Recent overview on reuse and biotransformation of industrial sludge into organic fertilizer through vermicomposting

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Abstract

Currently, industrial sludge is generated in large amount annually. Industrial sludge is a solid or semi-solid material consisting of all compounds removed from the wastewater, as well as any substances added into the biological and chemical operation units during the treatment process. The composition of the sludge may vary considerably. Furthermore, distinctive treatment and disposal methods are necessary as sludge produced from different industries would have different characteristics. Therefore, processing and disposing of industrial sludge is a challenging and complex environmental problem. Landfilling, incineration and agricultural land application are the three most commonly employed methods for disposing industrial sludge. Among the three methods, agricultural land application is a convenient and economic disposal alternative for industrial sludge. However, industrial sludge could have high putrescible content and pathogenic hazards, which might threaten soil quality, crop yield and subsequently contaminate human food chain. One possible way to ensure that the industrial sludge could be reused on agricultural land is by conditioning and stabilizing the sludge using a pretreatment process. One of the pretreatment processes which could be used in this context is vermicomposting. Vermicomposting is an alternative for biological stabilization of organic wastes, with an addition of earthworms. Through vermicomposting, industrial sludge could be transformed into matured organic fertilizer or vermicompost in a shorter period of time. Thus, this paper reviewed the recent literature on utilizing vermicomposting process to manage industrial sludge in order to assess the feasibility of this technology. The present review would also provide a brief overview on the production and treatment methods of industrial sludge.

1 Introduction

Industrial sludge is one of the main by-products produced from the treatment of industrial water or wastewater and it is generated in large amount annually. Industrial sludge can be generated from wastewater treatment processes of numerous industries such as pulp and paper, chemical manufactures, power plants, cement manufactures, tanneries, food processing, oil refineries and other. The particulates and colloidal matters are concentrated to form industrial sludge. The sludge is a solid or semi-solid materials, consisting of all the compounds removed from the wastewater, as well as any substances added into the biological and chemical operation units during the treatment process [1]. Industrial sludge are also riddled with contaminants such as: 1) inorganic contaminants (metals and trace elements); 2) organic contaminants (polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins/furans (PCDD/Fs) and surfactants); and 3) microbial pollutants (pathogenic bacteria, viruses, protozoa and parasitic helminthes). In cases where industrial sewage system is combined with municipal sewage system, sludge produced may have higher heavy metals or soluble organic matter content [2, 3]. In addition, the industrial sludge composition may vary considerably, depending on the wastewater qualities and treatment processes [4]. Sludge produced from different industries would have different characteristics, which require distinctive treatment and disposal methods [5]. Therefore, processing and disposal of industrial sludge is a challenging and complex environmental problem.

Legislation has been enacted to prevent the dumping of organic materials such as wastewater sludge into the ocean [6]. Hence, finding a way to dispose the sludge that would not permanently damage the environment is always the challenge in achieving sustainable sludge management [7]. Currently, the three most common disposal methods of industrial sludge are landfilling, incineration and agricultural land application [7, 8]. Other innovative disposal technologies like pyrolysis, wet oxidation and gasification are still far from commercial application in the European region [9].

Landfilling of industrial sludge has been the most widely used disposal method in the world. It is the simplest, cheapest and cost-effective as compared to other disposal methods [10]. However, the poor physical nature of industrial sludge should be well stabilized and dewatered before disposing the sludge to landfill. Stabilizing and dewatering process of the sludge help to reduce the emission of odour, gas such as methane and percolating water. Industrial sludge is recommended to have a minimum solid fraction of 25% before it can be disposed to landfill for easy handling. However, the diminishing availability of landfill space and more stringent environmental standards are making landfilling an unsustainable disposal method. Moreover, most European countries have banned landfilling and are looking towards to more environmental friendly disposal methods [2].

Incineration of industrial sludge involves combustion of the sludge at high temperatures. Currently, incineration is not the most popular sludge disposal method, but with technology advancement, the global employment of incineration in sludge management will increase in the future [11]. By utilizing incineration technology, the sludge volume could be reduced significantly and pollutants (pathogens and toxic organic chemicals) could be destroyed thermally [2]. The ash residual which is produced from incineration process could be thought as a mineral and deposited at a central location. Nevertheless, handling and disposal of the ash residual do incur additional costs. The major concern of incineration is the water content in the industrial sludge. The sludge is suggested to be dewatered to water content of less than 50%, so that enough energy could be produced to make the incineration process self-sustaining. However, no process to date has been able to achieve this without the use of chemical conditioning or an immense use of energy, which in turn making the process unsustainable [7, 12]. There are also concerns over emissions of pollutants (dioxins and furans), release of heavy metals and cost of treatment of flue gases for thermal processes [9].

Of the three disposal methods, agricultural land application is a more preferable option as industrial sludge is a valuable source of nutrients and contains high organic matter content that favors crop growth [5, 7]. Generally, recycling and reuse of wastes are preferred for sustainable development over landfilling or incineration [2]. Both incineration and landfilling destroy the potential of reutilizing the organic matter and plant nutrients which are found abundant in the sludge. Land application of industrial sludge is a convenient and economic disposal alternative. It also reduces the use of inorganic fertilizer [13]. Overall, agriculture land application of sludge results in lower global warming potential effect compared to other disposal processes [12]. However, industrial sludge could have high putrescible content and pathogenic hazards [4]. Certain pollutants could also be present in industrial sludge that can threaten soil quality, crop yield and subsequently contaminate human food chain [5]. In addition, sufficient land areas are required to meet the continuous increases of industrial sludge productions. Also, the uncontrollable application of nutrient rich wastes such as industrial sludge can cause overfertilization, ammonia toxicity, accumulation of heavy metals in the soil, increase in soil alkalinity, ground water pollution and establishment of anaerobiosis and anoxic decomposition pathways [14]. Thus, there is a need to limit sludge application in terms of quantity as well as frequency on agricultural land.

One possible way to ensure that the industrial sludge could be reused on agricultural land is by integrating with other sludge treatment technologies or stabilization process for volume reduction, odour controls, higher pathogen and toxic compounds removal. Treatment technologies such as thermal drying, composting, thermophilic anaerobic digestion, autothermal thermophilic aerobic digestion and lime treatment could be used [9, 15]. Composting is one of the best known and low cost technologies for biological stabilization of organic wastes [16, 17]. This process is well established and applied widely to organic waste management [14]. Composting is a biological and stabilization of organic wastes by microorganisms, usually under warm, moist and aerobic conditions. The final product (compost) is stable and can be applied to land without negatively affecting the environment. Pathogenic organisms and undesirable weed seeds are destroyed during thermophilic temperature phase achieved in a composting process [18]. Composting helps in recycling nutrients by returning them back to the soil through its use in landscaping, agriculture and horticultural [10]. One of the major challenges with composting process is maintaining aerobic conditions. Proper aeration, specifically oxygen is needed for aerobic metabolism and respiration of microorganisms as well as oxidizing organic molecules present in the moisture. Aeration provides sufficient oxygen for aerobic microbes which leads to a rapid composting process. Aeration can be improved by distributing the sludge, mixing with high proportion of coarse material such as green waste or mechanically agitating the sludge. Mechanical mixing requires high energy input due to the viscous nature of the sludge [19]. The loss of NH_3 during the thermophilic stage of the process is also one of the major drawbacks in the composting process [14].

An alternative to composting process is the vermicomposting process. Similar to composting, vermicomposting also involves stabilization of organic wastes but with the addition of earthworms. In vermicomposting process, earthworms and microorganisms are working together to decompose the organic wastes [10]. Earthworms are the process drivers to condition the substrate and alter biological activity whilst microorganisms are responsible for the biochemical degradation of organic wastes [20]. Unlike the composting process, vermicomposting does not require any mechanical mixing to ensure proper aeration due to the presence of earthworms. Earthworms create burrows naturally as they move throughout the soil. They enhance the accessibility of the sludge bed to air which allows oxygen to flow in. The burrows are pathways for water and particle movement as well as nutrient flow and aeration [19, 21]. Past studies revealed that both municipal and industrial sludge were excellent food for the earthworms with the right moisture content and suitable proportions of organic wastes [22, 23]. Neuhauser et al. [24] showed that activated sludge was superior than both horse and cow manure as food for the earthworm species, *Eisenia foetida*. The earthworm grew 1.7

times more rapidly in sludge as compared to manure largely due to its higher nutrient content and microbes in the sludge. The texture of the organic fertilizer (or vermicompost) produced from the vermicomposting process was finer and the heavy metals were found accumulated in the earthworm bodies [16, 17]. Also, the produced vermicompost could enhance the soil fertility physically, chemically and biologically [25]. Thus, this paper will focus on the formation of industrial sludge, the typical treatment methods of sludge and potential use of vermicomposting process in transforming the industrial sludge into organic fertilizer by the earthworms.

2 Industrial Sludge

2.1 Formation of Industrial Sludge

In general, sludge is made up of solids of different sizes produced at different stages of wastewater treatment. It is the settleable byproducts generated from preliminary treatment, primary treatment, secondary treatment or advanced treatment of wastewater treatment processes [5]. Subjecting to the nature of the treatment processes, industrial sludge can be categorized into primary sludge, secondary sludge, activated sludge or digested sludge. Sludge produced from different treatment processes or different unit operations has different characteristics. Table 1 shows the typical characteristics of different sludge. On the other hand, Figure 1 shows the sludge generation points of a typical wastewater treatment scheme.

Table 1 Typical characteristics of sludge

Sludge	Solid Fraction (%)	Characteristics
Primary (raw)	4 – 8	Gray-brown, odorous, vile, and mechanically dewaterable
Activated sludge	1 – 2	Yellow-brown, little odor, and high biological activity
Aerobically digested	2 – 4	Yellow-brown
Anaerobically digested	6 - 8	Black, little odor, musty, and drain well on drying bed

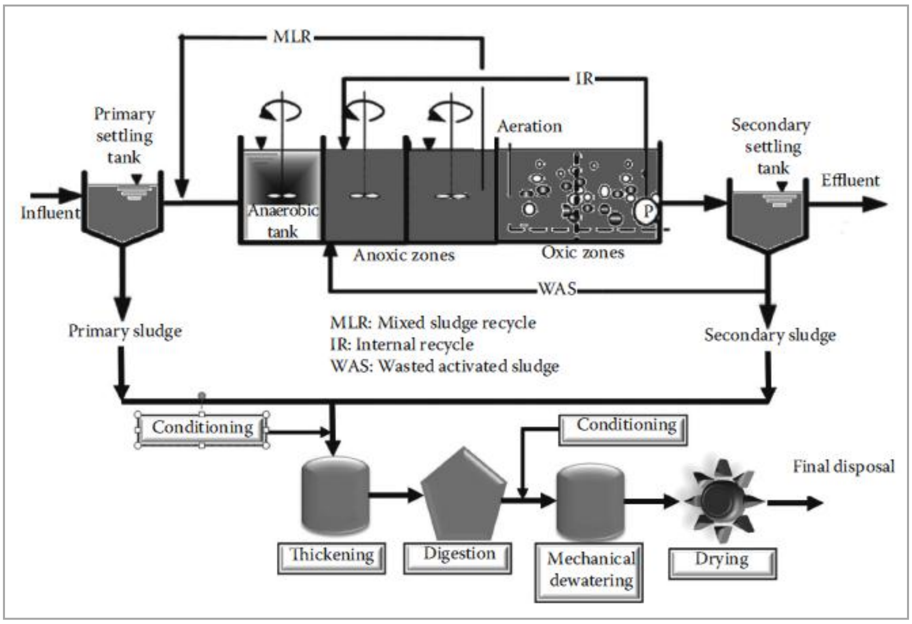

Fig. 1 Sludge generation points of a typical wastewater treatment scheme [26]

Primary sludge is produced from the primary treatment in the industrial wastewater treatment plant. It is a simple process used for removing the settleable solids in the stream. Primary sludge is grey in colour, strongly odorous and consisted of a high percentage of organic matters. Primary treatment is normally comprised of a mechanical process, in which the sediments are removed by the physical treatments. Solid content in primary sludge could range from 2 to 7%, depending on the wastewater qualities. The most commonly used physical treatment is sedimentation process, where gravitational force is utilized in separating the particulates and suspended solids from the liquid [27]. Primary sludge resulted from physical treatment can be relatively easy to dewater because it is consisted of distinct particles and debris, which will contribute to fairer solids capture with low conditioning necessities [26]. Removal efficiency of suspended solids in the primary treatment could be affected by several causes, including side streams of the treatment process and mechanical factors of the equipments such as poor flow distribution. On the other hand, concentration of primary sludge is affected by the factors such as the type of solids in the raw wastewater stream and the withdrawal frequency of sludge from the primary unit operations. When the primary sludge is removed less regularly from the primary settling tanks, it is left to be thicken further, thus increasing the concentration of primary sludge [26]. However, long detention time of sludge in the tanks is always the main cause of unpleasant odours generation.

Secondary sludge is generated from the secondary treatment, or biological treatment, of wastewater treatment process. It is the excess solids or sludge removed from the concentrated suspension settled at the bottom of settling tank in secondary treatment system. Removal of excess sludge is carried out in order to conserve the ratio of food to microorganisms in the biological treatment system in balance [28]. Secondary sludge is usually consisted of biological solids and biomass produced by microorganisms during the biological process as well as some inert materials. It also contains the non-biodegradable inorganic solids and heavy particles that are not removed in the primary treatment system. Secondary sludge can also be termed as biological sludge or waste activated sludge [26, 27]. It is normally brownish and has an unobjectionable earthy smell. Secondary sludge can be produced from different biological processes, including activated sludge process, membrane bioreactors and trickling filters [26]. Hence, the characteristics of sludge produced from secondary settling might vary with the type of biological process [16]. Secondary sludge contains solids concentration of 6-8% in dry solids weight. Nonetheless, secondary sludge is harder to be dewatered as compared to primary sludge due to the presence of light biological flocculent precipitates [26].

Another byproduct produced from secondary treatment of the wastewater treatment process is the activated sludge. Specifically, activated sludge is produced from the activated sludge process employed in the secondary treatment system. The process is suitable to be employed at industries that generate organic chemical waste, such as oil refineries, pulp and paper mills, food processing plants and chemical manufacturing plants [29]. Activated sludge process is an aerobic biological treatment process where biological floc consists of microorganisms, bacteria and protozoa are used to treat the organic matters in the wastewater. The process usually takes place in a bioreactor, also known as aerated tank, with well aeration and agitation to dissolve oxygen which promotes the growth and reproduction of the aerobic bacteria and microorganisms as well as to keep the suspension of the solids [28]. Besides, the growth of the bacteria and microorganisms can be encouraged by optimizing the process conditions, such as temperature, pH and sludge age. The organic materials in the bioreactor would be utilized and broken down by the microorganisms, forming flocculent settleable solids at the same time producing carbon dioxide and water. A great biomass concentration in the bioreactor will be maintained by recycling the activated sludge to preserve the high efficiency of the system [30]. Consequently, the suspended solids concentration in the bioreactor in the process system is elevated. Activated sludge is typically made up of a mass of microorganisms in the system as well as some inert materials and non-biodegradable suspended solids. The sludge is normally appeared in light gray or dark brown colour and has a flocculent appearance.

The suspended solids concentration of activated sludge is ranged from 0.4 to 1.5% in dry solids weight, and the pH is from 6.5 to 8.0. Due to the low solids concentration and high volume, thickening process of activated sludge is very crucial. However, the presence of the viscous microorganisms in the activated sludge makes the sludge hard to be dewatered [26].

In industrial wastewater treatment plants, chemicals are largely used to precipitate and remove solids. Chemicals such as lime, aluminium or iron compounds could be added to improve the sedimentation processes in primary and secondary treatment. One of the examples of using chemical to remove substance from wastewater treatment system is the chemical precipitation of phosphorus. Chemicals such as lime, alum, ferrous chloride or ferrous sulfate are commonly used for removal of phosphorus in wastewater treatment plant [26]. In the case of application of chemicals in secondary treatment system, a tertiary treatment would be needed to separate and remove the chemical precipitates. The sludge which is produced from the chemical treatment is known as chemical sludge. It appears to be darker in colour and has low dewatering characteristic due to the addition of chemicals.

Digested sludge is formed during the aerobic and anaerobic digestion processes. Aerobic and anaerobic digestions are typically carried out in a specific digester which contains aerobic and anaerobic bacteria, respectively. Aerobically digested sludge is brown to dark brown in colour, and it does not have an unpleasant odour. It has very low solids content, normally ranges from 1 to 2%, due to the endogenous respiration of the aerobic bacteria in the system. As a result of the low solids concentration in the aerobically digested sludge, it is very hard to be mechanically dewatered. However, Tunçal et al. [27] reported that aerobically digested sludge could be dewatered rapidly on drying bed when the sludge was well-digested. On the other hand, anaerobically digested sludge is dark brown to black in colour and has a solids concentration of 6 to 12% in dry solids weight. In addition, anaerobically digested sludge has fine mechanical dewatering feature and is comprised of significant amount of gases, mainly carbon dioxide and methane. According to Haider and Ashok [31], both aerobically and anaerobically digested sludge would not release offensive odour if the sludge was treated completely.

2.2 Processing / Treatment of Industrial Sludge

Heavy industrialization, intensive methods of agriculture and high population densities have led to the problem of exponentially increasing of wastewater, subsequently resulted in increasing amount of sludge being produced. Untreated sludge could be considered as hazardous waste materials due to its high metallic and organic content [27] Hence, finding a good way to process and treat the sludge is one of the most serious issues faced by the wastewater treatment plants today [5].

The methods employed in treating industrial waste are similar to those used in treating domestic sewage waste [32]. A typical sludge treatment system comprises the following stages before final disposal of the sludge: (1) thickening, during which moisture is separated from the sludge body to reduce sludge volume; (2) pre-treatment or conditioning stage, during which sludge characteristics are altered to enhance subsequence process performance; (3) post-treatment stage, for sludge stabilization or detoxification; (4) dewatering stage, for removing all the water after the post-treatment stage. Amount of sludge produced in the wastewater treatment is enormous, in which it contains more than 90% water. Thus, dewatering is a crucial step to reduce the quantity of sludge, as high moisture content would cause difficulty in pumping, conveying and transporting the sludge [5].

Thickening stage is the first step in sludge treatment to remove the moisture content and increase the solid content to about 2 to 5%. It is normally achieved by centrifugation, dissolved air flotation and gravity thickening [5]. Thickening stage would also reduce the volume of the sludge which is helpful to the stabilization process in the later stage. Gravity is normally utilized for primary sludge thickening whereas flotation thickening is used for activated sludge thickening [31]. In pre-treatment or conditioning stage, chemicals such as iron, aluminum salts and polyelectrolyte would be added to the process. Coagulation or flocculation is usually used to increase the floc size or to compress the floc interior to aid the solid-liquid separation [1]. The most common way of conditioning the sludge is the application of chemicals and heat treatment to increase the dewaterability of the sludge. Stabilization of sludge involving conversion of organic solids into inert forms is also important so that the treated sludge could be applied as solid conditioners without causing a nuisance. Stabilization of sludge could be carried out chemically or biologically, in which the latter is normally more common and effective. Lime stabilization is carried out to vary the pH of the sludge to a higher value (>11) so that microorganisms can be killed [5]. The sludge produced may also undergo further biological digestion, aerobically and/or anaerobically, to reduce the quantity of sludge as well as pathogens level in the sludge. In dewatering stage, most the water will be removed from the stabilized sludge prior to final disposal. Dewatering is normally carried out by using mechanical dewatering or thermal dehydration devices. Mechanical dewatering process is able to produce sludge with approximately 10-60% solids content, while thermal dehydration process is used to further decrease the moisture content to achieve sludge with around 90% solids content [5].

3 Vermicomposting of Industrial Sludge

Vermicomposting refers to the process where earthworms are used to convert organic materials into earthworm biomass and vermicompost. There is growing interest in vermicomposting of waste as the process adds value to the waste. Also, the bioconversion of waste using vermicomposting is usually faster than the typical composting process. Furthermore, vermicomposting reduces the volume of the waste to make its application easier. Vermicomposting process has more advantages as compared to traditional composting systems, such as shorter processing time and higher nutrients recovery [16]. Also, greater reduction of volatile solid and C/N ratio was observed in vermicomposting process [10, 33]. In addition, vermicomposting process consumes less energy and has lower cost as compared to composting [34]. There are also evidences showing that vermicomposting could effectively reduce the pathogens level as shown in study carried out by Eastman et al. [35]. Extensive researches have been done on vermicomposting of large variety of wastes such as animal manure, sewage and industrial sludge, agricultural wastes as well as industrial wastes [16]. The past studies showed that vermicomposting could be an efficient technology for waste management, including industrial sludge.

Amount of the industrial sludge produced by pulp and paper industry is increasing. Management and safe disposal of the sludge have become a challenge for pulp and paper industry due to stringent environmental regulations on solid waste disposal. Sludge resulting from pulp and paper industry is normally made up of carbohydrates, wood fibres including cellulose, hemi-cellulose and lignin, micro- and macronutrients, trace metals as well as water. Presence of structural polysaccharides and low nitrogen content (<0.5%) in the sludge make the biodegradation of sludge difficult. However, the problems could be overcome by adding some nitrogen-rich materials to the sludge which acts as natural inoculants of the microbial populations. Quintern [36] suggested that an addition of nutrients rich municipal biosolids in pulp mill solids was considered suitable for subsequent vermicomposting process. Fernández-Gómez et al. [37] investigated the potential of using vermicompositing in paper-mill sludge which was mixed with tomato-plant debris in different ratios. They reported that 2:1 mixture ratio of tomato-plant debris and paper-mill sludge was the most suitable feed ratio for optimum growth and reproduction of *E. fetida* during vermicomposting process. In addition, vermicompost which was produced from mixture with higher proportion of tomato-plant debris showed higher amount of humic acid. Sonowal et al. [38] investigated the feasibility of using *Perionyx excavatus* to biotransform pulp and paper mill sludge which was mixed with cow dung and food processing waste in different ratios. They found out that the total phosphorus was increased by 76.1%, total nitrogen was increased by 58.7% and total organic carbon was decreased by 74.5% in using the feedstock of sludge, cow dung and food processing waste in an equal ratio. They also concluded that vermicomposting was a better option in treating and disposing the sludge produced by pulp and paper mills.

Being the world's second largest sugar producer, accounting for about 10-12% of sugar production in the world, India is producing approximately 12 million tonnes of pressmud annually [39]. During the production process of sugar, considerable amount of by-products are produced such as pressmud sludge, bagasse, cane trash and fermentation yeast sludge. Pressmud sludge contains sugar, fibre and coagulated colloids such as cane wax, albuminoids, inorganic salts and soil particles. Prohibitive cost of sludge disposal, foul odour and longer time for natural decomposition are the disposal issue for managing pressmud sludge [40]. Vasanthi et al. [41] suggested that vermicomposting of pressmud sludge with an addition of organic nutrient would produce nutrient rich, odour free, more mature and stabilized final product. They successfully transformed pressmud sludge which was mixed with cow dung and Jeevamirtham *Azospirillum* by using *Eudrilus eugeniae.* The organic fertilizer which was produced after the vermicomposting process had higher nitrogen, phosphorus and potassium contents but lower organic carbon and C:N ratio. Similarly, Bhat et al. [40] employed *E. fetida* in biotransforming pressmud sludge mixed with cow dung in different compositions. They observed increases in nitrogen, phosphorus, sodium, electrical conductivity and pH while C:N ratio and potassium decreased at the end of the vermicomposting process. Their study also showed that the vermicomposting had reduced the genotoxicity of the pressmud sludge in the final vermicompost.

In recent years, sustainable disposal and management of the waste produced by food industries has become a challenge as huge amount of liquid and semi-solid waste are produced. Although waste generated from food industries contains a lot of organic matter, organic carbon, sugar, protein, enzymes, micro- and macronutrients, direct application of this waste on land will lead to foul odour. In addition, the food waste might cause pH variation as well as secondary salinization due to presence of heavy metals [42, 43]. In addition, an application of immature organic materials as a direct fertilizer might affect and cause plant growth inhibition due to the nitrogen starvation and production of toxic metabolites [43]. Recently, Yadav et al. [44] successfully carried out experiments on vermicomposting of sludge which was generated by bakery industry and mixed with cow dung as an amendment. The experimental results showed positive observations on the growth and reproduction of earthworms *E. fetida*. However, the growth and reproduction of earthworms were higher at lesser amount of sludge. Also, enzymatic and microbial parameters were affected synergistically by the earthworms during vermicomposting process. Garg et al. [45] also conducted various experiments on vermicomposting of food industry sludge which was mixed with cow dung, poultry droppings and biogas plant slurry employing *E. fetida*. They reported that total nitrogen, total available phosphorus, total potassium and total sodium were increased, whereas pH and C:N ratio were decreased after 15 weeks of vermicomposting process. The final vermicomposts produced were rich in micro- and macronutrients, low conductivity as well as optimal stability and maturity. Besides, earthworm biomass was increased significantly and considerable amount of earthworm cocoons were produced at the end of the vermicomposting process. They concluded that vermicomposting was suitable to be used in management of food industry sludge.

4 Conclusion

Vermicomposting can be utilized to manage various type of industrial sludge. Earthworms feed readily upon sludge components, rapidly converting the sludge into vermicompost. Earthworms are also able to remove the harmful pathogens to safe levels, ingest the heavy metals as well as mineralize the essential nutrients such as nitrogen, phosphorus and potassium from the sludge Furthermore, earthworms could mineralize the nitrogen and phosphorus in sludge to make it bio-available to plants as nutrients. Moreover, earthworms are able to create aerobic condition in the waste materials by the burrowing actions, which inhibit the action of anaerobic microorganisms that will release foul-smelling hydrogen sulfide, resulting in odorless process and also products. Generally, vermicompost shows a high content of organic matter and nutrients. Besides, through vermicomposting process, important plant nutrients in the substrate such as nitrogen, phosphorus and potassium can be converted into nutrients which are more soluble and available to the plants. In addition, vermicompost has "high porosity', 'aeration', 'drainage' and 'water holding capacity' which could improve soil texture and water holding capacity of the soil. In short, vermicomposting is an environmentally sustainable process for sludge management.

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