Sustainable approach to biotransform industrial sludge into organic fertilizer via vermicomposting: A mini-review

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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 wastewater, as well as any substances added to the biological and chemical operation units during the treatment process. The composition of 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 the disposal of industrial sludge. Among the three methods, the agricultural land application is a convenient and economical disposal alternative for industrial sludge. However, industrial sludge could have high putrescible content and pathogenic hazards. 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

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processes which could be employed in this context is vermicomposting. Vermicomposting is an alternative for biological stabilization of organic wastes, with the addition of earthworms. Through vermicomposting, industrial sludge could be transformed into matured organic fertilizer or vermicompost in a shorter period. Thus, this paper reviewed the recent literature on utilizing the vermicomposting process to manage industrial sludge in order to assess the feasibility of this technology. The present review would also provide a brief overview of the production and treatment methods of industrial sludge.

Keywords: Bioconversion; Biotransformation; Clean Processes; Waste Treatment and Waste Minimization; Biomass Valorization; Earthworm.

INTRODUCTION

Industrial sludge is one of the main by-products produced from the treatment of industrial wastewater, and it is generated in significant amount annually. Industrial sludge can be produced from biological wastewater treatment processes of numerous industries such as pulp and paper, chemical manufacturers, power plants, cement, tanneries, food processing, oil refineries and other. The production of sludge as a secondary pollutant from the coagulation-flocculation process is also one of the challenges faced by the treatment facilities.\textsuperscript{1,2} The particulates and colloidal matters are concentrated to form industrial sludge. The sludge is a solid or semi-solid material, consisting of all the compounds removed from the wastewater, as well as any substances added to the biological and chemical operation units during the treatment process.\textsuperscript{3} Industrial sludge is 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 helminths). In cases where industrial sewage system is combined with a municipal sewage system, the sludge may have higher heavy metals or soluble organic matter content.\textsuperscript{4,5} In addition, the industrial sludge composition may vary considerably, depending on the wastewater quality and treatment processes.\textsuperscript{6} Sludge which is produced from different industries could have different characteristics, which require distinctive treatment and disposal methods.\textsuperscript{7} Therefore, processing and disposal of industrial sludge is a challenging and complex environmental problem.

Legislation has been enacted to prohibit the dumping of organic wastes such as wastewater sludge into the ocean.\textsuperscript{8} For example, the Ministry of Land, Transport and Maritime Affairs (MLTM) of the Republic of Korea has enforced strict ruling on sludge management by banning the dumping of livestock manure and sewage sludge as well as industrial wastewater and sludge since 2012 and 2014, respectively.\textsuperscript{9} Hence, finding a way to dispose of the sludge that
would not permanently damage the environment is always a challenge in achieving sustainable sludge management. Currently, the three most common disposal methods of industrial sludge are landfilling, incineration and agricultural land application. Other innovative disposal technologies like pyrolysis, wet oxidation and gasification are still far from commercial application in the European region.

Landfilling of industrial sludge has been the most widely used disposal method in the world. It is the simplest, cheapest and cost-effective way as compared to other disposal methods. However, the poor physical nature of industrial sludge should be well stabilized and dewatered before the sludge is disposed into the landfill. Industrial sludge is recommended to maintain a minimum solid fraction of 25% before it can be disposed to landfill for easy handling. Nevertheless, the diminishing availability of landfill space and more stringent environmental standards are making landfilling an unsustainable disposal method. On the other hand, incineration is not the most popular sludge disposal method, but the global employment of incineration in sludge management is increasing. By utilizing incineration technology, the sludge volume could be reduced significantly, and pollutants (such as pathogens and toxic organic chemicals) could be destroyed thermally. The primary concern of incineration is the water content in the industrial sludge. The sludge should be dewatered to till less than 50% so that enough energy could be produced to provide a self-sustaining incineration process. However, no process to date can achieve this level without the use of chemical conditioning or an extensive use of energy, which in turn renders the process unsustainable. There are also concerns over the emissions of pollutants (such as dioxins and furans), the release of heavy metals and the treatment cost of flue gases for thermal processes.

Of the three disposal methods, the agricultural land application is a preferred because industrial sludge is a valuable source of nutrients and contains high organic matter content that favors crop growth. Macro and micronutrients, such as manganese, copper, zinc, nitrogen, and phosphorus present in the sludge are beneficial to plants and useful in promoting plant growth. Generally, recycling and reuse of wastes are preferred for sustainable development over landfilling or incineration. Both incineration and landfilling destroy the potential of reutilizing the organic matter and plant nutrients which are found abundantly in the sludge. Land application of industrial sludge is a convenient and economical disposal alternative. It also reduces the use of inorganic fertilizer. Overall, agriculture land application of sludge results in lower global warming potential effect compared to other disposal processes. However, industrial sludge could have high putrescible content and pathogenic hazards. Certain pollutants could also be present in the industrial sludge that can threaten soil quality, crop yield and subsequently contaminate the human food chain. In addition, sufficient land areas are required to meet the continuous increases in industrial sludge productions. Also, uncontrolled application of nutrient-rich wastes such as industrial sludge can cause overfertilization, ammonia toxicity, accumulation of heavy metals in soil, increased soil alkalinity, groundwater pollution and the establishment of
anaerobiosis and anoxic decomposition pathways. Heavy metals such as nickel, chromium, copper, zinc, and iron could be found in the sludge which is produced from industrial wastewater treatment plant. A disposal of the industrial sludge by the land application would cause significant impact to the environment due to the presence of high concentration of heavy metals, especially the transition metals like copper, chromium, and nickel. Moreover, industrial sludge is determined to cause more serious pollution as compared to the domestic sewage sludge. Thus, there is a need to limit sludge application in terms of quantity as well as the 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, odor control, and higher removal of the pathogen and toxic compounds. Treatment technologies such as thermal drying, composting, thermophilic anaerobic digestion, auto-thermal thermophilic aerobic digestion and lime treatment could be used. Composting is one of the best known and low-cost technologies for biological stabilization of organic wastes. This process is well established and applied widely in organic waste management. Composting is a biological process which involves 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 the thermophilic temperature phase of the composting process. Composting helps in recycling nutrients by returning them to the soil through its use in landscaping, agriculture and horticultural. One of the major challenges of the composting process is maintaining the aerobic condition. Proper aeration or agitation is needed to encourage aerobic metabolism and respiration of microorganisms. Aeration provides sufficient oxygen to the aerobic microbes for a rapid composting process. Aeration can be improved through sludge distribution by mixing it with a 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. The loss of NH₃ during the thermophilic stage of the process is also one of the major drawbacks of the composting process. An alternative to composting is the vermicomposting process. Thus, this paper will focus on the formation of industrial sludge, the typical treatment methods of sludge and potential use of the vermicomposting process in the transformation of the industrial sludge into organic fertilizer using earthworms.

INDUSTRIAL SLUDGE

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, primary, secondary or advanced wastewater treatment processes. Subjecting to the nature of the treatment processes; industrial sludge can be categorized into primary, secondary,
activated or digested sludge. Sludge which is produced from different treatment processes or unit operations has different characteristics. Table 1 shows the typical characteristics of different sludge. On the other hand, Fig. 1 shows the sludge generation points in a typical wastewater treatment scheme.

[Insert Table 1 here]

[Insert Fig. 1 here]

Primary sludge is produced from the primary treatment in the industrial wastewater treatment plant. It is a simple process used to remove settleable solids from the stream. Primary sludge is grey in color, strongly odorous and consists of a high percentage of organic matters. Primary treatment is normally comprised of a mechanical process, in which the physical treatment removes the sediments. The solid content in the primary sludge could range from 2 to 7%, depending on the wastewater quality. The most commonly used physical treatment is the sedimentation process, where the gravitational force is used in separating the particulates and suspended solids from the liquid. Primary sludge resulted from the physical treatment can be relatively easy to dewater because it consists of distinct particles and debris, which will contribute to fairer solids capture with low conditioning necessities. The 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 equipment such as reduced flow distribution. On the other hand, the concentration of primary sludge is affected by several 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 thicken further, thus increasing the concentration of primary sludge. However, long detention time of sludge in the tanks is always the main cause of unpleasant odors generation.

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

Another byproduct produced from the secondary 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 used in industries that generate organic chemical waste, such as oil refineries, pulp and paper mills, food processing plants and chemical manufacturing plants. The activated sludge process is an aerobic biological treatment process where the wastewater is being treated with biological floc which consists of microorganisms, bacteria, and protozoa. The process usually takes place in a bioreactor, also known as an aerated tank, with efficient aeration and agitation to dissolve oxygen which promotes the growth and reproduction of aerobic bacteria and microorganisms as well as to maintain the solids in suspension. 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 high concentration of biomass in the bioreactor could be maintained by recycling the activated sludge to preserve the high efficiency of the system. Consequently, the concentration of suspended solids in the bioreactor in the processing 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 has typically a floc-like appearance which is light gray or dark brown. The suspended solids concentration of activated sludge ranges from 0.4 to 1.5% by weight of dry solids with a pH of 6.5 to 8.0. Due to the low solids concentration and high volume, the process of thickening the activated sludge is very crucial. However, large amount of viscous bacterial cells found in the activated sludge dampens the dewatering of sludge.

In industrial wastewater treatment plants, chemicals are widely used to precipitate and remove solids. Chemicals such as lime, aluminum or iron compounds could be added to improve the sedimentation process in primary and secondary treatment. One of the examples of using chemicals to remove substance in the wastewater is the chemical precipitation of phosphorus. Chemicals such as lime, alum, ferrous chloride or ferrous sulfate are commonly used for the removal of phosphorus in wastewater treatment plants. In the case of chemicals application in the 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 of wastewater is known as chemical sludge. It appears to be darker in color 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 color, and it does not have an unpleasant odor. It has a very low solids content, typically ranging from 1 to 2%, due to the endogenous respiration of aerobic bacteria in the system. As a result of the endogenous respiration, the solids content of the sludge is significantly reduced.
result of low solids concentration in the aerobically digested sludge, it is tough to dewater the sludge mechanically. However, Tunçal et al. reported that aerobically digested sludge could be dewatered rapidly on a drying bed if the sludge was well-digested. On the other hand, anaerobically digested sludge has the color of dark brown to black and has a solids concentration of 6 to 12% by weight of dry solids. Also, anaerobically digested sludge has a fine mechanical dewatering feature and is comprised of a significant amount of gases, mainly carbon dioxide and methane. According to Haider and Ashok, both aerobically and anaerobically digested sludge would not release offensive odor if the sludge was treated thoroughly.

**Processing / Treatment of Industrial Sludge**

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

The methods employed in treating industrial waste are similar to those used in treating domestic sewage waste. A typical sludge treatment system is comprised of 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) pretreatment 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. The amount of sludge produced after the treatment of wastewater 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.

The thickening stage is the first step in sludge treatment to remove moisture content and increase the solid content to about 2 to 5%. It can be done by centrifugation, dissolved air flotation and gravity thickening. 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. In pretreatment or conditioning stage, chemicals such as iron, aluminum salts and polyelectrolyte would be added to the process. Chemicals are added to coagulate and flocculate the sludge particles while polyelectrolyte is added to reduce the repelling force of the particles. Coagulation or flocculation is usually used to increase the floc size or to compress the floc interior to aid solid-liquid separation. In addition, chemicals such as iron and aluminium salts are usually used in combination with lime to increase the efficiency of the dewatering process. The most common way to condition the
sludge is through the application of chemicals and heat treatment to increase the dewaterability of the sludge. Stabilization of sludge which involves the conversion of organic solids into inert forms is also important to ensure 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 widespread and effective. Lime stabilization is performed to vary the pH of the sludge to a higher value (>11) so that the microorganisms can be killed. The produced sludge may also undergo further biological digestion, aerobically and/or anaerobically, so that the sludge quantity and the level of pathogens in the sludge could be reduced. In the dewatering stage, most of the water will be removed from the stabilized sludge prior to final disposal. Dewatering is typically carried out by using mechanical dewatering or thermal dehydration devices. Mechanical dewatering process can produce sludge with approximately 10-60% solids content, while thermal dehydration process is used to decrease the moisture content of the sludge further and achieve around 90% solids content.

VERMICOMPOSTING OF ORGANIC WASTE

Similar to composting, vermicomposting also involves stabilization of organic wastes but with an addition of earthworms. Vermicomposting has been receiving extensive attention because it is a safe, effective and sustainable method for organic waste treatment. Vermicomposting refers to the biochemical degradation process where earthworms are used to convert organic materials into earthworm biomass and vermicompost with the help of microorganisms. Earthworms are the process drivers to condition the substrate and alter biological activity while microorganisms are responsible for the biochemical degradation of organic wastes. During the vermicomposting process, earthworms feed readily upon the organic waste components, rapidly converting them into vermicompost. Processes such as breaking up, splitting, synthesis, as well as enzymatic and microbial enrichment, take place in the earthworm’s intestine. The aerobic and anaerobic microflora present in the earthworm’s gut play an important role in the bioconversion process of organic waste. 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 sludge. They enhance the accessibility of the sludge bed to air which allows the flow of oxygen. The burrows are pathways for water and particle movement as well as nutrient flow and aeration. Past studies revealed that both municipal and industrial sludge with the right moisture content and suitable proportions of organic wastes were excellent food for the earthworms. Neuhauser et al. showed that activated sludge was superior than both horse and cow manure as food for the earthworm species, *Eisenia fetida*. The earthworm grew 1.7 times more rapidly in the sludge as compared to manure largely due to its higher nutrient content and microbes in the former. The texture of the organic fertilizer (or vermicompost) produced from the vermicomposting process was finer, and the heavy metals were
found to accumulate in the earthworm bodies.\(^{22,23}\) Also, the produced vermicompost could enhance soil fertility physically, chemically and biologically.\(^{40}\)

Parameters such as temperature, moisture, aeration, pH, food source, feedstock quality and C:N ratio would affect the vermicomposting process. These parameters should be controlled and optimized to ensure an effective transformation of organic wastes into vermicompost, along with better growth and reproduction of earthworms.\(^{38,41}\) Organic materials that have the following characteristics are more suitable to be consumed by the earthworms: 1) pH in the range from 5 to 8; 2) moisture content between 60-80%; 3) initial C:N ratio of around 30.\(^{22}\) Apart from that, organic waste is normally amended with bulking agents or amendments, and/or undergoing some form of pre-treatment process to make the waste more suitable for vermicomposting. Addition of bulking agents or amendments in the vermicomposting process would make the organic waste more palatable for the earthworms.\(^{22}\) In addition, mixing of amendments to the organic waste help enhance the C:N ratio, as an optimum initial C:N ratio is necessary for an efficient vermicomposting process. The addition of amendments or bulking materials would also help to reduce the concentration of harmful chemicals, at the same time improve the nutritive value of the organic waste. Under these favorable conditions, earthworms would maintain the aerobic condition in the vermicomposting process, ingest organic waste materials and discharge a humus-like substance which is also known as vermicompost. Castillo et al. suggested that lignocellulosic materials contain high carbon content and are suitable to be used as an amendment in organic waste that has low carbon content to enhance the initial C:N ratio.\(^{42}\) Apart from that, other amendments such as cow dung or cattle dung, matured vermicompost and fruit waste, are also commonly used in the vermicomposting process.\(^{43,44}\)

Adequate moisture content is also important for the survival of earthworms in vermicomposting process. The moisture content of 60-80% is the most suitable in a vermicomposting system. Low moisture content, typically lesser than 50%, is not suggested as the earthworms might shrivel and dry up.\(^{37}\)

There is a growing interest in vermicomposting of waste as the process adds value to waste. The bioconversion of waste using vermicomposting is usually faster than the typical composting process. The vermicomposting process has more advantages as compared to traditional composting systems, such as shorter processing time and higher nutrients recovery.\(^{22}\) Also, greater reduction of C:N ratio in the vermicompost was also observed during the vermicomposting process.\(^{22,40}\) In addition, higher nutrients contents in terms of calcium, magnesium, phosphorus, sodium, and potassium were observed in the vermicomposts as compared to the controls without earthworms.\(^{44,45}\) The vermicompost was finer in texture with a larger surface area because it was originated from the fragmentation and ingestion of waste in the earthworm digestive system.\(^{47}\) Besides, vermicompost contains other biochemicals that are essential in maintaining soil health and productivity, thus making vermicompost a better supplement to promote plant growth.\(^{28}\) Furthermore, the vermicomposting process consumes less energy and has lower cost as compared to
composting. There is also evidence showing that vermicomposting could effectively reduce the pathogenic level in waste as shown in a study carried out by Eastman et al. In addition, Nunes et al. reported that vermicomposting was able to reduce or eliminate the toxicity of industrial waste. On the other hand, most of the bioavailable portions of heavy metals could be effectively decreased by the vermicomposting process. Earthworms are capable of accumulating heavy metals found in the organic waste via skin absorption or in their intestine. This theory was confirmed by studies conducted by Suthar et al. and Suthar and Singh, where heavy metals were found in the earthworm’s tissues. Basic methods such as bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) have been used in evaluating the effect of the accumulation of pollutants such as heavy metals to the environment. Previous studies have shown that heavy metals content in the initial waste substrate was significantly reduced after the vermicomposting process. Also, reduction in heavy metals content was observed to be greater in experimental treatments with higher waste mineralization and better earthworm growth.

Extensive research has been attempted on vermicomposting of a large variety of organic wastes such as animal manure, sewage and industrial sludge, agricultural wastes as well as industrial wastes. The past studies showed that vermicomposting could be an efficient technology for waste management, including industrial sludge. Industrial sludge could be softened, transformed and subsequently digested by a proteolytic enzyme found in the earthworm digestive system. Table 2 shows the characteristics of wastewater sludge produced from various industries.

Vermicomposting of sludge from pulp and paper industry

The pulp and paper industry is on a path of constant growth, especially pulp production which is essential to many emerging markets. As of late, high and growing demand for pulp as well as the overcapacity of pulp production could lead to an increase in pulp and paper mill sludge production. Furthermore, Abdullah et al. reported that an estimated amount of pulp and paper mill solid waste had increased from 16,200 to 19,100 tons per day from the year 2001 to 2005, respectively. It is evident that the amount of industrial sludge produced by the pulp and paper industry is increasing. Management and safe disposal of sludge have become a challenge for the pulp and paper industry due to stringent environmental regulations on solid waste disposal. Sludge resulting from the pulp and paper industry is usually made up of carbohydrates, wood fibers including cellulose, hemicellulose and lignin, micro- and macronutrients, trace metals as well as water. The presence of structural polysaccharides and low nitrogen content (<0.5%) in sludge causes difficulty in the biodegradation of sludge. However, the problems could be overcome by
adding some nitrogen-rich materials to the sludge which acts as natural inoculants for the microbial populations. Quintern suggested that the addition of nutrients rich municipal biosolids to pulp mill solids is considered suitable to be subjected to the vermicomposting process. Fernández-Gómez et al. investigated the potential of using vermicomposting to biodegrade 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 the vermicomposting process. In addition, vermicompost which was produced from the mixture with a higher proportion of tomato-plant debris showed a higher amount of humic acid. Sonowal et al. investigated the feasibility of using *Perionyx excavatus* to vermicompost pulp and paper mill sludge which was mixed with cow dung and food processing waste in different ratios. By using the feedstock of sludge, cow dung, and food processing waste in equal ratio, they discovered that the total phosphorus and total nitrogen had increased by 76.1 and 58.7%, respectively but the total organic carbon had decreased by 74.5%. They also concluded that vermicomposting was a better option to treat and dispose the sludge produced by pulp and paper mills. Suthar et al. conducted a laboratory trial on the vermicomposting of paper mill sludge-amended with cow dung. Significant reduction in heavy metals content was observed in the final products after 60 days of vermicomposting process, with showed highest reduction in metal Pb (95.3-97.5 %) followed by Cu (68.8-88.4 %), Cr (47.3-80.9 %) and Cd (32-37 %). They concluded that vermicomposting could be a useful method for bioremediation of heavy metals from industrial sludge.

**Vermicomposting of sludge from sugar industry (agro-based industry)**

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. During the production process of sugar, a considerable amount of by-products is produced such as pressmud sludge, bagasse, cane trash and fermentation yeast sludge. Pressmud sludge contains sugar, fiber and coagulated colloids such as cane wax, albuminoids, inorganic salts and soil particles. The prohibitive cost of sludge disposal, foul odor and longer time for natural decomposition are disposal issues faced during the management of pressmud sludge. Vasanthi et al. suggested that the addition of organic nutrient during the vermicomposting of pressmud sludge would produce a nutrient-rich, odor free, more mature and stabilized final product. They successfully transformed pressmud sludge which was mixed with cow dung and *Azospirillum* by using *Eudrilus eugeniae* into fertilizer. 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. employed *E. fetida* in biotransforming pressmud sludge which was mixed with cow dung in different compositions. They observed an increase 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 vermicomposting had reduced the genotoxicity of pressmud sludge as evident in the final vermicompost.

**Vermicomposting of sludge from food industry**

In recent years, sustainable disposals and management of waste produced by the food industries have become a challenge as huge amounts of liquid, and semi-solid waste are produced. Although waste generated from food industry contains a lot of organic matters, organic carbon, sugar, protein, enzymes, micro- and macronutrients, direct application of this waste onto land will lead to foul odor. In addition, the food waste might cause pH variation as well as secondary salinization due to the presence of heavy metals. Furthermore, the application of premature organic materials as direct fertilizers might affect and inhibit plant growth due to nitrogen starvation and production of toxic metabolites.

Using vermicomposting, Yadav et al. successfully carried out experiments on biotransformation of bakery industry sludge which was 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 when a lesser amount of sludge was used. Also, enzymatic and microbial parameters were affected synergistically by the earthworms during the vermicomposting process. Garg et al. also conducted various experiments on vermicomposting of food industry sludge which was mixed with cow dung, poultry droppings, and biogas plant slurry by using *E. fetida*. The final vermicomposts were rich in micro- and macronutrients, and they showed low conductivity, optimal stability, and maturity. Besides, earthworm biomass had increased significantly, and a considerable amount of earthworm cocoons were produced at the end of the vermicomposting process. They concluded that vermicomposting was suitable to be used in the management of food industry sludge.

**Vermicomposting of sludge from milk processing industry**

The dairy industry, especially the milk processing industry is one of the largest sources of industrial wastewater in several countries. India, the largest milk producing country, has been producing 94.5 million tonnes of milk annually and the production has increased to 155 million tonnes in the year of 2015. The wastewater produced from the milk processing industry has raised numerous concerns, such as environmental issues as well as management and disposal of treated and/or untreated wastewater solid or sludge. Conventional disposal methods such as landfilling have caused pollution and contamination to soil and groundwater. In addition, emission of greenhouse gases from the landfilling practices has caused severe environmental impacts. Suthar carried out an experiment to stabilize the milk processing industry wastewater sludge mixed with cow dung as an amendment by using composting earthworm *E fetida*. He concluded that the waste mixture containing 60% wastewater sludge and 40% amendment showed better mineralization rate, with a significant reduction in pH, organic carbon and C:N ratio. The increase in total nitrogen, available...
phosphorus, exchangeable cations (K$^+$ and Ca$^{2+}$) and extractable trace elements (Fe, Mn, and Zn) in the waste mixture could also be observed. Significant mortality of earthworms was also observed in the experiment with a higher concentration of wastewater sludge, suggesting production of some substances such as ammonia, nitrogen oxide, and organic acids are harmful to the earthworms. On the other hand, Suthar et al. had also investigated the potential of applying vermicomposting on dairy industry wastewater sludge which was mixed with cow dung and plant waste (sugarcane trash and wheat straw) as bulky materials in different ratios. The study revealed that the waste mixture containing 60% wastewater sludge, 10% cow dung and 30% plant waste was the most suitable feed condition for optimum earthworm growth and activity. The results suggest that the vermicomposting process could be used to treat the amended wastewater sludge from the milk processing industry of certain proportion to produce vermicompost with rich soil nutrients.

**Vermicomposting of dewatered sludge**

The rapid development of urbanization and industrialization has led to a significant increase in wastewater treatment plants. Typically, the wastewater sludge consists of complex organic compounds, biological flocs and a lot of environmentally harmful contaminants. Treatment methods such as composting and vermicomposting have been considered as suitable methods to treat wastewater sludge. However, Fu et al. stated that the direct application of fresh sludge as a substrate for vermicomposting should be avoided as it might cause an anaerobic condition and release toxic gases that are harmful to the earthworms. Pretreatment is usually carried out to eliminate anaerobic conditions and remove any volatile gases potentially toxic to the earthworms. The anaerobic condition would generate volatile gases such as methane and ammonia which are proven to be fatal to the earthworms. It has been reported that the pelletized method could stabilize the sludge without going through a pretreatment process. Besides, the pelletization process could increase the specific surface area of the wastewater sludge and improve its aerobic extent which in turn provide a better growing condition for the earthworms. Fu et al. investigated the potential of using vermicomposting on pelletized dewatered sludge with particle sizes of 4.5 and 14.5 mm. The experimental results showed that the stabilization rate of the small pelletized dewatered sludge is faster than the sludge with bigger particle size. Similar outcomes have been obtained from the study conducted by Fu et al., in which 4.5 mm pelletized dewatered sludge was easier to be stabilized through vermicomposting than the 14.5 mm pelletized sludge. The mortality of earthworms was observed in the treatment of dewatered sludge without pelletization. The findings of the experiment also suggested that dewatered sludge with pelletization provided a healthier environment for the earthworms. They concluded that pelletization of dewatered sludge could be a better method to be used in wastewater sludge management via vermicomposting. On the other hand, Fu et al. studied the relationship between earthworms and microbial community during the vermicomposting of pelletized dewatered sludge. They reported that the microbial population and activity was
comparatively lower after-vermicomposting due to a reduction in the densities of bacterial and eukaryotic community. According to Fu et al., earthworms were able to modify diversity of the microorganisms and alter the microbial activity during vermicomposting, leading to the stabilization of the pelletized dewatered sludge.71

**Vermicomposting of sludge from tannery industry**

The tanning industry is one of the growth-oriented industries which generate a copious amount of industrial waste annually. Tanning is a chemical process that produces leather and leather related products from animal hides and skin. Tannery sludge typically contains organic materials that are rich in nutrients, sulfide, chromium, pathogens and volatile organic compounds. Besides, numerous amount of different chemicals that are being used in tanning process can be found in the waste and wastewater generated by the process. The disposal of tannery sludge with a high content of chromium as well as organic and inorganic compounds would cause significant impact to the environment. Hence, proper management of tannery sludge is necessary to avoid environmental pollution. A substantial study has been carried out by Vig et al. on the vermicomposting of tannery sludge mixed with cattle dung as bulking agent.74 Experimental results proved that the vermicomposting could be an efficient method for treating and converting tannery sludge into a value-added product with higher nutrient content and lower C:N ratio. Malafaia et al. employed vermicomposting on different types of tannery sludge (liming and primary) mixed with cattle dung in various proportions.75 It was observed that the concentrations of nitrogen, potassium, calcium, magnesium, and sodium had increased, but the total organic carbon and C:N ratio had decreased in the vermicomposts produced from both types of tannery sludge. They further explained that the vermicomposting of primary sludge at higher concentration would lead to a lower concentration of copper, while vermicomposting of liming sludge at higher concentration would result in higher concentration of all other elements. They concluded that the vermicomposting process could be efficiently applied to convert tannery sludge mixed with cattle dung into vermicompost which could be used as a soil conditioner. On the other hand, Nunes et al. employed vermicomposting on tannery sludge mixed with cattle manure and sawdust as bulking materials to obtain a more beneficial product.51 They observed decreases in pH, total organic carbon, C:N ratio and organic matter while the total nitrogen and cation exchange capacity increased at the end of the vermicomposting process. Additionally, Cr (VI) was undetected after 135 days of vermicomposting. This result confirms the biological transformation of Cr (VI) into Cr (III) which is in a more stable form, due to the action of earthworms present in the waste mixture.

**Vermicomposting of sludge from other industries**

Now, most of the industries are facing difficulties in treating and disposing solid waste or sludge produced from industrial processes. Textile industries with a diverse capacity can be commonly found in a country like India. Textile
mill sludge typically contains a high amount of organic matter, nitrogen, phosphorus, potassium and some micronutrients. However, the composition of sludge might vary depending on the chemicals used in the process. The current management methods of textile sludge require long processing time and high costs. Hence, a more efficient way of managing the textile sludge should be introduced. Bhat et al. successfully employed vermicomposting on textile sludge which was mixed with cattle dung as an amendment. The experimental finding showed that the textile sludge mixed with cattle dung in the ratio of 1:3 produced the highest number of earthworms, earthworm biomass and number of cocoons after 75 days of vermicomposting. They also reported that higher sludge concentration caused a decrease in the number of earthworms and cocoons, which could be attributed to the sludge toxicity.

In the distillery industry, a lot of raw materials would be converted into waste after undergoing the fermentation and distillation process. Distillery sludge has high organic materials, chemical oxygen demand (COD), biochemical oxygen demand (BOD) and offensive odor. Direct disposal of the sludge would cause severe environmental issues which might negatively affect the available nutrients in the soil as well as the growth of crops. Singh et al. had successfully converted distillery sludge mixed with cattle dung into a valuable product through vermicomposting. They explained that the growth of earthworms and the production rate of cocoons are related to the quality of the feed or substrate. For instance, a substrate with a lower C:N ratio would result in better earthworm growth. They concluded that the best mixtures for the vermicomposting process of distillery sludge and cattle dung were 1:9 and 1:3. Their study also showed that the final product which was produced from vermicomposting of distillery sludge mixed with cattle dung could be applied as a fertilizer without imposing negative effects on the soil or crops.

Calcium carbide is one of the raw materials used for the production of acetylene gas. A considerable amount of waste carbide sludge is produced as a by-product during acetylene gas production. Varma et al. investigated the feasibility of utilizing vermicomposting on waste carbide sludge which was collected from the acetylene gas production plant in India. Waste carbide sludge in various proportions was mixed with vegetable waste, cow dung, and sawdust in a ratio of 5:4:1 by using dried leaves as bulking materials. Different amount of waste carbide sludge was mixed with 0.27 kg of dried leaves (bulking material) and agricultural waste which was composed of vegetable waste, cow dung and saw dust in (5:4:1) ratio. Earthworm population and biomass showed positive increasing trends throughout the vermicomposting process. They concluded that the approach of using vermicomposting to transform the waste carbide sludge mixed with agricultural waste and dried leaves into a more valuable product was successful, with 1.5-2% sludge to be the optimum concentration.

Contaminants such as arsenic are normally found in untreated groundwater. In groundwater treatment plant, slaked lime and ferric sulfate are added to the contaminated water to adjust the pH and to precipitate contaminants and
thus waste sludge is formed. Excessive formation of waste sludge has led to the improper disposal of sludge that could subsequently cause an introduction of heavy metals into the environment. Maňáková et al. investigated the effect of vermicomposting on waste sludge produced from a groundwater treatment plant as well as the concentration and mobility of arsenic in the final product. The substrate for the vermicomposting process was prepared by mixing the waste sludge with horse manure and grass in the ratios of 3:6:1. After 90 days of vermicomposting, arsenic availability was observed to be significantly reduced by 1/3. The experimental results also showed that the arsenic was in a more stable form and consequently less available for plant uptake. They further suggested that earthworms can accumulate the arsenic through passive diffusion and convert it into a less toxic or inorganic form.

Gum arabic has many different functions and is usually used in food products, pharmaceutical, confectionery, cosmetic, printing, and textile industry. However, an enormous amount of solid waste or sludge would be generated during the refining process of gum arabic. Due to stringent environmental regulations and lack of dumping sites, disposal of sludge produced from gum arabic refining has become a serious issue. Research on the application of vermicomposting to biotransform sludge, which was generated during gum arabic refining process, was carried out by Das et al. During the vermicomposting process, healthy growth of the earthworms could be observed throughout the experiment, which indicated that the waste mixture of gum arabic refining sludge with cattle dung and soil was a suitable substrate for vermicomposting. They further stated that the final vermicompost contained few beneficial thermophilic bacteria and it was pathogen free and rich in plant nutrients. Hence, they concluded that the vermicomposting process was a cost-effective and sustainable method to transform gum arabic refining sludge into a value-added product.

CONCLUSION AND FUTURE PERSPECTIVE

Vermicomposting can be utilized to manage various type of industrial sludge. Earthworms can feed readily upon sludge components, and rapidly convert the sludge into vermicompost. Earthworms are also able to remove harmful pathogens to safe levels, ingest heavy metals as well as mineralize essential nutrients such as nitrogen, phosphorus, and potassium from 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 an aerobic condition in the waste materials through their burrowing actions, which inhibit the action of anaerobic microorganisms that will release foul-smelling hydrogen sulfide, resulting in an almost odorless process and soil like smelling products. Generally, vermicompost shows a high content of organic matter and nutrients. Besides, through the vermicomposting process, essential 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. Also, vermicompost has ‘high porosity’, ‘aeration’, ‘drainage’ and ‘water holding capacity’
which could improve soil texture and water-holding capacity of the soil. Vermicomposting is gaining interest as a sustainable alternative in treating organic waste, such as sludge. Despite the benefits of the vermicomposting process and the positive effect of vermicompost, there are some challenges related to the process. The vermicomposting process is highly dependent on several factors such as nature of the waste substrate, moisture content, and aeration. Hence, deviation in agro-climatic and edaphic conditions might affect the efficiency of vermicomposting process and survival of the earthworms. Besides, considerable variance in vermicompost quality can be obtained due to the changeability in nature of the waste substrate and species of earthworms used. Furthermore, lack of knowledge and experience in the society, especially among the farmers, in the vermicomposting process has led to difficulty in utilizing the technology to manage the waste. To optimize the effectiveness of the vermicomposting process, integrations of composting and vermicomposting processes can be introduced in the treatment of the organic waste. Composting process is able to reduce the size and volume of the waste substrate and the subsequent vermicomposting process can decompose the waste and increase available nutrient recovery at a much higher rate. Besides, most of the vermicomposting studies conducted are at laboratory scale and under controlled conditions. Various studies showed that vermicomposting had been successfully employed to treat different organic waste, such as pineapple waste and lignocellulosic waste from the olive oil industry, in pilot-scale. However, the study of vermicomposting of industrial sludge in pilot-scale is scarce. Hence, pilot-scale or field-scale vermicomposting process can be used to manage industrial sludge. Vermicomposting process in pilot or field-scale is capable of handling a more substantial amount of waste substrate or industrial sludge. Additionally, suitable types of vermicomposting systems could be employed to provide a better environment which ensures optimum survival and growth rate of earthworms. Co-digestion of organic waste can also be introduced before the vermicomposting process. The co-digestion process helps to make the substrate mixtures more available and thus providing a better opportunity to both earthworms and microorganisms in the biotransformation of waste. In short, vermicomposting is an environmentally sustainable process for sludge management.

Acknowledgements

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References


**Caption of Figure 1**

*Fig 1.* Sludge generation points of a typical wastewater treatment scheme.26
Fig. 1
### Table 1 Generic characteristics of industrial sludge at different stages of wastewater treatment

<table>
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<tr>
<th>Sludge</th>
<th>Solid Fraction (%)</th>
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<tr>
<td>Primary (raw)</td>
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<td>Yellow-brown, little odor, and high biological activity</td>
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<td>Aerobically digested</td>
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<td>Yellow-brown</td>
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<td>Black, little odor, musty, and drain well on drying bed</td>
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*EC: Electrical Conductivity.*
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<td>Groundwater</td>
<td>Eisenia</td>
<td>Grass (G), 3:6:1 (S:HM:SL)</td>
<td>2.0 kg</td>
<td>8.40</td>
<td>6.60</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Refining plant</td>
<td><em>Eudrilus eugeniae</em></td>
<td>Cattle dung (CD), soil (SL)</td>
<td>1:1:1 (S:CD:SL)</td>
<td>-</td>
<td>8.20</td>
<td>7.50</td>
<td>720.00</td>
</tr>
</tbody>
</table>

*EC: Electrical Conductivity.*