Chapter 2
Review of Literature

In the present review an attempt has been made to document the work done in past on the role of earthworms in bioremediation of bio-solid wastes and for enhancement of bioavailability of the nutrients present in them. Along with this the literature on use of vermicompost as a biofilter has also been compiled.

2.1 Composting Vs Vermicomposting

Composting and vermicomposting are two of the best-known processes for stabilization of solid organic wastes. The difference between ordinary composting and vermistabilization is that heating above 35°C is necessary for the former but must be avoided in the latter as it is lethal to the worms (Mitchell, 1979). Meunchang et al. (2005) reported that excessive composting could lead to loss or immobilization of nutrients such as nitrogen and phosphorous.

Composting involves degradation of organic matter by microorganisms under controlled conditions, in which the organic material undergoes (i) a characteristic thermophilic stage leading to quick degradation that also sanitizes the waste by the elimination of pathogenic microorganisms and (ii) a maturing stage which is marked by a decrease in temperature to the mesophilic range, where the remaining organic compounds are degraded at a slower rate. Duration of the active phase depends upon the characteristics of the waste and on the management of controlling parameters (aeration and watering) (Benitez et al., 1999; Lung et al. 2001). The extent of maturation phase is variable and is normally marked by the disappearance of phytotoxic compounds. Composting is well established at the industrial scale for solid organic waste treatment, although loss of nitrogen through volatilization of NH₃ during thermophilic stage is one of the major drawbacks of the process (Eghball et al., 1997).

Vermicomposting involves non thermophilic bio-oxidation and stabilization of organic material by the joint action of earthworms and microorganisms (Arancon et al., 2004a). Although microorganisms biochemically degrade the organic matter in this process also but earthworms are the crucial drivers as they aerate, condition and fragment the substrate, there by drastically alter the microbial activity. In fact they
modify the physical and chemical status of organic matter by gradually reducing the ratio of C: N and increasing the surface area exposed to microorganisms. Thus the earthworms make the waste much more favourable for further decomposition and release of nutrients by microbes (Domínguez et al., 1997; Domínguez, 2004; Loh et al., 2005). Vermicomposting also occurs in two phases i.e an active phase which is like the maturation phase in composting. The second phase is marked by displacement of the earthworms towards fresher layers of undigested waste, where the microbes have already initiated decomposition of the waste. In vermicomposting along with characteristics of the waste, the species and density of earthworms and their ability to ingest the waste, collectively determine the duration of these two phases (Lores et al., 2006).

Combination of composting and vermicomposting is now a days considered as a better way of achieving stable products and it reduces the expenses as well as the duration of the treatment process also (Tognetti et al., 2007a). Lazcano et al. (2008) evaluated effectiveness of the active phases of composting, vermicomposting and also a combination of composting and vermicomposting for reducing the polluting potential and for stabilizing cattle manure in a short-term. For this, degree of decomposition as well as microbial activity and microbial composition of the resulting products after the active phase of the three sets were analysed. They found that the combined treatment (composting + vermicomposting) was the most effective for stabilizing the cattle manure. The lowest values of microbial biomass and activity corresponded to the earthworm-worked substrates, in which fungal growth was also promoted. Combined activity of earthworms and microbes promoted retention of nitrogen and gradual release of phosphorous along with a reduction in electrical conductivity and a better quality product for agricultural use (Bajsa et al., 2003).

Earthworms also help to maintain aerobic condition with optimum moisture and temperature in the degradation piles (Edwards, 1988). Contreras-Ramos et al. (2005) reported that the numbers of human pathogens in vermicompost was greatly reduced, an effect obtained in traditional composting due to rise in temperature. The survival of pathogenic organisms like Salmonella, Shigella, faecal coliform and helminth eggs was reduced to nil after vermicomposting of sewage sludge and human faeces, proving that these pathogens were eliminated as they passed through the gut of earthworms. (Arumugam et al., 2004; Contreras-Ramos et al., 2005; Rodriguez-
The reduction of pathogen numbers has been co-related to the release of coelomic fluids by the earthworms during vermicomposting as it possesses antibacterial properties and kills pathogens (Pierre et al., 1982; Sinha et al., 2002).

As opposed to traditional microbial waste treatment (composting) vermicomposting is a cost effective technology for the processing or treatment of organic wastes (Hand et al., 1988). The product of vermicomposting is more stable and rich as compared to the products of composting (Frederickson et al., 1997) and has a significantly lower volatile solid content (Edward, 1998). Its homogeneous nature, desirable aesthetics, reduced levels of contaminants and tendency to hold more nutrients over a longer period, without adversely impacting the environment are characteristics responsible for it being considered as an excellent product (Fisher, 1988). Large quantity of plant hormones such as gibberellins, auxins and cytokinins are present in vermicompost and promote growth of crops (Tomati et al., 1983; Ismail, 1998). Vermicompost application stimulates root growth, facilitates nutrient absorption and thereby favours higher yield (Padmavathamamma et al., 2008). Improvement in plant growth and increase in fruit yields could be due partially to large increases in soil microbial biomass after vermicompost applications (Ndegwa and Thompson, 2001).

2.2 Composting earthworms

Earthworms are very important components for the maintenance of soil fertility and nutrient cycling. Since long earthworms have been known as farmer’s friends, natural ploughmen and intestines of the earth. The beneficial role of earthworms in the breakdown of dead plant material in the forest litter was documented first of all by Darwin (1881). It is believed that earthworms evolved about 570 million years ago (Sathe, 2004) and since then have been helping in conserving the natural environment. Out of the 3200 species of earthworms reported from the world over, about 374 species have been reported in India (Kale, 1991; Julka, 1993).

In 1977, Bouche classified the earthworms into three categories on the basis of ecological distribution in soil.
1) Epigeic earthworms: They are small sized, with uniform body colouration, live on surface litter or dung, and tolerate variable range of temperature. They have insignificant role in humus formation. These species are good for vermicomposting. Examples: *Eisenia fetida, Dendrobaena rubida, Perionyx excavatus* and *Eudrilus eugeniae*.

2) Anecic earthworms: They are large sized with pigmentation only at the anterior and posterior end. They are mostly phytophagus and play a useful role in mixing nutrients from deep layers to surface by casting. Examples: *Lampito mauritii, Aporrectodea longa, Lumbricus terrestris*.

3) Endogeic earthworms: They are large or small sized worms with weak pigmentation. These are geophagus and are found in the soil layer with organic and mineralized matter. Examples: *Metaphire posthuma, Octochaetona thurstoni, Allolobophora calignosa, Aporrectodea rosea, Octolaseon cynaeum*.

In 1985, Lee, however, classified earthworms on the basis of their feeding habits into two groups:

1) Detritivorous earthworms: Earthworms feed at or near the soil surface and mainly feed on plant litter or dead roots or mammalian dung. Example: *Eisenia fetida, Lampito mauritii, Perionyx excavatus* and *Eudrilus eugeniae*.

2) Geophagus earthworms: They feed deeper beneath the surface of soil and ingest large quantity of organically rich soil. Example: *Metaphire posthuma, Octochaetona thurstoni*.

Out of these categories epigeics are useful for biosolid waste management as these worms can hasten the composting process to a significant extent and produce better quality composts, compared with those prepared through traditional methods (Tripathi and Bhardwaj, 2004). *Ei. foetida* is used throughout the world for this purpose as it is ubiquitous, can tolerate a wide range of temperature and can live in wastes with good moisture content (Reinecke et al., 1992). *Eu. eugeniae* and *Pe. excavatus* are the other commonly used worm. *Eu. eugeniae* is large in size, grows rapidly but has poor temperature tolerance, hence, may be suitably used in the areas with less fluctuation of temperature (tropical areas). Some other useful species for Indian climates are *La. mauritii, Dichogaster bolani, Drawida willsi* and *Pheretima elongata* (Dash and Senapat, 1985; Shinde et al., 1992; Singh, 1997). There is a
species specific variation in food preference and accordingly the time taken for bioremediation also varies. A comparative study between exotic *Ei. foetida* and local *La. mauritii* species of earthworms for evaluation of their efficiency in vermicomposting of municipality solid waste showed that *Ei. foetida* was superior to *La. mauritii* in terms of TOC reduction, C/N ratio reduction, increase in EC and TK but *La. mauritii* was able to modify the soil characteristics (Kaviraj and Sharma, 2003). Tripathi and Bhardwaj (2004) also observed that both the species brought an increase in N, P, K and a decrease in C/N and C/P ratios after 150 days. There was faster decomposition by *Ei. foetida* in comparison to moderate decomposition by *La. mauritii*, when kitchen waste was amended with cow dung. Moreover, the average number of cocoons and adults produced by *Ei. foetida* were more than *La. mauritii*. Finally they concluded that *Ei. foetida* was a better adapted species for decomposition of kitchen waste mixed with cow dung under tropical conditions. Dominguez et al. (2001) found that *Eu. eugeniae* could grow fast in animal waste so it could also be a suitable candidate for vermicomposting. Out of the Indian species *Pe. excavatus*, *Di. modigilani*, *Dr. nepalensis* and *La. mauritii* could be exploited for vermicomposting because of their continuous breeding, high rate of cocoon production, short development time and high hatching success (Bhattacharjee and Chaudhuri, 2002).

Earthworm species *Eu. eugeniae*, *Ei. foetida*, *Pe. sansibaricus*, *Pontoscolex corethrurus* and *Megascolex chinensis* were compared for their efficiencies in biodegrading organic wastes and *Eu. eugeniae* was found to be superb of all these (Padmavathimma et al., 2008). Some scientists recommend that vermicomposting with polyculture gives faster results over monoculture (Dash and Senapati, 1985; Suthar, 2008). When three earthworm species, i.e. *Ei. fetida*, *Pe. excavatus* (epigeic) and *La. mauritii* (anecic) were used, the reactor with polyculture performed better than the traditional monoculture vermineactors (Suthar and Singh, 2008a). On the other hand Elvira et al. (1996) found that mixed cultures of epigeics (*Ei. fetida*, *Lu. rubellus* and *De. rubida*) did not show any advantage over pure cultures. *Ei. andrei* showed higher growth rates in mixed cultures, while the growth rate of *Lu. rubellus* and *De. rubida* decreased slightly in mixed cultures as compared to pure cultures.

### 2.3 Effect of temperature and moisture on earthworm

After conducting a series of experiments, Reinecke and Kried (1981), Reinecke and Venter (1987) and Reinecke et al. (1992) concluded that *Ei. foetida*
could survive well even in harsh environmental conditions, especially temperature (5 to 43°C) and fluctuating moisture conditions. However, growth and maturation of earthworms was best at 20°C and 85% moisture content under laboratory conditions. Dominguez and Edwards (1997) and Singh et al. (2004) also found that 80% moisture was optimum for vermicomposting of pig manure and hostel kitchen waste by *Ei. anderi* and *Pe. excavatus*, respectively. The data revealed a linear relationship between the ash content of the vermicompost and vermicomposting duration at this moisture.

Edwards et al. (1998) studied the life cycle of *Pe. excavatus* in a variety of organic wastes under various population density pressures and temperatures between 15°C and 30°C. Increasing temperatures up to 30°C accelerated the growth of earthworms and lessened the time to sexual maturity. However, the highest rates of reproduction occurred at 25°C both in cattle solids and sewage sludge. The mean time for egg hatching decreased and the degree of hatching success increased with increasing temperature and was best at 30°C. Earthworms grew at similar rates in cattle solids, pig solids and aerobically digested sewage sludge, but the earthworms did not grow well in horse solids and grew poorly in turkey wastes. The maximum individual growth rates as a function of earthworm population and the maximum earthworm weights as a function of time with a constant food supply at different temperatures were assessed. Edward (1998) in another study evaluated the optimal conditions for breeding *Ei. foetida* in a range of animal and vegetable waste under aerobic condition with temperature from 15-20°C, moisture 80-90%, ammonia content < 0.5 mg/gram, salt content <0.5% and pH in the range of 5-9. He found that the population density of worms per unit volume or weight of a waste was very important in affecting rate of growth and reproduction.

In 2001, Dominguez et al., made an observation on the biology and population dynamics of *Eu. eugeniae* in cattle waste solids by growing them in groups of 1, 2, 4, 8 or 16 hatchlings in 100 g of waste in incubators at 15, 20, 25 and 30°C. They found that earthworm biomass production was temperature dependent, maximum production being attained at the two highest population densities and highest temperature (30°C). The highest organic waste to earthworm ratio of 10:1 (10%) was recorded at the most dense earthworm population. The reproductive biology of seven Indian species of earthworm, viz. *Pe. excavatus* Perrier, *La. mauritii* Kinberg,
Polypheretima elongata (Perrier), Po. corethrurus (Muller), Eut. gammiei (Beddard), Di. modiglianii (Rosa) and Dr. nepalensis Michaelsen was studied in different seasons (natural variation in temperature) by Bhattacharjee and Chaudhuri (2002). The peregrine earthworms such as Pe. excavatus, Po. corethrurus, Di. modiglianii, and Poly. elongata were continuous breeders with high fecundity. Native La. mauritii and Dr. nepalensis were found to be semi-continuous, whereas, Eutypheues gammiei was a discrete breeder. There was a dramatic increase in cocoon production by most earthworm species of Tripura in the summer and monsoon months with peaks during April and July. Cocoon production decreased or ceased altogether during winter.

Temperature also affected the incubation period of cocoons. With increase in temperature within a temperature range of 28-32°C under laboratory conditions, incubation period increased in the endogeic worms (Po. corethrurus, Poly. elongata and Dr. nepalensis) and decreased in the epigeic worms (Pe. excavatus and Di. modiglianii). There was a significant (P < 0.05) positive correlation between number of hatchlings per cocoon and incubation period in La. mauritii only. Edwards and Arancon (2004) noticed that increasing temperatures up to 30°C accelerated the growth of Pe. excavatus and reduced the time for attaining sexual maturity. However, the highest rates of reproduction occurred at 25°C both in cattle solids and sewage sludge. The mean time for hatching of eggs decreased and the degree of hatching success increased with increasing temperature.

Elvira et al. (1996) studied the growth and reproduction of the epigeic species Lu. rubellus and De. rubida in cow manure and their possible interactions with Ei. andrei. The mean growth rate of De. rubida was 3.84 mg/d day, reaching sexual maturity at 54 days and producing an average of 1.45 cocoons per week. After collection, 85% of the cocoons of this species were viable, incubation took an average of 21.7 days and an average of 1.67 worms emerged from each cocoon. The mean growth rate of Lu. rubellus was 8.02 mg/day, maturity at 74 days, with a mean weekly production of 0.54 cocoons. After an incubation period of 36.5 days, 64% of the cocoons hatched, one worm emerged from each. The mixed cultures tested did not present any advantage over pure cultures, Ei. andrei showed higher growth rates in mixed cultures, while the growth rate of Lu. rubellus and De. rubida decreased slightly in mixed cultures as compared to pure cultures. On the other hand, maximum biomass gain by Pe. excavatus was 292 mg per gram cattle waste at 25°C. Increasing
temperatures up to $30^\circ$C accelerated the growth of earthworms and lessened the time to sexual maturity (Edward, 1998).

### 2.4 Synergistic role of earthworms and micro-organism in vermicomposting

Earthworms have the ability to eat and mix large amount of soil and organic matter and deposit it in the form of casts. They also enhance incorporation and decomposition of organic matter, increase soil aggregate stability, improve porosity and water infiltration and increase microbial activity. The earthworm activity is important for the initial breakdown of plant and animal residues before the organic matter is recycled by the soil micro-flora (Edwards and Lofty, 1977). Earthworms are important ecological contributors to the cycling and release of detritus bound nutrients and act as ameliorators of physical properties of the soil. Cooperating with microbes, earthworms can accelerate the decomposition of organic matter, enhance circulation of carbon, nitrogen and phosphorous and soil fertility (Hameed et al., 1994). In particular, protozoa and fungi are assumed to form a substantial part of their diet (Brown, 1995). Earthworms gained weight when reared in cultures of certain fungal species because of the chitin present in cell walls that contains high natural protein and amino polysaccharide (Kumar, 1995; Bonkowski and Schaefer, 1997; Edwards and Fletcher, 1998). The combined use of earthworms and cellulolytic micro-organisms results in more decomposition of kitchen waste than inoculation of earthworms or cellulolytic micro-organisms alone (Das and Talukdar, 2001). Aira et al. (2006) evaluated the role of Ei. foetida in cellulose decomposition, by conducting an experiment on pig slurry with microbial rich substrate in small-scale vermireactors with and without earthworms. The presence of earthworms in vermireactors significantly increased the rate of cellulose decomposition (0.43 and 0.26% cellulose loss per day, with and without earthworms, respectively). However, the direct contribution of Ei. foetida to degradation of cellulose was not significant, although its presence increased microbial biomass and enzyme activity (cellulase and beta-glucosidase). The activity of Ei. foetida triggered fungal growth during vermicomposting which led to more intense and efficient cellulolysis. The presence of fungi during vermicomposting process became additional supplement to the earthworms which contributed to the increased number and weight of the earthworms.

Microbial activities rise because the gut of earthworm contains easily metabolizable compounds that provide favourable physico-chemical conditions for
bacterial growth. Bacterial population in earthworm casts is often much higher than the surrounding soil, therefore it promotes release of available nutrients (Aira et al., 2007; Vivas et al., 2008). On the other hand there are reports claiming that compost exhibited higher culturable bacterial biomass and metabolic diversity than vermicompost (Atiyeh et al., 2000; Vaz-Moreira et al., 2008). Nutrients in the vermicompost are in a form that is readily available to plants due to chemical and microbial digestion in the gut of earthworm (Gunnarson et al., 1988).

Vitamins, DNA, and humic acid as additives improved growth and allowed reproduction of *Ei. foetida* in a cellulose based medium. Mature worms were not able to adapt to the medium as compared to 20 day old worms. Rates of growth and cocoon production were slightly less in a defined medium (7% organic content) than in a cow manure control medium (70% organic content) (Bouwman and Reinecke, 1991).

### 2.5 Growth rate of earthworm

The earthworms grow best in easily metabolizable organic matter and non-assimilated carbohydrates, these also favour their reproduction (Flack and Hartenstein, 1984). Growth and reproduction were found to be positively correlated to the volatilable solid content of the waste (Edward, 1998). Earthworm growth slows down when C: N ratio and temperature is high (Bostrom, 1987; Shipitalo *et al*., 1988). The biomass gain by *Ei. foetida* was found to depend on population density and food type with particle size playing a significant role in vermicomposting (Watanabe and Tsukamoto, 1976). Viljoen and Reinecke (1989) observed that single raised worm began to gain biomass at a higher rate (after 170 days) than those raised in batches (after 230 days). The population density of worms per unit volume or weight of a waste is very important in determining the rate of earthworm growth and reproduction. While Dominguez *et al*. (2000) reported a decrease in worm biomass even when additional feed was provided to worms every week. So the factors relating to the growth of earthworm may be considered in terms of physico-chemical and nutrient characteristics of waste along with temperature, pH and moisture content of feed stocks. The organic waste palatability and intensity of feeding by earthworm is directly related to the interaction of these parameters and consequently it affects growth and reproduction of earthworm (Suthar, 2007). In 1979, Hartenstein *et al*.

reported the regression equations for *Ei. foetida* with respect to age at which 50% of
the population became clitellate at 25 °C in relation to population density in activated sludge and in horse manure. Data provided age at which reproduction terminated in relation to population density, optimum population density for reproduction, and hatchability. A mean particle size of 0.3mm of horse manure proved superior in supporting a weight gain (+ 45%) than a particle size of 0.5mm or 1mm. Pure cellulose, newspaper or wood shavings as substrate were ingested by *Ei. foetida* but failed to result in weight gain. Neuhauser *et al.* (1980) and Neuhauser *et al.* (1988) also reported a weight loss in *Ei. foetida* for a longer duration in the waste. This was due to the conversion of most of the used substrate to vermicompost, which could not further support their growth.

Gunadi *et al.* (1998) reported that *Ei. foetida* and *Ei. anderi* grew faster in tea leaf wastes pre-composted for one week than in fresh waste because of the high protein content. However in fresh cattle solids, death of *Ei. foetida* was observed after 2 weeks by Gunadi and Edward (2003). They attributed death of earthworms to the anaerobic conditions which developed after 2 weeks in fresh cattle solids because all other growth parameters such as moisture content, pH, electrical conductivity, C: N ratio, NH₄ and NO₃- contents were suitable for the growth of the earthworms.

### 2.6 Sexual development, cocoon production, hatching rate and hatchlings

Food availability, type of food, population density and temperature determine the time of sexual maturation in earthworm (Neuhauser *et al.*, 1980). The growth rate of earthworm slows down at higher temperature was experimentally proved by Reinecke *et al.* (1992) observed that temperature above the optimum for growth decreased the incubation period of earthworm. Biochemical quality of the feed is an important factor in determining the time taken to reach sexual maturity, onset of reproduction and cocoon production (Edward *et al.*, 1998). The most rapid maturation in earthworm was at 25°C and degree of hatching success increased with increasing temperature and it occurred at 17.8 days at 25 °C and 15.3 days at 25-37 °C (Edwards, 1988; Reinecke *et al.*, 1992; Edwards *et al.*, 1998). Reinecke and Venter (1987) observed that the first and last cocoon produced by *Ei. foetida* were less viable than those produced between days 30 and 120 during degradation of waste. Incubation period was 23 days with 2.7 hatchlings per cocoon. Reinecke and Viljoen (1988) observed that production of cocoons by *Eu. euginae* was more at 25 °C in different substrates. Evans and Guild (1948), however, observed a peak production of 3.8
cocoons per week per individual of *Ei. foetida* at 13°C. Edward (1998) reported that development time of cocoon for temperate epigeic worm was 32-73 days in *Ei. foetida*, 40-126 days in *Dendrobaena veneta* and for tropical epigeic worms *Eu. euginae* and *Pe. excavatus* it was 13-27 days and 16-21 days. The average incubation period for cocoons of *Eu. euginae* between 70 and 100 days of age was 16.89 days. A mean of 2.12 hatchlings per cocoon were produced after incubation in cattle manure, moist filter paper and distilled water. However, a smaller batch of cocoons incubated in cattle manure produced a mean of 2.7 hatchlings per cocoon. The hatching success of the cocoons was 84% in cattle manure, 50% in distilled water, and 48% on moist filter paper. The first clitellum in *Eu. euginae* developed between 25 and 30 days and cocoons were produced even though copulation had not taken place but these cocoons failed to hatch (Viljoen and Reinecke, 1989). On the other hand Venter and Reinecke (1988) in their studies observed clitellum for the first time in *Ei. foetida* after 60 days and according to them mating was a pre-requisite for cocoon production.

A positive correlation was observed by Satchell (1967) between number of cocoons and the zone of soil inhabited by worms. The species of the deeper soil layer protected from adverse environmental condition produced few cocoons, whereas those living near the surface and facing adverse condition produced more cocoons. Olive and Clark (1978) reported that temperature beyond optimum level decreased neurosecretory activity and thus affected cocoon production. Hartenstein *et al.* (1979) reported that cocoon weighing about 6 mg is required if one offspring is to emerge with an approximate weight 2.3 mg at birth. The cocoon from which the largest number of hatchlings emerged had lighter worms present among the progeny. Lavelle (1981) found a positive relationship between the size of the adult and cocoons produced by the earthworms but Senapati and Sahu (1993) reported that the size of worms bore a negative relationship with the number of cocoons. They asserted that greater rate of cocoon production by small to medium sized epigeic earthworm *Di. modiglianii* and *Pe. excavatus* and top soil endogeic worms *Po. corethrurus* and *La. mauritii* was due to exposure to the high mortality risk environment. Lee (1985) and Edwards and Bohlen (1996) proposed that cocoon size was not always correlated with worm size as cocoon production and time for maturation of cocoon varied with species, population density and external factors especially soil temperature, moisture
and energy content of the available food and age of worms. Also there was a positive correlation between the age at which cocoon production started and mortality of worms. Barne and Striganova (2005) noticed higher mortality with increase in density of worms but Jager et al. (2006) reported that changing the density of earthworm *Ei. veneta* hardly affected the growth curves but had an unexpected effect on reproduction. At higher density, the earthworm produced cocoons at larger body size and the maximum reproduction rate was lower. Reinecke and Viljoen (1988) found no significant correlation between cocoon size and number of hatchlings produced. Hatching success of cocoon produced by worms younger than 60 days was low, the rate of hatching increased as the worms grew.

Gunadi et al. (2002) reported that the numbers of cocoons were less with increasing time of pre-composting but there was no clear pattern of effect of pre-composting on the number of hatchlings produced in cattle solids. Weight of hatchlings varied from 2.5 to 2.6 mg/ cocoon. However, total cocoon production of *Ei. foetida* over 12 weeks was observed to decrease significantly with increasing period of pre-composting by Frederickson (1997).

Reinecke et al. (1992) reported that 14% of cocoons produced two hatchlings and 2% produced three while Edwards (1998) noticed that less than 5% cocoons produced two hatchlings but usually one hatchling was produced. Bhattacharjee and Chaudhuri (2002) observed that temperature affected production and the incubation period of cocoons. With increase in temperature between 28-32°C incubation period increased in the endogeic worms like *Po. corethrurus, Poly. elongata and Dr. nepalensis* and decreased in the epigeic worms, *Pe. excavatus* and *Di. modiglianii* under laboratory conditions.

### 2.7 Physico-chemical quality of the feed wastes and vermicompost

The chemical composition of the vermicompost is known to be influenced by the kind of feed given to the animal, bedding material used and the way the waste is collected, stored and handled before utilization (Kemppainen, 1989). A detailed review of various physico-chemical parameters of feed material and their influence on the quality of the vermicompost is given in the following section.
2.7.1 pH and EC

Variation in pH of vermicompost has been reported by several workers. The differences in the pH of vermicompost are directly dependent on the raw materials used for vermicomposting. Different substrates could result in different intermediates and hence show a different behaviour in pH shift. The neutral pH recorded throughout the bed profile is optimal for the growth of *Ei. fetida* (Kaplan *et al.*, 1980). The occurrence of acidic environment may be attributed to the bioconversion of organic acids or higher mineralization of the nitrogen and phosphorous into nitrates/nitrites and orthophosphate, respectively (Mitchell, 1997; Atiyeh *et al.*, 2000; Ndewga *et al.*, 2000; Alves *et al.*, 2001; Gunadi and Edwards, 2003; Loh *et al.*, 2005, Li *et al.*, 2011). The pH of cow dung and sheep manure vermicompost came out to be 8.48 and 8.6 (Gutierrez-Miceli *et al.*, 2007), cattle manure had a pH of 6.0 - 6.7 (Jordao *et al.*, 2002; Alves *et al.*, 2001) pig manure had a pH of 5.3- 5.7 (Atiyeh *et al.*, 2001; Atiyeh *et al.*, 2002) and the one derived from sewage sludge had a pH of 7.2 (Masciandaro *et al.*, 2000). The lower pH of the final vermicomposts might be due to production of CO$_2$ and organic acids by microbes during the process of bioconversion of different substrates in the feed given to earthworms (Hartenstein and Hartenstein, 1981; Haimi and Hutha, 1986; Elvira *et al.*, 1998; Chaudhuri *et al.*, 2000, Yadav and Garg, 2010). The decline in pH may be directly related to reduction in volatile solids and to the growth of earthworm’s biomass. The larger the increase in biomass growth, the greater the reduction in volatile solids and the more shift towards the acidic condition (Ndewga *et al.*, 2000). A decrease in pH may be an important factor in nitrogen retention as this element is lost as volatile ammonia at higher pH value. The lower pH was due to production of fulvic acid and humic acid during decomposition (Albanell *et al.*, 1988).

The change of mesophilic to thermophillic condition changes pH from acidic to alkaline due to conversion of organic –N- to NH$_4^+$ (Fang *et al.*, 1998; Guerra-Rodriguez *et al.*, 2000 and 2001; Beck-friis *et al.*, 2001). Rynk *et al.*, (1992) suggested that the excess of organic nitrogen not required by microbes was released as ammonia which got dissolved in water and increased the pH of the vermicompost. Datar *et al.* (1997) and Singh *et al.* (2010) also reported an increase in pH during vermicomposting of solid waste and beverage biosludge. Jadia and Fulekar (2008) asserted that an increase in pH during composting and vermicomposting process was...
due to progressive utilization of organic acids and an increase in mineral constituents of the waste.

The reports regarding electrical conductivity during vermicomposting process are contradictory, some workers reported decrease in electrical conductivity (Garg et al., 2006; Singh et al., 2010) and others an increase in electrical conductivity (Fang et al., 1998; Gupta and Garg, 2008; Khwairakpam and Bhargava, 2009a; Sellami et al., 2008, Hait and Tare, 2011). The decrease has been attributed to a decrease in ions after forming a complex whereas the increase has been attributed to the degradation of organic matter to release cations and release of different mineral salts in available forms such as phosphate, ammonium and potassium (Guoxue et al., 2001).

2.7.2 Nitrogen

Nitrogen generally declines during traditional composting due to use of nitrogen by the rapidly multiplying heterotrophic bacteria but it increases during vermicomposting (Brady and Weil, 2002; Kaur et al., 2010; Singh et al., 2010). Chaudhuri et al. (2000) attributed the decrease in nitrogen and potassium content during the vermicomposting of kitchen waste by Pe. excavatus. This is probably due to NH₃ volatilization, incorporation into earthworm tissue and leaching into bedding material with as well as without earthworms or due to release of ammonia (Guest et al., 2001). Although, nitrogen content increased during the process of vermicomposting of various materials (Manna et al., 2003; Jadia and Fulekar, 2008; Adi and Noor, 2009, Nahrul Hayawin et al., 2010) but final TKN content in vermicompost was always dependent on the initial nitrogen present in the feed material and the degree of decomposition (Crawford, 1983; Kale, 1998; Araujo et al., 2004; Tripathi and Bhardwaj, 2004; Garg and Kaushik, 2005; Hobson et al., 2005; Suthar, 2006; Suthar, 2007, Yadav and Garg, 2010). According to Needham (1957), Tillinghast (1967) and Viel et al. (1987) losses in organic carbon might be responsible for nitrogen addition along with it mucoproteins in the mucus secreted by epidermal glands, urea excreted through nephridia and ammonia through the gut with cast materials helped in enhancing the nitrogen in the vermicompost. Decaying tissue of dead worms also adds a significant amount of nitrogen to the vermicomposting system. *Ei. foetida* also produce favorable condition for nitrification of cow slurry. The worm excreta convert it into the mineral form as ammonium in mucoproteins and the ammonium in the soil get further converted into nitrates (Hand et al., 1988).
Earthworms may influence microbial N transformation such as mineralization, nitrification and denitrification through their interaction with soil biota and increase concentration of ammonia in the fresh vermicasts (Blair et al., 1995). Whalen et al. (1999) found that much of the $^{15}$Nitrogen released from decomposing earthworm tissue was cycled through microbial biomass within four days and 70% of $^{15}$Nitrogen from decomposing earthworm accumulated in plant shoot biomass after 16 days. Whalen et al. (2000) observed that juvenile of Lu. terrestris excreted significantly more $^{15}$Nitrogen than adults at 10 °C but in Aporrectodea tuberculata $^{15}$Nitrogen excretion was significantly greater for adults than for pre-clitellate individual at 18 °C. Soils incubated with earthworms tended to have higher concentration NH$_4$-N, NO$_3$-N than soil incubated without earthworms for 48h. The substantial proportion of N excreted by earthworms may be readily available for microbial and plant uptake. Amador et al. (2003) estimated that the organic nitrogen released by dead earthworms reached to 21.1-38.6 t / h / year.

While Kumar et al. (2010) revealed that the nitrogen content decreased during vermicomposting which may have been due to ammonification, NH$_3$ volatilization and denitrification. The decrease in nitrogen was also supported by Benitez et al. (1999) who observed a 36% loss of total nitrogen during vermicomposting of sewage sludge.

2.7.3 Organic carbon and C: N ratio

Earthworms modify the soil through their feeding, casting, and burrowing activities, which may lead to more decomposition and respiration in aerobic microsites and more denitrification in anaerobic microsites. A decline in C: N ratio to less than 20 indicates an advanced degree of organic matter stabilization and reflects a satisfactory degree of maturity of organic wastes (Senesi, 1989; Morais and Queda, 2003; Sen and Chandra, 2007). Earthworms also increase CO$_2$ and N$_2$O fluxes from unfertilized agro-ecosystems. Speratti and Whalen (2008) observed that mean CO$_2$ and N$_2$O fluxes during the study period tended to be greater from enclosures with added earthworms than the control (no earthworms added), but were non significantly different due to the low survival rate of introduced earthworms. Better control of earthworm populations in the field is required to fully assess the impact of earthworms on CO$_2$ and N$_2$O fluxes from temperate agro-ecosystems. Tognetti et al. (2007a) also found that the rate of CO$_2$ production from vermicompost piles was
much higher than that of traditional compost. During vermicomposting period faster decline in C: N ratio (from 17.92 to 10.15%) as compared to compost without earthworm was also observed by Cabrera et al. (2005). However, Atiyeh et al. (2000) reported that the C: N ratio of the manure with or without earthworms decreased progressively from 36 to 21.

The ash and nitrogen contents increased largely for a few weeks after the introduction of earthworms, reflecting a rapid breakdown of carbon compounds and mineralization by earthworms. CO₂ evolution decreased rapidly indicating increased stability of the organic matter. The faster reduction in carbon and lowering of C/N ratio during vermicomposting could be achieved either due to higher loss of CO₂ by respiratory activity of earthworms and microorganism or due to an increase in nitrogen brought by microbial mineralization of organic matter in combination with the addition of nitrogenous wastes by worms. The C/N ratio of vermicompost reduced to 12-17:1 from 21-69:1 (Senapati et al., 1980; Elvira et al., 1998; Ghosh et al., 1999; Gunadi et al., 2002; Kaviraj and Sharma, 2003; Tripathi and Bhardwaj, 2004; Christy and Ramalingam, 2005). Aira and Dominguez (2008) noticed that earthworms increased microbial biomass and enhanced carbon losses which was not at all affected by the rate of pig slurry applied. Briones et al. (2008) suggested that calciferous organs of worms provided a mechanism of CO₂ regulation and both environmental and metabolic CO₂ could be fixed by this organ.

2.7.4. Phosphorus

Phosphorus is an important nutrient for plants and is used for seed germination, photosynthesis, protein formation, overall growth and metabolism, flower and fruit formation. However, a large fraction of soil phosphorus is in mineral form and not readily available for plants but the potential activity of phosphate solublising microorganisms and earthworm increases phosphorous availability for plants (Ilmmer et al., 1995; Kumar and Singh, 2001).

Edwards and Lofty (1972), Satchell and Martin (1984) and Krishnamoorthy (1990) asserted that the rise in total phosphorous during vermicomposting was probably due to mineralization and mobilization of phosphorus as a result of bacterial and faecal phosphatase activity of earthworms. In 1999, Patron et al. noted that earthworm activity accelerated transformation of organic phosphorous to plant
available phosphorus form. An increase of up to 25% in total phosphorus of paper waste sludge was noted by Bayon and Binet, (2006), earlier Ghosh et al. (1999) found 12-20.9% increment in the amount of easily extractable phosphorus during vermicomposting of different waste materials, hinting towards the efficiency of earthworm in increasing availability of phosphorus and decreasing the magnitude of fixation of released phosphorus into insoluble inorganic forms (Guerra- Rodriguez et al., 2000).

According to Kaviraj and Sharma (2003), acid production during organic matter decomposition by the microorganisms is the major mechanism for solubilisation of insoluble phosphorus and potassium. Therefore, presence of a large number of microflora in the gut of earthworm might play an important role in increasing phosphorus and potassium content in the vermicompost. The effects of phosphate solubilising bacteria (PSB) Bacillus megaterium and earthworm Ei. foetida and Pheretima guillelmi on phosphorous turn over and transformation in soil was investigated by Mba (1997) and Wan and Wong (2004). They found that the number of PSB was enhanced in all the treatments with earthworm. The activity of acid phosphatase increased in the treatments having earthworm Pheretima guillelmi along with a significant increase in both inorganic and water soluble phosphorus. Acid phosphatase promoted the rate of hydrolysis of organic phosphorus compound into inorganic phosphorus and the PSB found in the worm casts of Eu. euginae played an important role in improving phosphorus recycling as well as increasing carboxymethylcellulose, carbon recycling and nitrogen fixation.

### 2.7.5 Potassium

There are contradictory reports regarding the total potassium content in vermicomposts obtained from different substrates due to the differences in the chemical nature of the initial raw materials (Orozco et al., 1996). Benitez et al. (1999) have reported that the leachates collected during vermicomposting process had higher potassium concentrations. The decrease in total potassium of vermicompost after bioconversion of paper pulp mill sludge and sugar mill sludge by Ei. andreii was attributed to leaching by Elvira et al. (1998), Garg et al. (2006) and Sangwan et al. (2008).
Delgado et al. (1995), Guerra- Rodriguez et al. (2000) and Suthar (2006) revealed that mineralization process significantly enhanced the concentration of exchangeable potassium during vermicomposting. Suthar (2008), Nahrul Hayawin et al. (2010) and Yadav and Garg (2010) also reported higher potassium content in the vermicompost produced from distillery sludge, oil farm waste and food industrial sludge respectively.

2.7.6. Polysaccharides

Reid (1979) reported that lignin mineralization was limited by available phosphorous. The reduced lignin mineralization rate in the later stages was due to reduction of phosphorous and carbon availability. The study of Chen et al. (1989) showed that the carbohydrate content decreased but the content of aromatic and carboxyl groups increased during composting process. Marhan and Scheu (2005) found that the earthworm Octolasion tyrateum strongly increased lignin mineralization during the first 6 weeks of incubation. The increase was due to more availability of phosphorous and different microbial community. Earthworms digest long chains polysaccharides and enhance microbial colonization. Simultaneously the structure of lignin also changes leading to production of smaller polysaccharides but an increase was observed in total aliphatic carbon and polysaccharide at the end of vermicomposting which suggested neosynthesis or insolubilization during vermicomposting (Sen and Chandra, 2007).

2.7.7 Transition metals/ Heavy metals

The increasing exploitation of natural resources by human beings during the past few centuries has adversely affected the global balance of heavy metals causing a gradual increase in the concentration of metals in the soil ecosystem (Nriagu, 1990). Heavy metals are important trace elements for well being of plants, animals and humans (Zn, Cu, Mn, Cr, Ni), but their excess is known to have toxic effects (Kizilkaya, 2004 and 2005). Among essential trace elements, Zn occupies a significant position for the metabolic functions of organisms. It shows toxic effect above certain levels and exposure duration. Whereas biocidal and non-biodegradable properties of Pb have been known for thousands of years. It gets deposited in different tissues and disturbs almost every metabolic activity in a living body (Hopkin, 1989). In order to maintain the environmentally sound soil quality, investigators are seeking
methods to reduce the mobility of heavy metals from wastes to soil ecosystem. Metal mobility and availability can be reduced by raising the soil pH (Brady and Weil, 2002). Various physico-chemical techniques have been employed to treat industrial wastes (Dong-Mei et al., 2004), but the requirement for high capital and recurring expenditures limits their commercial use. Phyto-remediation is recognized as the most commercially viable and environment friendly technology but till now only a limited number of plants have been found to have phyto-accumulation ability and a very less number can be used for field phyto-remediation because of low biomass production. Therefore, immobilization of metals in contaminated soils using earthworms seems to be a valuable alternative in place of all these more expensive and laborious remediation methods (Lasat, 2000). According to Hopkin (1989), the earthworms have specific capacity to regulate metals, particularly trace metals, such as Cu and Zn, in their bodies. The accumulation and regulation mechanisms could be species specific. Earthworms can be used as bio-indicators for evaluating the extent of soil contamination with heavy metals, pesticides, agricultural run off and acid rain etc. (Paoletti et al., 1991). At the same time the feasibility of earthworms to mitigate the metal toxicity and to enhance the nutrient profile of organic wastes might be useful in sustainable land restoration practices on low-input basis (Suthar, 2008). Heavy metals bind with ligands of the tissues of organisms and this leads to their bioaccumulation and biomagnification in the food chain (Tavares and Carvalho, 1992). Lukkari et al. (2004) found that diversity, total numbers and biomass of earthworms increased with increasing distance from the emission sources of industries. A positive correlations between metal concentrations in the earthworms and those in the soils were observed with differences in bioaccumulation factors for different metals, this could be due to a variable metabolic requirement of earthworms for metals (Lukkari et al., 2006).

Maboeta et al. (1999) studied the effects of sub lethal concentrations of lead nitrate on growth and reproduction of the Asian composting earthworm Pe. excavatus. When the worms were exposed to lead nitrate-contaminated food over a period of 76 days, growth was affected negatively by the presence of lead while maturation rate and cocoon production was not affected but cocoon viability was affected negatively by lead, making this a sensitive toxicity end point.

Earthworms are known to inhabit and survive in sites heavily contaminated with metals (Lukkari et al., 2004) and have the ability to accumulate heavy metals in
the cells of yellow tissue (Fischer and Molnar, 1992). Survival in heavy metal environments provides circumstantial evidence that some earthworm populations may develop mechanism by which they can tolerate or resist the effect of metal induced stress. Such tolerance or resistance may be acquired through either reversible changes in an earthworm’s physiology or through a variation in their genetic structure. Toxicity tests have shown that heavy metal pollution negatively affects life-history characteristics of earthworms such as growth, reproduction and survival (Spurgeon and Hopkin, 1999). Field simulating experiments in soil-filled plastic containers showed that earthworms tried to escape moderately toxic situations and that they were much more sensitive than oribatid mites. The total copper concentration in the body of the earthworm Octolaseon cynaem was measured in experiments with different soil types and different amounts of added CuSO₄. The copper concentrations in the earthworms increased in response to the higher concentrations of the copper fraction extractable with 2.5% acetic acid in the soil. Furthermore, internal copper concentrations showed a slight tendency to oscillate. The worms died when the concentrations within their bodies exceeded 100-120 ppm, calculated on a dry weight basis. The accumulation of methyl-mercury in the earthworm, Ei. foetida (Savigny) was investigated by Beyer et al. (1985) and its effect on regeneration after excision of the caudal end were also studied. They found that earthworms treated with 25 ppm or 125 ppm methyl mercury did not survive while the survival rates after 12 weeks were high and these were 97% in control, 92% in 1 ppm and 79% in 5 ppm. All surviving earthworms in the control regenerated but 29% of earthworms in 5 ppm group only healed without regenerating their tail end. Whereas Boudou and Ribeyre (1997) reported that the absolute concentration of total mercury and monomethyl mercury bioaccumulated in Ei. foetida were higher in the earthworm exposed to the higher mercury soils and lower in the less mercury contaminated soils. It is well known that metallic and inorganic mercury do not bioaccumulate in terrestrial organisms to the same degree as that of methyl mercury. Burton et al. (2006) investigated the rate of uptake and bioaccumulation of total mercury and mono-methyl mercury in Ei. foetida from the soil. The bioaccumulation factors for total mercury and mono-methyl mercury were larger in earthworms exposed to less contaminated soils and smaller in more mercury contaminated soils. Zhang et al. (2009) reported that Bioaccumulation factors of methyl mercury from soil to earthworms were much higher than those of
total mercury, which suggested that methyl mercury might be more easily absorbed by and accumulated in earthworms because of its lipid solubility.

Maenpaa et al. (2002) showed that the high phosphorous treatments significantly reduced lead, zinc and cadmium bioavailability to the earthworm due to formation of metal–phosphate complex in the soils. This amendment may therefore reduce ecological risk to soil-inhabiting invertebrates exposed to heavy metal contaminated soils although other soil characteristics also had an effect on the bioavailability of metals. Malley et al. (2006) reported that earthworm could provide an index for heavy metals that are present in the materials and are bioconverted, giving an indication of potential environmental hazard. The capacity of earthworm to store and redistribute heavy metals especially Cu and Zn in their body might lead to a balance between uptake and excretion which helps them to survive to certain extent in metal contaminated soil. Hobbelen et al. (2006) using a dynamic energy budget model (DEB-model) observed the dependence of Cu on the litter consumption by the earthworm *Lu. rubellus* as well as temperature and food density. So these induced effects should also be taken into account in the risk assessment of heavy metal pollution for the functioning of detritivores. Kızılkaya (2005) observed that the earthworm *Lu. terrestris* had the potential to accumulate significant levels of zinc, and thus earthworm ingestion may result in zinc transfer to higher trophic levels (e.g. various birds and small mammals). Twenty-one days after organic wastes treatment, the cast and earthworm bodies receiving the highest Zn dose showed significantly higher Zn content than the non-treated soil. At all Zn doses, earthworms from soils treated with organic wastes having high C/N ratio (wheat straw and hazelnut husk) had the highest Zn concentrations. In addition, the lowest bioaccumulation factor (BAF) value occurred in low C/N ratio of organic wastes. The effect of earthworm (*La. mauritii*) activity on mobility of Pb$^{2+}$ and Zn$^{2+}$ in the soil (DTPA-extractable) and its composting potential in the presence of these metals was investigated by Maity et al. (2008). It was observed that the metal burden in the earthworm tissue increased with the increase in metal treatment. *La. mauritii* elevated the soil pH of all the metal treated beds and lowered the soil C/N ratio in the cast by reducing the organic carbon and fixing additional nitrogen. Earthworm activity significantly increased the availability of phosphorous, potassium and concentration of Pb and Zn in earthworm’s tissues increased significantly with the increase in metal treatment and
decreased the amount of DTPA-extractable Pb\(^{2+}\) and Zn\(^{2+}\) in the cast, which implies the immobilization of metals in soils. These findings suggested the use of *La. mauritii* in amelioration of metal contaminated soil.

Liu *et al.* (2005) noticed that on incubation of the sewage sludge with *Ei. fetida* for 60 days, the contents of Cu and Cd in the earthworms increased with the increase of addition of Cu up to 250 mg/ Kg and Cd up to 10 mg/ kg. Bioconcentration factors (BCF) were higher than 1 only for Cd when the rate of addition was lower than 5 mg/ kg, which indicated that the earthworms could only accumulate Cd when the concentration of Cd was low in sewage sludge. Bioavailability of Cd and Cu to cabbage plants was evaluated by applying sewage sludge (with and without earthworm treatment) to soil. The results showed that earthworm treatment increased the biomass of cabbage and decreased the bioaccumulation of Cd and Cu in the cabbage plants.

The earthworms were grown in wood preserved with chromated copper arsenate (CCA) and alkaline copper quaternary (ACQ) and then treated with artificial rainwater, to generate leachates containing As, Cr and Cu. These leachates were then applied to two soils at the rates of As 13–169 mg /kg soil (dry weight basis), Cr 12–151 mg/kg and Cu 10–216 mg/kg. Metal bioavailability was evaluated after 28 days using the earthworm *Ei. foetida* (Savigny). Metal concentrations in earthworm tissue ranged from negligible to 80 mg As /kg (dry weight basis), 89 mg Cr /kg and 90 mg Cu /kg, which appeared to be non-lethal to *Ei. foetida*. There was less Cu available to earthworms in the Courval soil (pH 7.8) than the Chateauguay soil (pH 6.8), but earthworm growth and reproduction were not affected by exposure to Cu from ACQ-treated wood. In contrast, earthworms exposed to As, Cr and Cu from the CCA-treated wood gained weight more quickly in the Courval soil (1.3–21 mg/ g initial biomass days) than in the Chateauguay soil (0.2–7.8 mg /g / day). It was seen that less than 20% of the cocoons deposited by the faster-growing earthworms hatched by the end of the 56 days. It appeared that *Ei. foetida* could allocate more energy to growth than reproduction, delaying cocoon development and hatching in some situations (Leduc *et al.*, 2007).

During their investigation on the effect of two earthworm species, *Lu. rubellus* and *Ei. fetida*, on the fractionation /bioavailability of Pb and Zn before and after soil leaching with EDTA, Udovic and Lestan (2007) found that both the species actively
regulated soil pH, but did not significantly change Pb and Zn fractionation in remediated soil. Sivakumar and Subbhuaram (2005) reported the effects of Cr (III) and Cr (VI) on the survival, behavior, and morphology of the earthworm, *E. fetida*, in water at pH 6, 7 and 8 and their toxicity in 10 different soils and an organic substrate. A decrease in the pH of water resulted in increased toxicity of Cr to the earthworm. In water, both Cr species produced behavioral changes and morphological symptoms. The 48-h LC₅₀ values of Cr (III) at pH 6, 7, and 8 were 1.93, 2.55, and 2.78 mg/L, and those of Cr (VI) were 0.47, 0.61, and 0.63 mg/L, respectively. The 14-day median lethal concentrations (LC₅₀) of Cr (III) and Cr (VI) for earthworm ranged from 1656 to 1902 mg/kg for Cr (III) and from 222 to 257 mg/kg for Cr (VI) in soil. In the organic substrate, the LC₅₀ values of Cr (III) and Cr (VI) were 1635 and 219 mg/kg, respectively. Stepwise multiple regression analysis predicted that clay content of soils accounted for 92% and 88% of the variation in the LC₅₀ values of Cr (III) and Cr (VI), respectively.

The steady state and non-steady state kinetics of five metals, cadmium, copper, lead, nickel, and zinc in earthworms was studied by Neuhauser *et al.* (1995) in the fields. The worms from contaminated and uncontaminated sites were collected and measurements were made for concentrations of metals in the earthworms and soils. For each of the metals, evidence suggested that bioconcentration depended on the metal concentrations in the soil and bioconcentration was greater at lower metal concentrations. The studies of non-steady state kinetics involved uptake and elimination experiments in which worms were transferred from an uncontaminated soil to a contaminated soil (uptake studies) or from a contaminated soil to an uncontaminated soil (elimination studies). The voiding time was an important experimental variable in determining the levels of metals in earthworms because experimental measurements were usually made on a worm-soil complex (i.e. the soft tissue of the worm and the soil in the gut of the worm). Thus, for metals that were bioconcentrated in worm tissue, increase in the voiding period increased their concentration in the worm-soil complex. Conversely, for metals that were not bioconcentrated, increasing the voiding time led to a decrease in their concentrations in the worm-soil complex. Arnold *et al.* (2008) noticed that *Dendrodrilus rubidus* was able to tolerate significantly higher soil Cu concentrations and exhibited significantly less change in weight. Low viability and scanty cocoon production from the mine site
population prevented the determination of toxicity parameters in the F₁ generation so these could be used as an indicator of the cost of tolerance of the population.

Wei-bao and Hong-qiang (2008) elucidated role of earthworms and microbes in improving soil structure and controlling bioavailability of soil nutrients including heavy metals through bio-absorption, enrichment, precipitation, dissolution, and oxidation-reduction. The influence of salinity on partitioning of, uptake in and toxicity of zinc to earthworms was studied by Owojori et al. (2008) by exposing *Eisenia fetida* in the laboratory for 28 days in OECD artificial soil spiked with either NaCl (experiment 1) or a combination of Zn and NaCl (experiment 2). In the first experiment, NaCl was added in the following concentrations: 0, 1000, 2000, 4000, 6000 and 8000 mg/kg NaCl. Mortality, growth and cocoon production were assessed at day 28. The results showed 28-day LC₅₀ at 5436 mg/kg for NaCl. The EC₅₀s for growth and cocoon production were 4985 and 2020 mg/kg NaCl, respectively. In the second experiment, Zn was added as ZnCl₂ in a range of sub lethal concentration (0, 250, 500, 750 mg/kg Zn) and combined with 0, 2000 or 4000 mg/kg NaCl. Apart from the total zinc concentration in the substrates, DTPA and CaCl₂ extractable Zn concentrations were also determined at day 1 and 28 to assess how salinity influenced the partitioning of this metal in the substrates. There was a significant increase in CaCl₂ and DTPA extractable Zn in the substrates as salinity increased suggesting that salinity influenced the partitioning of Zn in the substrates. Weight and mortality of worms were not significantly affected by NaCl and Zn as individual substances, but in combination both had significant effects on the studied parameters. In contrast, cocoon production was significantly affected by increased NaCl and Zn administered as individual substances, and the effects were more severe when both substances were present together. It was concluded that an increase in salinity had an additive to synergistic effect on influencing the toxicity of Zn to these earthworms. Frank et al. (1983) noted slight increase in the metal contents in worm castings except for Cr and Zn over the worm feed mixture. This could be explained by the fact that organic matter was being reduced on passage through the gut of worms but actually worms did not appear to bioaccumulate metals within their tissue. Elvira et al. (1998), Deolalikar et al. (2005), Sangwan et al. (2008), Kaur et al. (2010) and Singh et al. (2010) reported an increase in heavy metal content in the vermicompost of paper mill sludge. The increase was more appreciable for Fe and Cu. The weight and volume
reduction due to breakdown of organic matter during vermicomposting might have been the reason for increase in heavy metal concentrations in vermicompost. A 2% increase in Cu and a decline in the concentration of Mn, Zn and Pb in vermicompost were reported by Khwairakpam and Bhargava (2009b).

2.8 Suitable materials for vermicomposting

The cow slurry was more efficient in promoting earthworm growth than mixture of slurry with other solid wastes. The presence of *Ei. foetida* increased the nitrate-nitrogen content of the substrate with very little animal mortality (< 44%) (Hand *et al.*, 1988). Kale *et al.* (1982) reported enhanced decomposition of cellulose and lignin present in agricultural waste and sugarcane trash by *Eu. eugeniae* and *Pe. excavatus*. Senapati *et al.* (1985) found a considerable increase in decomposition of domestic garbage by *La. mauritii* for 75 days. Percentage decomposition of the garbage was 36% without earthworms and 54% in the presence of earthworms. The C/N ratio decrease was also more in the experiments with worms. Haimi and Hutha (1986) mixed miscellaneous wastes and activated sewage sludge with sieved pine bark and observed that *Ei. fetida* Savigny had the capacity to maintain the required biomass for a long period. Wastes were converted into odourless castings of good physical structure if sufficient population was present from the beginning and fresh waste was added regularly. The earthworms accelerated mineralization rate and converted the animal wastes into castings with a higher nutritional value and degrees of humification. When the castings of *Ei. foetida* from sheep manure alone and mixed with cotton wastes were compared with the same manures in the absence of earthworms. The castings obtained from manure mixed with cotton wastes exhibited good agronomic quality, suggesting that the worms could be used for recycling nutrients from such wastes (Albanell *et al.*, 1988).

Suitability of a variety of wastes like cow dung, poultry manure, horse dung, pig manure and sugarcane trash was studied by Jambhekhar (1992). Their results revealed that C/N ratio of earthworm treated wastes decreased to 15:9 as compared to 31.1 in an untreated waste within one month, and was further reduced to 12.0 after 45 days. Worms could not survive in fresh cattle solids, pig solids, fruit wastes and vegetable wastes, however, their growth in pig wastes was faster than in cattle solids. A variety of different residual bulking agents (paper, cardboard, grass clippings, pine needles, saw dust and food wastes) have been used for vermicomposting when mixed
with sewage sludge. Maximum weight and highest growth rate was attained in the mixture with food waste (755 ± 18 mg and 18.6 ± 0.6 mg/day respectively) whereas, the smallest size and the lowest growth rate was achieved in the mixture of sewage sludge with sawdust (572±18 mg and 11±0.7 mg/day respectively) (Bonkowski and Schaefer, 1997).

Vermicomposting of mustard residue and sugarcane trash mixed with cattle dung resulted in a significant reduction in carbon to nitrogen ratio and increase in mineral nitrogen, after 90 days of composting with *Ei. foetida* (Bansal and Kapoor, 2000). Chaudhuri and Bhattacharjee (2002) studied the biomass production and reproduction of *Pe. excavatus* in cow dung mixed with paddy straw, bamboo leaf litter and kitchen wastes. Maximum rate of biomass increase and reproduction was noticed in the mixture with paddy straw and bamboo leaf litter and it was minimum in the feed containing kitchen waste. Cow dung was found to be marginally better than kitchen waste containing feeds. Attempts have been made to convert different weeds like Taro (*Colocasia esculenta*), Water hyacinth and Salvinia into vermicompost by different workers (Abbasi and Ramasamy, 2001; Gajalakshmi et al., 2002a and 2002b; Kurien and Ramasamy, 2006). Gunadi and Edwards (2003) also found that the multiple additions of substrates prolonged the fecundity of worms, but there was a decrease in weight of worms after 60 weeks of the experiment. Castillo et al. (2005) studied the influence of earthworm *Ei. anderi* on different waste mixtures like Pine sawdust + Poultry litter (M1), Cotton industry + Poultry litter (M2), Shredded paper + Horse manure (M3) and Cotton industry + Poultry litter (M4). They noticed that earthworm biomass decreased in M1 and M2 and increased in M3 and M4. The earthworm activity was more in M3 but M4 had the best chemical and physical properties. Garg et al. (2006) also found that *Ei. foetida* lowered pH, electrical conductivity, potassium and C: N ratio and enhanced nitrogen and phosphorus contents of cow, buffalo, horse, donkey, sheep, goat and camel manures. Total K was lower in the final cast than in the initial feed. C: N ratios of the vermicomposts ranged from 16.2 ± 2.17 to 75.4 ± 6.84. Microbial activity measured as dehydrogenase activity in buffalo, donkey and camel wastes increased with time up to day 90. But in sheep and goat wastes, maximum dehydrogenase activity was recorded on day 60 and then it decreased there after. The highest number and biomass of hatchlings was recorded in horse excreta followed by cow, goat and sheep excreta. Pramanik et al.
(2007) studied the vermicomposting of different organic waste like cow dung, grass, aquatic weed, municipal solid waste with lime and microbial inoculant. They found that cow dung was the best substrate for vermicomposting while addition of lime and inoculation of microorganism increased the nutrient content in vermicompost.

Tognetti et al. (2008) highlighted that cocomposting of municipal organic waste (MOW) and biosolids was an important alternative for MOW management, as it increased product degradability and nutrient release capacity (highest net N and C mineralization, extractable-P release, and microbial biomass-N). Shredding MOW increased C mineralization, while the addition of wood shavings decreased net N mineralization, but generally did not affect C mineralization. Sellami et al. (2008) investigated the co-composting of exhausted olive-cake with poultry manure and sesame shells. These organic solid wastes were watered by the confectionary waste water having high COD due to high content of residual sugars. The stability of the biological system was noticed after 70 days. The final products were characterized by their relatively high organic matter content, and low C/N ratio in the range of 14–17. The humidification of the windrows with the wastewater seemed to have accelerated the composting process in comparison to a windrow humidified with water. In addition, the organic matter degradation was enhanced to reach 55–70%.

2.9 Industrial waste

Vermicomposting has not been fully adopted for management of industrial solid wastes (Domínguez et al., 1997) the major problem being that most of the times industrial organic residues require pretreatment before being vermicomposted as they may contain substances that are toxic for earthworms (Nair et al., 2006). To obtain stabilized end products appropriate for agricultural purposes, industrial sludge needs to be mixed with other nitrogen-rich organic wastes in order to provide nutrients and an inoculum of micro-organisms to carry out the degradation efficiently (Hartenstein, 1978; Butt, 1993; Elvira et al., 1997, 1998; Jeyabal and Kuppuswamy, 2001, Kaur et al., 2010; Singh et al., 2010). Since the temperature is always in the mesophilic range, pathogen removal is not ensured (Domínguez et al., 1997) although some studies provide evidence. A detailed review of recycling industrial sludges and industrial effluents with the help of vermicomposting is documented in the following sections.

2.9.1 Industrial Sludge
India produces on average 270 million tones of sugar cane per year. During the production process of sugar byproducts such as pressmud, bagasse and trash are produced. During the transformation of sugar mill sludge amended with biogas plant slurry into vermicompost by an epigeic earthworm *Ei. fetida*, Sen and Chandra (2007) reported a rapid decrease in C: N and lignocellulosic (lignin, cellulose, hemicellulose) content in the vermicompost during early phase of the process. Aromatic and carbomyl groups showed an initial increase followed by a decrease after 40 days indicating extensive mineralization during final stages of vermicomposting. Laxmibai and Vijayalakshmi (2002) observed that *Eu. euginae* was ideal for sugar factory waste management as it helped in biocconversion of the waste in a shorter period of time. Sangwan *et al.* (2008) noticed a decrease in pH, TOC, TK and C: N ratio and an increase in TKN and TP of vermicompost from sugar industry sludge mixed with cow dung. They inferred that addition of 30–50% of PM with BPS had no adverse effect on the fertilizer value of the vermicompost as well as on the growth of *Ei. foetida* after 90 days. Suthar (2008) found a significant decrease in pH (7.9-19.2%), organic carbon (8.5-25.8%) and an increase in total nitrogen (130.4-170.7%), P (22.2-120.8%), K (104.9-159.5%), Ca (49.1-118.1%) and Mg (13.6-51.2%) in the vermicompost from distillery sludge. Maximum mortality, growth rate and reproduction rate were observed respectively in the mixtures with 80%, 20% and 40% sludge. Suthar and Singh (2008b) mixed distillery industry sludge and cow dung in different proportions and composted it with *Pe. excavatus* for 90 days. The worms showed capability to accumulate a considerable amount of metals in their tissues from the substrate. Rate of biomass gain, growth (mg weight/ worm/ per week) and cocoon production was maximum in the mixture with 40% sludge and minimum in the mixture with 80% sludge. Vermicomposting significantly reduced the pH of substrates at the end (P<0.01), the reduction was maximum in 60% sludge (~19.5% than initial), and minimum in 80% sludge (~10.5%).

Subramanian *et al.* (2010) examined the temporal changes in physico-chemical properties during vermicomposting of sago industry waste by earthworm *Ei. fetida*. The result revealed that vermicomposting of sago wastes, cow dung and poultry manure mixed at equal proportion (1:1:1) produced a superior quality manure with desirable C: N ratio and higher nutritional status than composting. The study
suggested that the sago industry solid waste could be effectively converted into highly valuable manure that can be exploited to promote crop production.

Butt (1993) observed that paper mill sludge had no deleterious effects on *Lu. terrestris* although worm growth rate was poor. The low level of nitrogen (<0.5%) was considered a limiting factor. By the addition of spent yeast from the brewing industry, the C: N ratio of this sludge was adjusted in the mixture with 66 parts paper mill waste and 1 part spent yeast. *Lu. terrestris* grew from the hatching stage (50 mg biomass) to maturity (3-4 g biomass) within 90 days with a low level of mortality. Elvira *et al.* (1996) found that 3:1 mixture of paper pulp mill sludge and primary sewage sludge was suitable medium for optimum growth and reproduction of *Ei. anderi*. They noticed that presence of earthworms accelerated mineralization of organic matter, favoured breakdown of structural polysaccharides and increased humification rate.

When paper mill sludge (PS) was mixed with sewage sludge (SS), pig slurry and poultry slurry in different ratios by Elvira *et al.* (1997) the mixture of 3:2 (PS: SS) ratio resulted in the highest growth rate and the lowest mortality of *Ei. anderi*, whereas, paper mill sludge mixed with pig slurry exhibited highest mortality. High mortality was not due to lack of food but the polysaccharide breakdown modified the structure of the substrate so that water retention capacity decreased and in turn increased worm mortality. However, when Elvira *et al.* (1998) mixed paper-pulp mill sludge with cattle dung at pilot-scale there was a 22 fold increase in earthworms number and 2.2 to 3.9 fold increase in worm biomass in different feed mixtures. The vermicompost was rich in nitrogen and phosphorus and had a good structure. Although concentrations of metals were higher in the product than the initial substrates. These increases were more appreciable for Fe, Zn and Ni in the control treatment. The total potassium concentration in the initial substrates had decreased significantly by the end of vermicomposting period. Further during 1999, Elvira *et al.* observed that the feed mixtures with 30% (dry wt.) of paper mill sludge and 70% cow manure were most favourable for vermicomposting. Banu *et al.* (2001) indicated that 25% concentration of paper mill sludge with standard bedding material (*Mangifera indica* foliage (40%) + cow dung (40%) + Saw dust (20%)) was ideal for *La. mauritii, Eu. eugeniae* and *Ei. foetida* but *Ei. foetida* proved to be the best for management of this sludge.
Mixture of paper, cardboard and sewage sludge the earthworms had much higher reproductive rates (2.82 ± 0.39 and 3.19 ± 0.30 cocoons earthworm⁻¹ week⁻¹ respectively) in comparison to sewage sludge alone (0.05 ± 0.01 cocoons earthworm⁻¹ week⁻¹). They found that only the mixture of sewage sludge with food waste showed a significantly higher growth rate than the control (sewage sludge alone) which might have been due to an increase in the amount of microorganisms that provided a suitable nutrient source. The marked differences between rates of cocoons production in different mixtures was related to the quality of the bulking agent (Dominguez et al., 2000).

Ndewa et al. (2000) tested four stocking densities of Ei. fetida and three feeding rates for degradation of biosoilds. A stocking density of 1.60 kg worms/m² and a feeding rate of 1.25 kg feed/kg-worm/ day resulted in the highest bioconversion of the substrate into earthworm biomass. The best vermicompost was obtained at 1.60 kg worms/m² and a feeding rate of 0.75 kg-feed/ kg-worm/ day. Ndegwa and Thompson (2000) extended the study and found that this stocking density and feeding ratio resulted in the best fertilizer-value of the product, with the lowest potential for environmental pollution. Marsh et al. (2005) fed mixture of shredded solids removed from aquaculture effluent and aquaculture sludge to the worms and noticed an increase in growth rate with increasing sludge concentration, with a highest growth rate in 50:50 mixture.

Solid textile mill sludge could be potentially useful as a raw substrate in vermicomposting if mixed with 30% cow dung (Kaushik and Garg, 2003). The author observed that Ei. fetida resulted in a significant reduction in C: N ratio, an increase in TKN and total P and a decrease in total K and Ca in the final product as compared to the initial feed mixture. Microbial activity measured as dehydrogenase activity increased up to 75 days and decreased on further incubation. Total heavy metal contents were lower in the final product than the initial feed mixture. Further in 2004, Kaushik and Garg mixed solid textile mill sludge, cow dung and agricultural wastes and fed it to Ei. fetida for 11 weeks in the laboratory under controlled environmental conditions. They found that worms grew and reproduced favourably in 80% cow dung + 20% solid textile mill sludge and 70% cow dung + 30% solid textile mill sludge. Addition of agricultural residues had adverse effects on growth and reproduction of worms. However, when textile mill sludge was spiked with poultry droppings Garg
and Kaushik (2005) recorded that replacement of cow dung with poultry droppings had little or no effect on worm growth rate and reproduction potential as worms grew and reproduced favourably in 70% poultry droppings (PD) + 30% solid textile mill sludge and 60% PD+ 40% textile mill sludge. Vermicomposting resulted in a significant reduction of C: N ratio and an increase in nitrogen and phosphorus contents. Total potassium, total calcium and heavy metals’ (Fe, Zn, Pb and Cd) contents were lower in the final products than the initial feed mixtures.

Ghatnekar et al. (2002) converted fly ash generated at a thermal power plant by Lu. rubellus into vermicompost. Bhattacharya and Chattopadhyay (2002) found that the concentration of phosphate solublizing bacteria increased many fold in the Ei. fetida treated fly ash compared with the series without earthworms. Among different combinations of fly ash and cow dung, phosphorous availability was found to be significantly higher in the 1: 1 mixture. Singh et al. (2005) found a linear relationship between the ash content and time in the effective range of the vermicomposting duration. The model parameters of this linear relationship also had linear correlation with the moisture content. The study showed that a moisture content of 80% was optimum for stabilization of the waste in a shortest possible time. Fang et al. (1998) found that the enzyme activity of microbes decreased with composting time while beta-glucosidase and alkaline phosphatase activity decreased with an increase in ash residue. Singh et al. (2010) observed that minimum mortality and maximum population build up of Ei. fetida were observed in 50:50 mixture of biosludge of beverage industry and cattle dung. Nitrogen, phosphorous, sodium, transition metals and pH increased, while electrical conductivity, organic carbon and potassium declined in all the mixtures with worms in comparison to the mixtures subjected to traditional composting. Degradation of 50:50 mixture was achieved in 75 days when worms were inoculated at 25 g/kg feed mixture but the best quality product was obtained after 105-110 days with 7.5 g worms/kg feed mixture.

Yadav and Garg (2010) reported the recycling of nutrients by vermicomposting of cow dung (CD), poultry droppings (PD) and food industry sludge (FIS) employing earthworms (Eisenia fetida). The earthworms have good biomass gain and cocoon production in all vermicomposting units but the waste mixture containing 50% CD + 25% PD + 25% FIS had better fertilizer value among studied waste combinations.
2.9.2 Treatment of effluents

Athanasopoulos (1993) treated anaerobically stabilized effluents of dried vine fruit industry with *Lu. rubellus* and found that up to 0.2 Kg COD/m$^2$d loading, the reactors responded well for an operation period of 15 months i.e when the experiments ceased. COD removal was 95 % for loadings of 0.10 and 0.15Kg COD/m$^2$d. Earthworm biomass was in its upper bearing capacity of approximately 2 Kg/m$^2$ and did not increase seriously with time. Temperature change did not have any counter effect on the process.

However, on using vermicompost as a filter, Pereira et al. (2003) observed reduction of metal concentration in synthetic sample and real sample (mineral water) with Cd concentration of 5 micro gram per litre. It was due to a great number of adsorption sites on humic substances present in the vermicompost. Matos and Arruda (2003) reported that pH in the range of 2.0-5.0 was required for removal of metals when vermicompost was used as natural adsorbent for removing metal ions from laboratory effluents. High adsorption capacity for metals was due to presence of negatively charged functional groups, such as carboxylic acid, phenolic and alcoholic hydroxyls in the humic acid. In 2007, Jordao et al. found that the removal of metals Cu, Ni and Zn from the electroplating effluent was 50-60% when it was passed through vermicompost, with increase in pH of the effluent the metal retention values were close to 100%. Cu concentrations in lettuce leaves grown with this vermicompost enriched with the metal were below the range of critical toxicity level to plants, i.e., from 20 to 100 mg/ L. However, the estimated Cu concentrations in the roots were much larger (reaching 246.3 mg/ L) than that of the natural vermicompost.

Jordao *et al.* (2008) reported that the adsorption of Zn (II) from both synthetic solution and kaolin industry waste water by cattle manure vermicompost was dependent on various operating variables viz., solution pH, and particle size of the vermicompost, mass of vermicompost/unit volume of the Zn (II) solution, contact time and temperature. The optimum conditions for Zn adsorption were pH 6.0, particle size of ≤ 250 m, 1 g per 10 ml adsorbent dose, contact time of 4 h and temperature of 25 °C. Langmuir and Freundlich adsorption isotherms fitted well in the experimental data and their constants were evaluated with $R^2$ values from 0.95 to 0.99. In synthetic solution, the maximum adsorption capacity of the vermicompost for Zn$^{2+}$ ions was 20.48 mg/ g at 25 °C when the vermicompost dose was 1 g per 10 mL
and the initial adjusted pH was 2. The batch adsorption studies of Zn (II) on vermicompost using kaolin waste water have shown that the maximum adsorption capacity was 2.49 mg/g at pH 2 (natural pH of the waste water). Martin-Gil et al. (2007) have studied the composting and vermicomposting of asphaltenes from the prestige oil spill. Result revealed that by microorganisms living in either earthworm intestine or vermiculure substrate degraded and eliminated the polycyclic asphaltenes into CO₂ and H₂O and helped in their evaporation and resulted in purification of water.

Sun et al. (1998) designed the filtration system which combined sedimentation, soil infiltration and biofilm processes, to treat domestic waste water from toilet, bathroom and restaurant. The system was found to be excellent with the removal rates of 92.6, 97.6, 86.8 and 81.72% for chemical oxygen demand (COD), biochemical oxygen demand (BOD₃), suspended solid (SS) and NH₄⁺-N, respectively. The effluent of the system was good for watering lawns, flush roads or rinse toilets. Taylor et al. (2003) quantified the effect of filter bed depth and solid waste inputs on the performance of small-scale vermicompost filter beds that treated the soluble contaminants in domestic waste water. The study also evaluated environmental conditions within the filters by quantifying the oxygen content and pH of the waste water held within it. Small-scale reactors were designed to enable waste water sampling at five reactor depths in 10-cm intervals. The extent of denitrification was found to be a function of BOD leached from the solid waste. The environmental conditions measured within the bed were found to be suitable for earthworms living within them.

Gonzalez-Martinez et al. (2007) reported the highest removal of total and dissolved COD values were 81 and 84%, respectively in municipal wastewater. For TSS the best removal value was 95%. Up to 75% ammonia removal was achieved at the lowest organic load of 0.8 kg COD/m³ d. Ammonia removal decreased to 36% with a higher organic load of 1.6 kg COD/m³ d. Hughes et al. (2007) reported the buffer capacity of a vermicompost + manure media and concluded that it had a high buffering capacity for pH. The toxicity after the buffer capacity experiment showed that the key species could survive between pH levels of 6.2 and 9.7. At the higher and lower pH levels, however, the survival of juveniles was impaired, probably due to their ability to uptake greater amounts of soluble salts and inability to regulate them.
Li et al. (2008) investigated the use of vermifiltration in management of swine waste water treatment. A reduction in ammonia emission was observed of about 50% for the whole system during vermifiltration than the conventional breeding on a slatted floor. Sinha et al. (2008) reported that earthworms body acted as a biofilter and there was a reduction of 5 days BOD by over 90%, COD by 80-90%, total dissolved salts by 90-92% and TSS by 90-95% of the waste water. They suggested that this generally happened by the ingestion and biodegradation of organic wastes, heavy metals and solids from waste waters as well as their adsorption through the body wall. Hughes et al. (2009) investigated to assess the toxicological risks from sodium accumulation in a vermifiltration wastewater treatment system to the key worm species, *E. fetida*. The study found that sodium chloride (NaCl) was the more toxic of all the common sodium salts found in wastewater to the worms. The research further found that the worms had an ability to detoxify NaCl although reproduction was impaired if the worms are exposed to moderate concentrations of NaCl for a long period of time. The actual risk from NaCl toxicity in the vermifiltration process was low due to the low solid-water partitioning constant of NaCl, which led to a very low predicted environmental concentration (PEC) for NaCl.

Jenssen et al. (2010) reported the removal of organic matter [measured as biochemical oxygen demand (BOD)] 80%, total phosphorus (TP) less than 94% and total nitrogen (TN) ranged from 32 to 66%. The investigation revealed that the majority of the BOD and nitrogen removal occurred in the pre-treatment filters and the phosphorus and bacteria removal was more prominent in the saturated filters. Wang et al. (2010) reported that the average removal rates of COD, BOD, ammonia nitrogen (NH₄⁺-N) and phosphorus by the vermifiltration system were 78.0%, 98.4%, 90.3% and 62.4%, respectively at a hydraulic loading rate of 4 m³ m⁻² day⁻¹. Vermifiltration was effective for removal of insoluble organic matter and suspended solids whereas the converter slag–coal cinder filter played an important role in phosphorus removal.

Xing et al. (2011) studied the reduction and stabilization of sewage sludge during the clarification of municipal waste water by vermifiltration using an epigeic earthworm *E. fetida*. It was observed that the sludge yield of the CVB (Ceramsite Vermibed) ranged from 0.07 to 0.09 kg SS/kg COD removed at ambient temperature of 4–29 °C, representing 81% and 50% lower than that of the SVB (Quartz sand
Vermibed) and other reduction systems mentioned in this study. In addition, the sludge morphology variations described that the vermicast sludge from the CVB was more completely digested by earthworm than that of the SVB. The abrasions of the body wall of the earthworms in the CVB depicted less injured than that of in the SVB. So the ceramsite as filter media was better suited for the vermicfiltration than the quartz sand.

The literature shows that hardly any work has been done on the effect of stocking density of earthworm on the rate of biodegradation of the waste and physico-chemical characteristics of the products. No report is available on the use of vermicompost as a biofilter for remediation of industrial effluent. Therefore there is a dire need for exploiting earthworms for an integrated strategy for bioremediation of solid as well as liquid wastes of various industries.