedi and Sahoo 2017).

10.2 Properties of FA

The physical, chemical and mineralogical properties of FA (Fisher et al. 1978; Page et al. 1979; Adriano et al. 1980; Carlson and Adriano 1993; Pandey 2020a) depend on the quality of coal, extent of thermal combustion and storage-handling methods. Therefore, ash compositions vary with burning of anthracite, bituminous and lignite coals. Elements present in coal are intense in FA. Physically, FA is very fine with mean diameter of <10 μm, light in texture. It has low to moderate bulk density (BD) and more surface area. Its water holding capacity is of 49–66% on the weight basis (Sharma and Kalra 2006). Its pH ranges from 4.5 to 12 largely depending on the S content in the coal. FA is chemically heterogeneous in nature as it contains variable proportions of different trace and heavy metals such as Be, B, Cd, Cr, Co, Hg, Mo, Mn, Pb and oxides Al, Ca, Fe and Si.

Incorporation of FA alters physicochemical properties of soil and works as soil conditioner or modifier (Kalra et al. 1998; Pandey and Singh 2010; Pandey 2020b). It alters the texture of soil (Kalra et al. 2000), reduces BD and increases porosity, water holding capacity and aeration due to its silty nature. Kuchawar et al. (1997) and Bhaisare et al. (1999) have shown an increase in cation-exchange capacity (CEC) as a result of FA amendment in soil. It also improves soil bacteria count and enzyme activity viz. dehydrogenase, urease and alkaline phosphatase that promote plant growth (Yeledhalli et al. 2007). Comparative physicochemical properties of soil and FA, and also FA in combination with press mud (PM) have been depicted under Table 10.1 (Singh and Pandey 2013).

According to the Intergovernmental Panel on Climate Change (IPCC), lime application for soil amelioration releases carbon dioxide (CO_2) gas which ultimately adds to global warming. In United States of America, the Environment Protection Authorities (EPA) has estimated emission of 9 Tg (teragram = 1.012 g = 106 t) of CO_2 from an approximate 20 Tg of agricultural lime applied in 2001. FA could be the befitting substitute for it minimizing global warming process (West and McBride 2005). It has also been estimated that 1 tonne of FA has the ability to sequester up to 26 kg of CO_2 (i.e. 38.46 tonnes of FA per tonne of CO_2 sequestered).

10.3 Verms as Bioreactor

Earthworms, regarded as the intestine of earth (Aristotle), are the terrestrial invertebrates, belonging to the phylum Annelida, and class Oligochaeta and they have more than 3000 species across the globe (Berridge 2020). They act as bioreactors in recycling the organic wastes to reusable plant nutrients at a very low or marginal cost of production and because of that, they act as 'farmers' friends'. Wastes from the agricultural field after harvest, and urban and rural solid organic wastes can very well be used in vermicomposting. Vermicomposting of agricultural residues and its effects on plant growth, microbial population and nutrient transformation at different concentrations in soil rhizosphere have been studied with much attention and interest.

10.4 Research Status on FA Use and Vermiremediation

The research on FA use began in late 1970s to evaluate its suitability for improving soil environment and increasing crop productivity (Dwibedi and Sahoo 2017). In developed countries, its utilization is more than 70% but in developing countries; it is still less than 5%. FA may be applied as soil amendment along with organic substrates such as farmyard manure, compost and microbial culture. A lot of research on use of FA in agricultural crops such as rice, maize, grams, beans, vegetables, etc. in pot culture and field trials has already been conducted. Its far-reaching consequences on soil bio-physicochemical properties have also been evaluated in long-term experiments.

Table 10.1 Comparative ash/soil properties with different levels of FA treatment

Characteristics	FA	Soil
(A) *Physicochemical properties of Indian fly ash and soil* (*source* Kumar et al. 2000; Goyal et al. 2002)		
Bulk density (g cc^{-1})	<1.0	1.33
Water holding capacity (%)	35–40	<20
Porosity (%)	50–60	<25
K (%)	0.19–3.0	0.04–3.0
P (%)	0.004–0.8	0.005–0.2
S (%)	0.1–1.5	0.01–0.2
Metals (mg kg^{-1})		
Zn	14–1000	2–100
Mn	100–3000	100–4000
Fe	36–1333	10–300
Cu	1–26	0.7–40
B	46–618	0.1–40

(B) *Soil properties and metal composition as influenced by combined application of FA and press mud (PM)* (*source* Singh and Pandey 2013)

Treatments parameters	Control	PM + FA (10 t ha^{-1})	PM + FA (50 t ha^{-1})	PM + FA (100 t ha^{-1})	*P* value
Soil properties					
pH	6.9 ± 1.3	7.1 ± 1.6	8 ± 1.8	8.3 ± 1.5	<0.01
EC (ds m^{-1})	2.4 ± 0.7	3.5 ± 0.2	6.3 ± 0.6	6.9 ± 0.8	<0.01
Soil moisture (%)	17.2 ± 1.2	25.7 ± 2.2	28.4 ± 2.3	28.5 ± 2.1	<0.01
Inorganic-N (NH_4-N and NO_3-N)	32 ± 1.2	22.2 ± 1.3	26.2 ± 1.3	26.6 ± 1.3	<0.01
Metal (μg^{-1})					
Cr	3.68 ± 0.33	4.37 ± 0.23	5.64 ± 0.48	7.6 ± 0.63	<0.01
Cd	1.8 ± 0.06	2.43 ± 0.19	3.6 ± 0.63	4.12 ± 0.45	<0.01
Cu	4.34 ± 0.58	5.23 ± 0.33	6.23 ± 0.48	7.89 ± 0.23	<0.01
Ni	5.52 ± 0.46	7.2 ± 0.33	9.06 ± 0.35	12.21 ± 0.42	<0.01
Methanotrophs number (× 104 g^{-1} of soil)	23.4 ± 6.1	53 ± 11.5	29.4 ± 6.1	25.2 ± 6.1	<0.05

Modified from Source Bhattacharya and Kim (2016)

The role of FA in reclamation of acidic and sodic soils has been well acclaimed. Its utilization in agriculture has been a proven support as it improves physicochemical properties of soil resulting in better fertility and increased crop yield (Rautaray et al. 2003). However, heavy metal accumulation with FA amendment is a great concern. Researchers are in view of its application in lower concentrations as soil microbial population and availability of plant nutrients are affected at higher concentrations.

Earthworms are the ecological engineers having profound role in amelioration of soil physical, chemical and biological properties (Shi et al. 2017). The significant role played by earthworms in soil fertility enhancement, biodiversity restoration and detoxification of contaminated soil was studied since early 1800s (Edwards 2004) while much stress on soil remediation was given during 1980s (Sinha et al. 2010). In the recent past, 'vermiremediation', a new approach has been invoked (Gupta and Garg 2009). Attempts have also been made to study the composting behaviour of earthworms at varying levels of FA substrates to prepare vermi-ash.

10.4.1 FA Impact on Soil Characteristics

FA has tremendous potential as a valuable resource in agriculture, building, road and bridge construction and other related areas. Its soil amending and nutrient-enriching properties contribute to agricultural production (Pandey 2020c). It contains considerable quantities of both macro and micronutrients (Singh et al. 1997) which when applied to soil sustain crop growth and development, even in poor soils. As mentioned above, FA is deficient in N, P and organic matter and hence, its amendments with organic materials or microbial inoculants help in plant growth. Its possible agricultural applications such as liming material, fertilizer and physical amendment have been illustrated by many researchers. For effective and efficient vermiremediation of FA, it is imperative to understand the effects of FA on soil properties and agricultural crops as remediated land may simultaneously or subsequently be brought under cultivation. A brief review of the earlier studies on FA use in agriculture is hereunder for general reference.

FA is helpful in increasing the physical properties of soil that ultimately improve soil fertility and enhance crop yield (Rautaray et al. 2003). FA amendment in sunflower fields decreases BD of the soil (Pani et al. 2015). Wong and Wong (1990) noticed alteration in soil texture, bulk density and porosity. FA addition in sandy soil alters soil texture and increases micro-porosity (Ghodrati et al. 1995). Increase in porosity and decrease in bulk density in soil was also reported by Zibilski et al. (1995). Water holding capacity of soil increases with FA amendment in sunflower fields (Pani et al. 2015; Parab et al. 2012). FA amendment in clay soil improves infiltration whereas in the coarse soil it reduces infiltration as reported by Dhindsa et al. (2016).

The pH of soil (pH 6.65) increases with the addition of FA (pH 7.56) due to acid-neutralizing capacity of the latter one in presence of oxides of Ca and Mg in it. The soil becomes more alkaline with FA amendment in sunflower fields (Pani et al. 2015). Such increase in pH was also reported by Lee et al. (2006) and Sarkar et al. (2012). However, Sikka and Kansal (1995) reported no significant increase in pH with FA amendment. Electrical conductivity (EC) of the soil (281 dS cm^{-1}) increases with the addition of FA (600 dS cm^{-1}) in radish field, possibly due to precipitation of soluble cations (Singh et al. 2011a, b) and binding of metal ions to soil separates that facilitates ready availability of plant nutrients (Pani et al. 2015) in FA amended soils. However, elevated EC may suppress normal plant growth (Singh et al. 2011a, b). Organic carbon (OC) decreases with increase in FA concentration in radish (Sarkar et al. 2012) whereas in brinjal, the value of OC increases with FA (Singh et al. 2011a, b). FA improves nutrient levels in soil (Rautaray et al. 2003). Singh et al. (2011a, b) have observed increase in availability of N, P, K, Co, Ni, Cu, Zn, Mo, Al, V, Se, etc. as well as toxic metals such as Cr, Pb and As with addition of FA at different grades. Sarkar et al. (2012) have reported increase in availability of Na, K, Ca, Mg and Fe with significant reduction in total N, available P and OC under FA soil amendment. FA is also used to rectify B and S deficiencies in soil (Chang et al. 1977). P availability increases with the addition of FA (Lee et al. 2006). Reddy et al. (2010) have reported 'the highest available N (224.6 kg ha^{-1}), P (24.6 kg ha^{-1}), K (366.7 kg ha^{-1}), S (8.80 mg kg^{-1}), Fe (10.62 mg kg^{-1}) and Zn (0.95 mg kg^{-1}) content after harvest of rice crop with application of FA at 15 t ha^{-1} + FYM at 10 t ha^{-1} (FA_{15} + FYM_{10}), which were at par with FA_{10} + FYM_{10}'. However, Sikka and Kansal (1995) reported no significant increase in available N and P in soil with the addition of FA whereas the available K increased.

The nematode population as observed in Chandrapura Thermal Power Station, reduced significantly (Singh et al. 2011a, b) with 40% FA amendment (Ahmad and Alam 1997; Khan et al. 1997) due to inhibitory effect (Khan et al. 1997; Tarannum et al. 2001) of FA. The carbon dioxide efflux from the soil as an indirect method of knowing soil biotic activities increased with 0–100 t ha^{-1} addition of FA than 400–700 t ha^{-1} amendments. Several metals present at potentially toxic levels in FA might have suppressed soil heterotrophic microbial activities at higher levels (Arthur et al. 1984).

10.4.2 FA in Agriculture

Direct use of FA in crop fields is not so promising due to poor bioavailability of plant nutrients such as C, N and P that inhibit mineralization through reduced microbial activities (Lazcano 2009/66). When applied to soil directly, it severely inhibits microbial process, N cycle and enzyme activity (Lazcano 2009). Pandey et al. (2009a) observed accumulation of Fe, Zn, Cu, Cd and Cr in *Cajanas cajan* when the soil was mixed with FA. FA amendment affects rice germination count in initial stage but after 115 h, it picks up again equalizing with the untreated soil. Such delay in germination could be due to increase in soil impedance/ strength (Kalra et al. 1997). However, no such inhibitory effect is noticed in green gram, golden gram and black gram at 0, 10, 20, 30, 40 and 50% FA amendment, except at 100%; possibly due to balance between growth promoters and inhibitors (Singh et al. 2011a, b). The highest rice seed germination is at 20 and 30% FA amendment (Adriano and Weber 2001) while the lowest is at 100% (Panda and Tikadar 2014). Germination of rice and maize in wet season is less sensitive to moderate FA than dry season (Kalra et al. 1998) whereas germination decreases with further increase in ash concentration (Panda and Tikadar 2014).

Shoot and root length of green gram, golden gram and black gram increase with application of FA and the maximum length occurs at 30–40% while in radish, FA shortens plant height (Singh et al. 2011a, b). Shoot length of *Luffa cylindrica* increases up to 180 t ha^{-1} FA but at higher dose, the plant shortens (Singh et al. 2011a, b). At 25% FA, taller rice plants with longer roots are observed compared to no or higher levels (Panda and Tikadar 2014). Tiller count in rice goes on increasing with the addition of FA up to 75 t ha^{-1} (Priatmadi et al. 2015) but on further addition, it declines (Sarkar et al. 2012). Chlorophyll a and b and carotenoid pigment concentration in chickpea, golden gram and black gram improves significantly at moderate levels of FA (120–180 t ha^{-1}) but at 240 t ha^{-1}, the pigmentation decreases (Singh et al. 2011a, b). Dry matter accumulation in rice seedlings reduces with increase in concentration of FA from 25 to 100% in rice nursery (Panda and Tikadar 2014). FA and FYM amendments enhance the rates of N transformation processes, plant available-N and paddy productivity (Singh and Pandey 2011) and can be used to enrich nutrient-poor soils for crop productivity and yields. The mixture of FA and press mud shows positive effect on crop growth, physicochemical, microbial and enzymatic activities of sodic soil (Singh et al. 2016a). The mixture of 40% soil + 20% FA + 40% vermicompost is proved as most promising blend for wet rice nursery raising and for remediating the coal FA in agricultural production system (Dwibedi et al. 2021). Recently, it is proved that phytoremediated FA can be used as a fertilizer up to 100% for peas farming as metal concentrations was reported either below detection limit or below the WHO permissible limit (Bhattacharya et al. 2021). The application of FA for agriculture production is explored in great depth using the facts of plants, amendments, FA doses range and remark (Pandey et al. 2009b).

10.5 What is Vermiremediation?

The term 'vermiremediation' has come from two Latin words: 'vermis' means 'worm' and 'remedium' means 'correct' or 'remove an evil' (Shi et al. 2020). The term was coined by Edward and Arancon (2006) while Rodriguez-Campos et al. (2014) first attempted to define it as 'the use of earthworms for removing contaminants (Sinha et al. 2008) or not recyclable compounds (Gupta and Garg 2009) from the soil'. However, a better definition by Shi et al. (2020) has come up later which expresses 'vermiremediation as an earthworm-based bioremediation technology that makes use of the earthworm's life cycle (i.e. feeding, burrowing, metabolism and secretion) or their interaction with other abiotic and biotic factors to accumulate and extract, transform, or degrade contaminants in the soil environment'. As per this definition, few synonymous terms viz. vermiaccumulation and vermiextraction, vermitransformation, vermiconversion and drilodegradation or drilostimulation could be used to understand the mechanisms and processes of vermiremediation (Shi et al. 2020).

Vermiaccumulation and vermiextraction, similar to term phytoaccumulation, refer to the process of ingestion of contaminants (organic and inorganic) from the soil by earthworms and accumulation of pollutants in their body parts (Shi et al. 2020). Accumulation of contaminants occurs through preferential dermal or intestinal sequestration involving sub-organismic (preclitellum, clitellum, post-clitellum), tissue (body wall, gut, body fluids) and sub-cellular (intra and extracellular fractions) body parts of the earthworm (Shi et al. 2020). The process of biotransformation of contaminants by earthworms into harmless products by enzymes (such as peroxidases) and microbes (bacteria and fungi) in the alimentary canal and ultimately egested out as compost is known as vermitransformation or vermiconversion (Panda and Tikadar 2014). Drilodegradation or drilostimulation refers to the microbial decomposition, degradation or elimination of toxic materials by microbes present in the drilosphere, the 2 mm thick zone of earthworm burrow wall (Bouché 1975; Brown et al. 2000). Drilospheric soil is rich in earthworm mucus and casts that stimulate microbial growth which subsequently promotes the growth of protozoa and nematodes (Stromberger et al. 2012). Drilosphere, a habitat rich in energy and nutrients, mostly C and N, acts as hotspot for soil microbial communities (Kuzyakov and Blagodatskaya 2015). The nutrients are mixtures of low-molecular organic acids such as amino acids, nucleic acid derivatives, carbohydrates, phenolics and enzymes (Zhang et al. 2009). The labile organic carbon supply in drilosphere can sustain microbial communities that supplement utilizable sources of energy (Tiunov and Scheu 1999). And hence, drilospheric microorganisms have tremendous ability to remediate the potential pollutants (Shi et al. 2020).

10.5.1 Advantages of Vermiremediation

Vermiremediation is an emerging concept that needs rigorous investigation and exploration for gaining ecological milestones over conventional physicochemical methods. Primarily, it is one of the cheapest, easiest, efficient and in some cases, the fastest way of remediating the contaminated land without disturbing the topsoil. Furthermore, it is not substrate-specific, rather a useful technology for treating a wider range of hazardous pollutants. Synthetic insecticides, herbicides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), crude oil and FA in soil can be removed by engaging earthworms (Rodriguez-Campos et al. 2014). It is environmentally sustainable self-regenerating *in-situ* approach to remediate polluted land. Furthermore, vermiremediation enhances soil quality through addition of organic matter, supplementation of plant nutrients and proliferation of biodiversity (Sinha et al. 2008).

10.5.2 Limitations of Vermiremediation

Vermiremediation technology has its own limitations as it can only be applicable in moderately or slightly contaminated soils that allow survival of the earthworms. In severely contaminated soil, earthworms may not survive due to toxic effects of the pollutants (Rodriguez-Campos et al. 2014; Shi et al. 2019). Vermiremediation is also restricted to the earthworm habitats depending on the species used and ambient environmental conditions-beyond which its efficacy is limited. Earthworms are categorized into epigeic, anecic and endogeic groups (Fig. 10.1) depending on the species used, body size, mobility, fecundity, habitat, feeding and burrowing behaviour, casting activity, etc. (Lazcano et al. 2009) of the earthworm. *Dendrobaena octaedra*, *Dendrobaena attemsi*, *Dendrodrilus rubidus*, *Eiseniella tetraedra*, *Heliodrilus oculatus*, *Lumbricus rubellus*, *Lumbricus castaneus*, *Lumbricus festivus*, *Lumbricus friendi*, *Lumbricus rubellus, Satchellius mammalis, Eisenia fetida and Eudrilus euginae* live on the upper layer of the soil profile and feed mainly on organic debris and thus are classified as detritivores under epigeic group. Endogeic (means within the earth) earthworms such as *Allolobophora chlorotica*, *Apporectodea caliginosa*, *Apporectodea icterica*, *Apporectodea rosea*, *Drawida grandis, Murchieona muldali*, *Octolasion cyaneum, Octolasion lacteum, Anecies longa, Anecies nocturna and Octochaectona thurstoni* remain deep inside the soil and are geophagus in nature. Whereas anecics or anegeic (out of the earth) earthworms, e.g. *Aporrectodea longa*, *Aporrectodea nocturna, Lumbricus friend, Lumbricus terrestris and Letmpito mauritii*

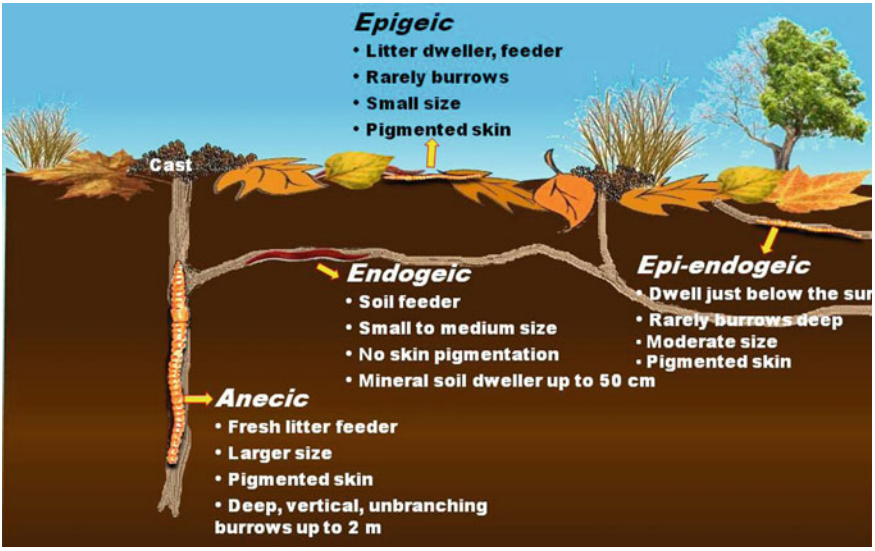

Fig. 10.1 Three major ecological groups of earthworms identified basing on feeding and burrowing behavior. *Source* Adapted and modified from Brown and Sherlock (2021)

are sub-surface dwellers and are phyto-geophagus in nature (Brown and Sherlock 2021; Bhattacharya and Kim 2016). Vermiremediation potential is dependent on food abundance and feeding preference of earthworm species (Curry and Schmidt 2007). Earthworms are sensitive to temperature, moisture and other climatic and seasonal conditions that may inhibit their survivability thereby affecting the vermiremediation process (Butt and Lowe 2011). Additionally, accumulated contaminants in earthworms can become a potential threat if get transferred into food chain under mismanagement in disposal schedule (Shi et al. 2014).

10.6 Biology of Earthworm and Its Functional Significance in Waste Degradation

Before getting into the process of vermiremediation in FA-contaminated soils, it is imperative to know the biology of earthworm and the mechanism of waste degradation with relation to soil health. They prefer moist and dark habitats with optimum moisture of 60–75% and their skin is permeable for which they need moist environment to prevent from drying out (Shi et al. 2020). Although they can survive temperature range of 5–35 °C, but the optimum is 20–25 °C. Most of them prefer neutral pH and C/N ratio of 2–8 (Sharma and Garg 2018). Within a life span of 220 days, they produce 300–400 offspring (Shi et al. 2020). They are bisexual and under ideal soil temperature, moisture, pH and food availability they can multiply 2^8 times in every six months (Shi et al. 2020). They mostly feed on detritus materials, living bacteria, fungi, protozoa, nematodes and many other microorganisms (Sharma and Garg 2018). Earthworms have digestive tubes housed inside their thick cylindrical muscular outer body tube (Berridge 2020). They swallow considerable amount of food materials along with soil through their mouth present at 1st segment and shred down by gizzard present at 8th or 8th to 9th segment. The elementary canal of earthworm includes mouth (1st), buccal cavity (2nd and 3rd), pharynx (3rd and 4th), esophagus (5th to 7th), gizzard (8th or 8th and 9th), stomach (9th or 10th to 14th), intestine (15th up to the last segment except anus) and anus (Aryal 2020). They also passively absorb dissolved chemicals through their body wall (Shi et al. 2020). These absorbed and eaten substrates are mixed with intestinal fluid and enzymes from microbes. Earthworm's intestine acts as warehouse for microbes and enzymes such as lipase, amylase, nitrate reductase, protease, phosphatase, cellobiase, etc. that bioprocess disintegration of ingested foodstuffs.

Earthworms maintain and improve soil quality parameters (Bhadauria and Saxena 2009) and act as bioindicators of soil quality (Fründ et al. 2011). Abundance and species composition of earthworms, their behaviour in contact with the soil, assimilation of chemicals in their body parts and biochemical or cytological stress markers can indicate soil quality (Fründ et al. 2011). Earthworms produce pores and aggregates (biostructures) in soil, thus influencing soil's physical properties, nutrient cycling and plant growth (Lal 1999; Scheu 2003). Anecic species make permanent burrows in mineral soils; they drag surface organic materials into the soil for food. Endogeic species are the ecosystem engineers who make nonpermanent burrows in the upper surface mineral layer through which other organisms get accessibility to underground resources (Jones et al. 1994). No till or minimal disturbance to the soil, as in conservation agriculture, enhances organic residues, thus creating ideal conditions for earthworm habitat (Labenz 2021). Mucus production associated with water excretion by earthworms enhances the activity of soil beneficial microorganisms that help in improving soil structure and aggregate stability. Earthworm's excreta (cast) are rich in plant-available nutrients, thus concentration of N, P, K, Ca, Mg and many more trace elements in soil increases and toxic materials including heavy metals get accumulated in their gut (Usmani and Kumar 2017) which make them biologically potent for remediation of FA (Fig. 10.2).

Metal accumulation mostly occurs in the chloragogenous tissue at the posterior end of the alimentary canal of earthworm (Usmani and Kumar 2017; Morgan and Morris 1982). On exposure to metals, earthworms synthesize metallothioneins (MT) that have low-molecular weight, cysteine-rich proteins with high affinity towards Cd, Cu and Zn (Dallinger 1994). These proteins protect organisms against toxic metal stress and thus can be used as indicator of soil pollution. While dealing the unnecessary heavy metals, earthworms detoxify their effects through interaction with many chemicals in the metabolic processes. Bioaccumulation of metals and organocomplex formation results in decline in the availability of heavy metals in soil as part of enzyme antioxidant systems such as superoxide dismutase (SOD) and MT (Li et al. 2008).

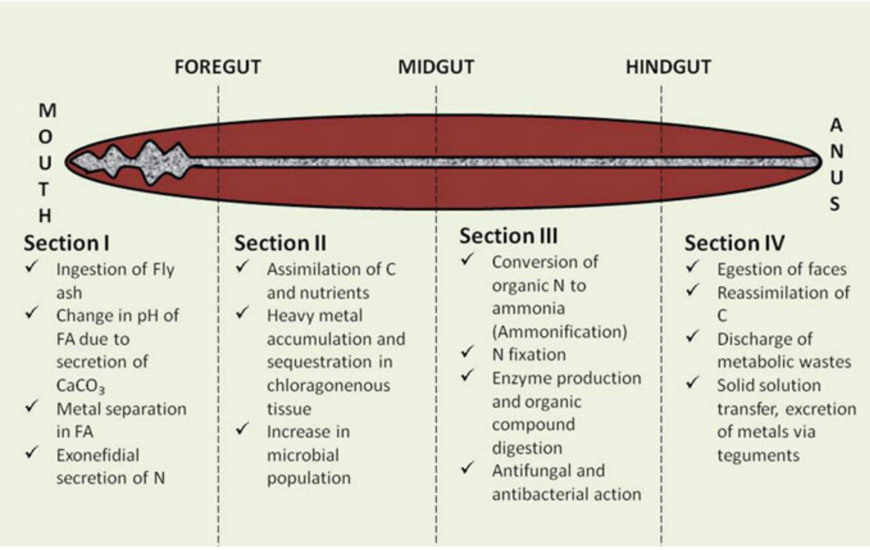

Fig. 10.2 Physicochemical transformations occurring in different compartments of earthworm illustrating heavy metal sequestration and nutrient assimilation on ingestion of FA [*source* Usmani and Kumar 2017 (Adapted and modified with the permission of the Publisher)]

As mentioned above, the highest metal accumulation occurs in the posterior alimentary canal (PAC) of the earthworm. Intracellular vesicles within PAC accumulate Pb and Zn and the superfluous metals interact with P ligands within the chloragosome matrix (Usmani and Kumar 2017; Morgan and Morgan 1990). The cation-exchange properties in chloragosomes (Fischer 1973, 1977) are considered as integral part for the physiological functioning of intracellular organelles (Morgan 1981; Fischer and Trombitts 1980). Microprobe X-ray analysis of air-dried chloragogenous tissue revealed Ca, Pb and Zn (in association with sulphur) accumulation in the chloragosomes while Cd was accumulated in an electron-lucent vesicular component called cadmosome (Usmani and Kumar 2017).

10.7 Process of Vermiremediation

Metal accumulation by earthworm (vermiremediation) may be in-situ or on-site treatment in the FA dumped sites (contaminated land), or it may be ex-situ through vermicomposting (Usmani and Kumar 2017). *Eisenia fetida* cannot tolerate 100% FA, thus addition of organic matter is essential (Niyazi and Chaurasia 2014). Considerable reduction in metal concentration occurs after vermiremedition. FA lacks N and C and thus organic matter addition is required to support microbial growth (Mupambw et al. 2015). Experiments on vermicomposting of cow dung with FA showed 30–50% reduction in heavy metal concentration up to 60% FA while 10–30% reduction was in 80% FA addition. Hence, 60% addition of FA with *E. fetida* was proposed to be a sustainable vermiremediation technique (Gupta et al. 2005). In another experiment, minimum mortality and maximum population growth were observed in 1:3 mixture of FA and cow dung. Significant reduction of heavy metals viz. Cu, Pb, Mn and Cr were also observed with vermiremediation at variable range of FA and cow dung mixtures. Vermistabilization resulted reduction in pH by 8–15.7%, EC by 16.2–53.6%, total organic carbon by 15.6–32.5% and C:N ratio by 43.2–97.4% (Singh et al. 2016b). A decline in heavy metal concentration in vermicompost was reported by Niyazi and Chaurasia (2014) like Anderson and Laursen (1982), Morgan and Morgan (1990) who observed variations in metal accumulation depending on inter-specific metal intake ability, worm age, their physiological utilization and transformation, season and many other factors (Usmani and Kumar 2017).

10.8 Strategies for Vermiremediation

Earthworm survival and mobility of contaminants are the two limiting factors in vermiremediation (Usmani and Kumar 2017). The performance of earthworms is affected by poor soil quality, environmental conditions and high concentration of pollutants (Sinha et al. 2008). Vermiremediation of FA-contaminated soils needs controlled mobility and bioavailability of toxicants and facilitated growth of earthworms under ameliorated soil environment. Nutrient and organic amendments and provisioning for better soil physical properties should be the prime management strategies for efficient and effective vermiremediation. The vermiremediation capacity of different earthworm species needs through assessment before their engagement in contaminated land reclamation. Suitability of crops to differential FA and organic residue amendments and bioaccumulation of toxic heavy metals across trophic levels need in-depth investigation for validation of the remediation technologies. Safe and timely evacuation of earthworms in vermiremediation is mostly lacking, which requires burning as specialized for hazardous waste (Sheoran et al. 2010; Ali et al. 2013). A brief account of different harvest methods of the earthworms used in vermiremediation is presented under Table 10.2. Vermiremediation can be facilitated through appropriate microbe-earthworm combined interactions as is evident in phosphorous solubilizing bacteria inoculated FA amendments (Lukashe

Table 10.2 Potential harvest methods of earthworms used in vermiremediation—based on the summary of earthworm sampling methods

Classifications		Expellant	Characteristics	References
Ethological methods	Chemical methods	Mustard or hot mustard	Non-destructive or 'environmental friendly'; more effective on anecic species; expensive	Chan and Munro (2001) Lawrence and Bowers (2002)
		Formalin	A standard method for the expulsion of earthworms; highly toxic to soil organism	Čoja et al. (2008)
		Detergent	Toxic	East and Knight (1998)
		Allyl isothiocyanate (AITC)	Environmental friendly; effective on deep-burrowing anecic species	Zaborski (2003)
		Onion solution	Environmental friendly	Steffen et al. (2013)
	Electrical method	Electroshocking	Little damage	Eisenhauer et al. (2008)
Hand-sorting	–	–	Physical disturbance of soil system; labour-intensive; time-consuming	Valckx et al. (2011)
Mechanical separation	–	–	Energy consuming	–

Source Shi et al. (2020)-reproduced with permission et al. 2018). Harmonious integration of phytoremediation, vermiremediation and effective microorganisms has been far better option against any two of these remediation techniques to clean up residual contaminants (Deng and Zeng 2017). In heavily contaminated soils, vermiremediation can be used as polishing step after primary remedial treatment (Sinha et al. 2008). Another way of enhancement of vermiremediation is through quality food supplementation and optimization of the inoculation conditions (temperature, pH, aeration, moisture, etc.) that ultimately increase earthworm biomass and rate of uptake of contaminants as well (Curry and Schmidt 2007). Improvement of agronomic conditions such as soil texture, organic matter, hydraulic conductivity and homogenization of contaminants to avoid hotspots will certainly enhance vermiremediation (Gerhardt et al. 2017). Since it is impracticable and time-consuming to study individual species under all possible conditions, various models viz. empirical, rate, equilibrium-partition, mechanical and fugacity models predicting uptake and accumulation of toxic materials in earthworms need to be validated (Shi et al. 2020).

10.9 Conclusions and Prospects

Vermiremediation as an expanding, sustainable, ecofriendly and cost-effective technology available for treatment of polluted soils, including FA, has been well acknowledged widely. Unlike physiochemical remediation, vermiremediation is an environmental supportive and relatively cheaper, easier, effective and efficient technique that should be highlighted. Many researchers have studied vermiremediation of FA over past few decades thereby opening up an innovative scientific approach in remediating contaminated land. Vermiaccumulation and vermitransformation play important roles in vermiremediation of pollutants like heavy metals in FA. Furthermore, emphasis is to be given for enhancing bioavailability of organic residues and by providing congenial environment for optimum growth of earthworms. Integration of effective microorganisms, agronomic practices, phytoremediation, biomass enhancement, etc. has the potential to facilitate vermiremediation. Safe and timely harvest and disposal of contaminated earthworms could prevent biomagnification of pollutants in natural food chains which should be considered seriously. Available models for predicting uptake and accumulation in earthworms need to be validated so that the capacity, contribution and mechanism of different processes in vermiremediation are fully clarified.

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