Biological and Thermo-chemical Treatment Technologies for Sustainable Sludge Management

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1 Introduction

Natural resources are under severe pressure due to exponential growth of population, improved quality of lifestyle and an increasing need of neat, pure and worth living environment. Wastewater in the form of effluents from different industrial and domestic activities contains higher amount of organic, inorganic and heavy metal contaminants which needs to be removed physically, chemically or biologically prior its disposal into natural water resources of dumping in open surface, however wastewater is rich source of energy (Gude 2015). Most of the wastewater methods in practice these days are energy consuming and are not economical such as aerated systems. Sewage sludge (SS) is the end-product of wastewater treatment that is produced in bulk quantities and is used as chief source of energy feedstock (Rulkens 2008). Wastewater treatment includes primary, secondary and tertiary treatment. Primary treatment includes physical and chemical separation through sedimentation pH adjustment and aeration, being followed by secondary treatment (biological and chemical treatment by organic substrate degradation with the help of microbes along with biochemical procedures) and subsequently other treatment approaches such as disinfection, filtration and aeration, called tertiary treatment (Costa et al. 2019).

Such treatment is used as standard method of wastewater treatment plants globally and usually named as biological or secondary treatment. The process of

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wastewater treatment might be energy intensive but there are several approaches that can be adopted to make it energy-efficient and energy producing (Longo et al. 2016).

Sewage sludge may contain sludge from both sources i.e., from industrial and municipal but authorities have more concern with municipal sewage sludge because it may contain a huge content of human excreta as it comes from municipal wastewater treatment plants (WWTPs). Usually, there is 1% wastewater inflow in municipal WWTPs before the processes of dewatering and thickening. Sewage sludge contains a reasonable amount of fecal components, nutrients, and organic components hence it has diverse application as soil conditioner and medium-level fertilizer. Application of SS as soil conditioner or fertilizer may have better results compared to artificial fertilizer because it holds more nutrients and make those nutrients available for plants for longer time (Wiśniowska et al. 2019). However, there are many health risks associated with the soil application of SS are because of higher content of pathogens including bacteria, virus, protozoa or helminths and other organic or inorganic micro-pollutants (Wiśniowska et al. 2019). In general, there is about 3% of total nitrogen (N), 30–55% of organic matter (OM) content, 0.7% total potassium (K), 0.7–1.5% phosphorus (P), 10–20% carbon to nitrogen (C/N) ratio and different concentration of heavy metals content in stabilized SS, while its pH ranges from 6.5 to 7.5. Total energy yield from dry SS can be 12–15 kJ kg^{-1}. SS may contain a variety of plant essential nutrients and other components including sulfur (S), potassium (K), and magnesium (Mg) (Kijo-Kleczkowska et al. 2012).

Upon comparison, it is found that fecal sludge has more nutrient contents compared to sludge produced from WWTPs as it has higher amount of suspended solids (SS) 3% versus 1%, greater chemical oxygen demand (COD) (can be higher than 10,00 mg/L) (Niwagaba et al. 2014). Sewage sludge may have higher content of fecal coliform bacteria and helminths eggs i.e., 1×10^5 CFU/100 mL and up to 16,000 number/L, respectively. We can treat such SS in same way. Sludge produced from industrial activities can be very toxic as it may possess a varied physical and chemical properties and may contain a variety of hazardous compounds in higher quantity (Wiśniowska et al. 2019). When SS is treated in plants through the processes of mechanical dewatering, anaerobic or aerobic digestion and incineration, it normally costs about 50% of total cost in the whole facility. Treatment of SS in plants has significant importance because it reduces the volume and hence decreasing the disposal cost. Consequently, while planning SS management strategies, it is vital to take in consideration all the possible alternative technologies for SS management and removal (Zhang et al. 2019). As a result of industrialization and improvement in lifestyle, increased sewerage, building of new and up-gradation of existing infrastructure has increased the rate of sludge production hence the modern society is facing the perilous problem of SS management in a way that is sustainable in both ways economically and environmentally. Along with this, there are more problems regarding finding the disposal facilities as well as fulfilling the legislative requirements concerning environmental quality. Additionally, from the last few decades there is an increasing trend of energy recovery approaches and re-use of waste materials as well as making a global strategy to follow regarding prioritization of the different waste (Zangmo 2017).

2 Composition of Sewage Sludge

Generally, many factors directly affect the characteristics and composition of SS such as the coagulants in use, source of wastewater stream, treatment approach used for wastewater, as well as time and prevailing conditions during storage. SS consists-of microbes, micronutrients and macronutrients, non-essential trace elements and organic compounds and micro-pollutants (Sun et al. 2019).

2.1 Strategies in Sludge Management

The end-product of wastewater treatment processes is a semi-solid filtrate called SS. It may consist of a large variety of organic or inorganic compounds, biodegradable compounds, along with a reasonable amount of heavy metals and other pathogenic content. Sludge is also seen as a potential source of energy and nutrients which can be restored by the application of economically practicable techniques. The total energy efficiency can be increased, and carbon footprints can be decreased by reusing and recovering the energy content of by-products (Zhang et al. 2014).

The management of SS is very of prime importance because of its concerned environmental contamination and health hazards. The optimization of handling techniques is a serious concern and hence an extremely detailed rheological compositional properties of SS has been given in order to aid in SS management, treatment and disposal services. While concerning with the disposal activities, selection of both procedure and equipment in order to transport the SS or for the direct land application is stalwartly inter-linked with consistency of sludge. However, instead of solid contents, the shear strength of sludge directly affects the formation of SS pile for composting or landfilling (Spinosa and Lotito 1999).

From past few decades, researchers have conducted detailed research work on the handling, treatment and disposal techniques of the SS and meaningful innovations in both technical and administrative context have been accomplished. But on the other hand, convincing the community about the use, nutritient value and importance of sludge is another challenge. It is also stated that a preliminary decrease in the total quantity or improving the quality of SS may have a direct or indirect positive impact on the further processes such as energy recovery or extraction of useful component (Spinosa 2004a). After a series of research work and innovative technologies we are standing at the point stating that SS is a renewable source of nutrients, organic matter, water and energy; hence not a waste. Co-digestion of SS along with organic waste such as food materials in order to enhance biogas productivity, phosphorus recovery and for other agricultural applications, is one of the central aim of energy value harvesting technologies mainly energy recovery by thermal process and anaerobic digestion on which sludge treatment and management is based. Application of SS in agriculture is routinely practiced but it will be more difficult because there is a general shift in trend of SS quality for land use hence limiting concentrations of certain pathogens, contaminants, and heavy metals (Silva et al. 2018).

Another expected alteration is the change in wastewater treatment processes to decrease the SS production in future either by the conversion of aerobic to anaerobic process or by the use of preliminary treatment technologies. Moreover, innovation is also required in the processes of both thickening and dewatering technologies. Ultimately, SS consists of water up to 95–99% and tis water content is determinant of further treatment processes to be selected as well as the viability of future land use, landfilling and incineration (IWA 2019).

2.2 Sludge Treatment and Disposal

Basically, SS is the by-product of WWTPs, and it may be solid, semi-solid or any residue in the form of slurry that can be categorized into primary and secondary SS. Primary processes such as sedimentation, chemical precipitation and others produce primary SS while secondary processes such as biological treatment forms secondary SS. Some on-site wastewater treatment system loads SS plants with septic tanks solids. Meanwhile, sometimes SS from both primary and secondary sources are mixed prior additional disposal or treatment (Aradelli and Cantù 2016). Wastewater treatment plants are mainly designed on the basis of treatment and disposal approach to be used for SS. Most of the times, SS is only treated before disposal in order to decrease its final volume as well as for the stabilization of organic materials. After stabilization, SS becomes less odorous and its handling is easy in context of health risks. Eventually, less volume lessens the pumping, transportation, and storage costs (Britannica 2020).

2.3 Treatment Methods

Sewage sludge management methods include treatment, recovery, recycling or disposal.

These terms were defined by Directive 2008/98/EC of European parliament and Council (Directive 2008/98/EC, 2008) as:

- *Recovery* refers to any process that results in the useful function of waste or discarded materials by the direct use in replacement of any raw materials to be used or being processed in plat to meet a specific purpose.
- *Recycling* is any further reprocessing or waster or discarded materials which results in new products, substances or materials that can be re-used for specific

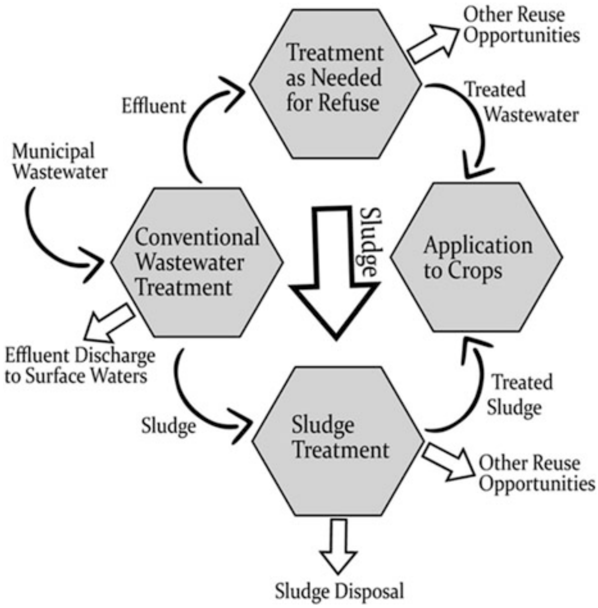

Fig. 1 Fate of sewage sludge

purpose. In this technique organic materials are reprocessed for further use as fuels and other needs such as backfilling activities with an exemption of energy recovery.

- Disposal refers to such processes that are not listed under recovery even in secondary value the operation is not done for the energy or material recovery.
- *Treatment* includes processes done before the final disposal or recovery hence it refers to the disposal or recovery operations.

Primary and secondary sludge have total energy content of 15–15.9 $MJkg^{-1}$ and 12.4–17.3 $MJkg^{-1}$ respectively. Hence, if the sludge is subject to co-digestion after primary and secondary treatment in combination with other organic waste (including fats, oils and grease) from different industrial processing units may increase the energy recovery rendering it even more energy positive as shown in Fig. 1. When co-digestion is unviable, primary sludge recovery can be done using many processes including amendments. Sewage sludge treatment involves a variety of thermal, chemical, and biological processes along with thickening, dewatering and digestion processes.

2.4 Thickening

When SS treatment starts, it is necessary to do thickening because handling of raw SS having solid suspending in water in the form of a thin slurry is unpractical and this whole procedure is done in a tank named gravity thickener. Thickening can decrease the SS volume by 50% of its original volume. Another procedure that can be done instead of thickening is dissolved-air flotation including air bubbles carrying suspended solids to upward surface forming a layer of thickened sludge (Van Lier et al. 2008).

2.5 Digestion

Digestion of SS is a process involving microorganisms decomposing organic solids into stable compounds. As a result, a sludge is produced with less total mass of solids, less pathogens and hence dewatering or drying of such sludge is more feasible as well as less odorous and physically resembling the fertile potting soil (Elalami et al. 2019).

Microorganisms such as bacteria are used for the anaerobic metabolization of organic substances in most of the large SS treatment units involving two-stage digestion system. First of all, the SS is thickened and reduced to 5% and then kept in a closed tank with heating and mixing for many days. During this process, microbiological activity occurs, and acid-forming bacteria are involved in this action by hydrolyzing and breaking larger molecules including lipids and proteins into simpler ones eventually forming different fatty acids by the fermentation of these simple molecules. This thickened and microbiologically decomposed sludge then moves to another tank, second phase, in which conversion of dissolved matter into biogas; mixture of methane and carbon dioxide is done by some other bacteria. Methane is inflammable and hence it can be used in primary digestion tank as a fuel and it can generate electricity for other processing units as well (Meng et al. 2017) (Fig. 2).

Anaerobic can be influenced by many factors including acidity, temperature, pH and many more hence it need careful handling and control. In order to enhance the activity of bacteria involved in the process of digestion, sometimes SS is injected with some additional hydrolytic enzymes at the initial stage. This enzymatic inoculation is useful in destroying the harmful pathogens present in SS as well as it also generates more quantity of methane and carbon dioxide eventually biogas during the process of digestion. This conventional two-stage digestion process can be enhanced in another way and that is thermal hydrolysis or the use of heat to breakdown the complex molecules into simpler ones and it is done prior digestion at a separate stage (Lin et al. 2018). Usually, thermal hydrolysis of such SS is done that is dewatered and having a solid part up to 15%. First of all, steam is combined and homogeneously mixed with steam in a tank called pulper that is further supplied to another reactor having temperature about 165 °C and kept under pressure for almost 30 minutes over there. Subsequently, produced steam is drained off to the pulper and as this hydrolytic breakdown completes some of the sludge under high pressure is curtly released in another flash tank. This abrupt change in pressure causes disruption in the cell walls of solid material. The resulting hydrolyzed sludge is

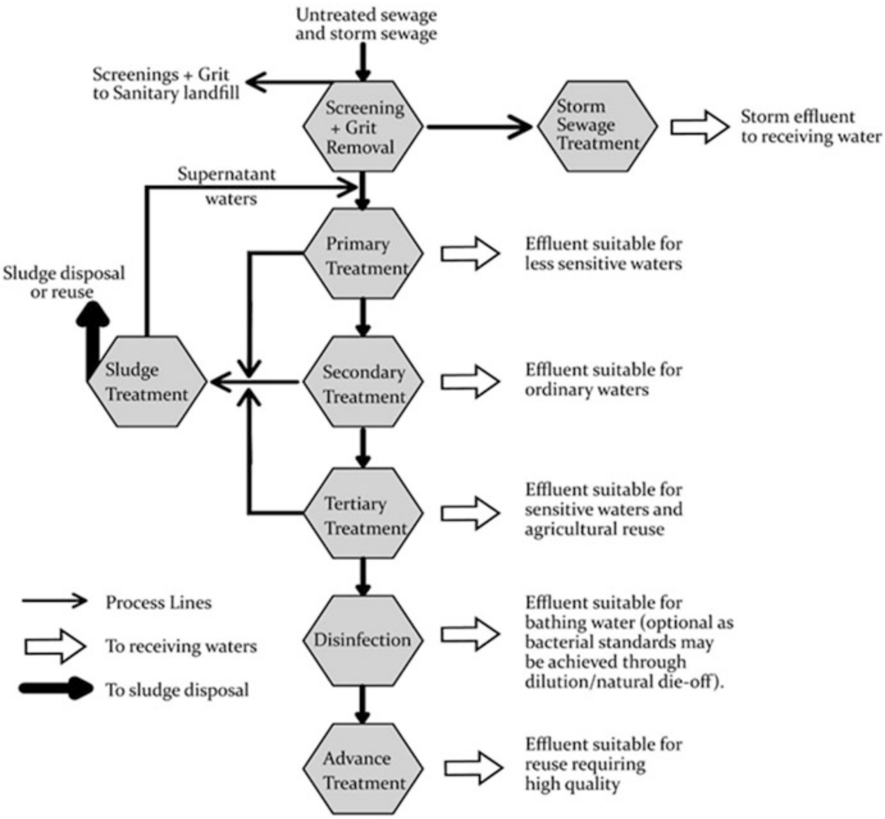

Fig. 2 Sewage sludge treatment methods

cooled and diluted using water and subjected to second stage of anaerobic digestion that may occur aerobically as well. Aeration of SS is done in open tank for the duration of 20 days, but this process does not produce methane (Kumar and Samadder 2020).

Generally, aerobic systems are easier to handle and operate as compared to anaerobic but anaerobic systems are economical when it comes to cost because aerobic systems need more power supply for continuous aeration. Anaerobic digestion is sometimes coupled with stabilization systems or some extended aeration. When we treat SS using aerobic or typical anaerobic digestion processes then most of its solid organic contents is converted into gases or liquids. Anaerobic digestion after the thermal hydrolysis of SS converts 60–70% of solid content into liquid or gas. Hence, the quantity of solid end-products is lessened compared to conventional digestion as well as the biogas production can be used to fuel the wastewater treatment plants self-sufficient in energy (Ward et al. 2014).

2.6 Dewatering

Sewage sludge is commonly dewatered or dried prior to its disposal. In spite of dewatering, sludge still contain moisture content up to 70% but meanwhile it cannot be seen as liquid even with this much moisture content and hence can treated and managed as solid material. Dewatering can be done with minimal cost by the use of sludge drying beds in which digested sludge slurry is openly placed over the sand and permitted to remain over there till it dries. Evaporation and gravity drainage can be the major factors in drying (Zhen et al. 2017). A wide range of piping network is installed under sand for the collection of water that is directly sent towards the head of wastewater treatment plant. SS after being dried for almost 6 weeks is converted into SS cake having solid content of almost 40% that can be detached with the help of front-end loader. During wet or cold weather this drying time can be decreased by building a glass or plastic tunnel over sand beds. This process of drying or dewatering is usually done in suburban or rural areas instead of urban or densely populated areas as a large land area is required for this purpose.

Sewage sludge drying beds include a variety of processes such as centrifuge, the belt filter papers and the rotary drum filters. Such mechanical systems are cost-effective and occupy less space as well as they have better operational control. As compared to SS-drying beds. Though these procedures are led by another step named sludge conditioning that involves addition of chemicals in slurry for the coagulation of solid contents and subsequently enhance the drainage (McGonigle et al. 2012).

2.7 Disposal

The ultimate destination of treated and improved SS is land disposal. Dewatered and dried sludge is directly buried into any dump site as well as it can be used as soil conditioner and fertilizer for agricultural lands. But this agricultural use of SS has some limitations as it may contain some hazardous toxicants for human health so we cannot spread it over that land that is intended for future staple crop production. Incineration is an alternative technique for SS disposal in an area where a suitable dumping site is inviable such as in densely populated urban areas. It absolutely removes the moisture through evaporation and transforms the organic content (solids) into stolid ash hence decreases the volume and cost of SS that can be disposed-off later on in a cost-effective way. Air pollution is the major concern when incineration of sewage sludge is done for this reason use of proper air pollution control devices such as wet and dry scrubbers is mandatory. Direct dumping of sewage sludge in oceans and sea was once considered as most economical and cheapest way by residents in coastal areas but it is not an appropriate method anymore. As United States has put ban on many coastal communities for waste disposal in ocean (Britannica 2020).

2.8 Biological Method

When the biological treatment of SS is done, some carbon containing solid materials are converted and degraded into another forms such as such as carbon dioxide gas emission causing more environmental pollution as well as a potential source of biofuel or energy is also lost. An increase in algae and biomass production, nutrient removal and carbon uptake can be done by the use of algae-bacteria mix consortium. Use of algae for sequestration of carbon dioxide and inclusion of sunlight results in more SS that can be used for biogas production. This procedure is totally mixotrophic as a pure medium of bacteria and algae is not required and it may work with a mixture medium of photoautotrophic and heterotrophic algal species. This in-situ algal reaction produces more oxygen that will be enough to meet the energy demands by making it available for both organic oxidation processes and microbial respiration hence this process is economical. Biological method of SS treatment can produce energy and co-digestion using algal SS is considered a favorable technique for alternative energy production (Dogaris et al. 2020).

As it is stated that treatment units using algae are cost effective as they need less energy for its oxygen demand but meanwhile it produces more quantity of SS for co-digestion with the help of microbial biomass. Such as, wastewater treatment plants involving the algae integration is more validated than other methods because it lessens the energy and aeration cost of wastewater treatment. Biofuel generation can be enhanced by the use of algae biomass in secondary effluents containing higher amount of nutrients or dissolved carbon dioxide. Exposure of algae biomass to a series of thermochemical processes may generate higher amount of biofuel and the energy recovery can be enhanced by exposing their residues to anaerobic digestion (Dogaris et al. 2020). Hydrothermal or thermochemical processes are more pledging as it generate more quantity of biofuel by catching all of the carbon matter of biomass. Integrative studies about the biogas and biofuel are not reported as much. Bio-electrochemical processes such as microbial fuel or microbial electrolysis cells can be indirectly practiced, decreasing the sludge volume in which sludge growth is dripped down to almost 50–70% as compared other conventional activated sludge procedures. Subsequently, such treatment processes directly result into valuable bioproducts as well as clean energy from organic biomass. But the problem is that current operating systems are not efficient with minimal output and less economics to support the large-scale applications. Extensive research is needed to be done in this area for the development of sustainable energy-positive bio-electrochemical systems (Britannica 2020).

3 Preventing Actions

Most of the SS contents are worthy to be recycled but they come up along with a variety of hazardous compounds in from of contaminants such as heavy metals, pesticides, polycyclic aromatic hydrocarbons, and pathogens etc., hence limiting the recycling options. The basic issue is that all of these hazardous compounds are found in a slurry, whereas sustainable treatment processes include the re-use and recovery of important products and degradation of toxic hazardous compounds. Hence, it is obvious that energy or valuable product recovery from sludge can be positively affected by decreasing total volume or amount of and/or by improving the quality of sludge. Such biological treatment of wastewater has more advantages over disposal techniques such as landfilling that directly results in increasing air pollution by producing on of the major greenhouse gas, methane. Hence, biological treatment converts organic waste into a safer end-product and reduces the environmental impacts of waste materials (Marmo 2002).

This treatment can be done both in aerobic (in the presence of oxygen) and anaerobic (in the absence of oxygen) conditions. Digestion that is done in the presence of oxygen generally results in the generation of gaseous emissions such as methane, carbon dioxide and water droplets that can subsequently be used to meet the need of fuel consumption or green fuel but meanwhile this whole approach is not economical or cost effective and subtle towards some of the environmental factors as compared to composting. Hence, there is more focus on decreasing the volume of sludge prior to its treatment or management by digestion ultimately cutting the sludge volume that is to be dumped later on. Specially, the microbial cell degeneration eradicate the need of hydrolysis stage that would otherwise be the limiting step of digestion. Thus, we can make the process of digestion more efficient and the rate of step also increases. Breakdown or disintegration of microbial cell walls can be done in many ways including biologically, thermos-chemically, and mechanically (Weemaes and Verstraete 2001; Müller 2001). There is a list of additional preventing actions that can be done to enhance the efficiency of systems and they include the utilization of complex organisms like metazoan and protozoa, other techniques such as vermicomposting, anaerobic and aerobic composting, advanced dewatering techniques involving electro-osmotic dewatering, advanced drying processes, Carver Greenfield evaporation, sludge conditioning through freeze-drying method as well as the to prohibit the direct release of toxic micro-pollutants into sewerage system, pretreatment of slurry including elimination of suspended and colloidal solids, and to remove the heavy metals from sludge by different means such as using organic and inorganic leachates, complex chelating agents or by microbiological leaching (Alavi et al. 2019).

3.1 Material Recovery

Material recovery ranges from the manufacturing or production of carbon source, organic matter, coagulants, pumice, bricks, artificial lightweight aggregate, slag, and Portland cement (Mañosa et al. 2021).

3.2 Organic Matter

The major fractions of SS being organic and inorganic content, and water out of which organic part depicts the energy source as well as beneficial to enhance the soil fertility specially with low humic constituents. Though the nutrients content of organic sludge is lower than the conventional sludge but meanwhile it is also carrying lesser heavy metals (Hansen 2001). Organic content of SS can also be used as raw material for activated carbon. Studies have revealed that specific surface of SS is 30–40% lower compared to commercial activated carbon but can be used as conventional activated carbon (Hagström et al. 2007).

3.3 Nutrients

The major nutrients of interest in SS are nitrogen (N) and phosphorus (P) (Hansen 2001). Nitrogen is generally available in the form of ammonium and organic nitrogen. Disintegration of nitrogen from SS can be done in many diverse methods but in handling of sludge the nitrogen mainstream is present in discarded liquid during dewatering, it is well treated. Ammonium separation can be done by stripping and/or struvite. Stripping is commonly practiced method for nitrogen recovery that results in formation of ammonium sulphate or ammonium nitrate, both of these products have significant application in agriculture. Precipitation of discarded water from dewatering can formulate magnesium ammonium phosphate or struvite, whereas ammonium separation can also be done by the means of ion exchange or adsorption methods such as by zeolites (Caraguay 2018).

Phosphorus is considered to be the most valued content in sludge; additionally, it is the not a renewable resource and within almost 150 years of time span the current phosphorus apatite mines are expected to be exhausted and there will be no potential source of phosphorus left for us hence the phosphorus content of sludge being the mainstream source of society is highly inviable to recover. Regrettably, enforcement of new rules and regulations and strict ultimatum regarding the quality of sludge can be the major factors limiting the sludge applications in agriculture sector. Subsequently, the phosphorus removal or recovery from sludge should be in a cleaner and less polluted manner. Phosphorus can be recovered from SS in many possible ways in today's advanced era and most convenient way of phosphorus recover is using biological methods. In anaerobic digestion, phosphorus separateor eliminates the phosphorus fraction that stays in the discarded water of the SS treatment stage called dewatering (Arun et al. 2020). SS is considered to be the purest source of phosphorus because all the heavy metals content of SS are lingering in dewatered or dried sludge and the phosphorus recovery output using this approach is about 50%. We can increase the yield proportion by using further physical or chemical processes. Keeping in mind the sludge quality, the nutrient recovery from SS specifically of phosphorus can reach up to 90% even only the acidification of sludge can yield more than 70% of P content. Unfortunately, acidification of sludge or treatment of sludge with acid dissolves not only phosphorus but the precipitates of other available heavy metals or chemicals may also be formed. So, we need to focus on the process that yields phosphorus content only so firstly the other metals have to be separated prior to phosphorus removal or phosphorus recovery should be done in an atmosphere that is not favorable for other metals to form precipitates. So, the end product is the purest and can be used as commercial fertilizer with zero or minimum pollution potential. Phosphorus recovery can also be done from the ash of incineration processes by mixing the ash with acid and phosphorus can be separated by dissolution, by formation of precipitates or by ion-exchange method (Gunarathne et al. 2020).

3.4 Carbon Source

Sewage sludge can yield a valuable "carbon source" upon hydrolyzation that can be used for biogas generation as well as to enhance the efficiency of denitrification (nitrogen removal), additionally other chemical, biological, and mechanical methods can also do the same (Kristensen and Jørgensen 1992). Primary SS is usually treated by the process of anaerobic fermentation within a closed reactor for short period of time and temperature lesser than digester ultimately forming the biological carbon source. Methane is not generated through this process, but SS can be incompletely degraded. Volatile fatty acids are the end-products of fermentation as in digester and hence the efficiency of bio-P process or denitrification improvement can be done using this process. Carbon source can be produced using other treatment processes such as chemical, enzymatic and mechanical sludge processes with lower or higher pH. Dissolved organic compounds within the cell are liberated upon the mechanical disintegration of SS because it directly damages the cell membrane. Sludge volume reduction and enhancement of biogas generation can also be done using mechanical disintegration (Hansen 2001).

3.5 Coagulants

Enhancement in efficiency of wastewater treatment plants and phosphorus recovery can be done using coagulants or precipitating chemicals and it is a rectifiable portion.

Coagulant can be dissolved by the process of acidification and it is recycled in wastewater treatment. Dissolution of phosphorus and other heavy metals occurs at comparatively lower pH and these compounds are then subsequently propelled back towards influent along with coagulants. After the recovery of coagulant, there are variety of processes available to separate the phosphorus and other heavy metals at lower concentration such as ion-exchange technique (Hansen 2001).

3.6 Bricks

The very first fully equipped brick plant was manufactured and operated successfully in Tokyo in 1991 having a total capacity of almost 5500 bricks per day from 15,000 kg of sludge incinerated ash. Notably, there was no leaching of heavy metals or other toxic compounds were reported from refined bricks even in extreme environmental conditions such as lowest pH (Okuno 2001). Using 100% ash to make bricks without using additives is mainly influenced by the process called molding, so it should be done cautiously as well as temperature should be continuously examined. Black core is the phenomenon take places upon the poor oxidization of organic substance hence to avoid this portent the temperature of brick kiln is once stopped when it touches 900 °C and then it is steadily enhanced and maintained for about 20 min at almost 1030 °C for the final modulation and heating of ash. This process is followed by a steady cooling stage of about 4 h to prevent the thermal strain breaking and in order to minimize the air temperature. SS bricks are comparatively more efficient and superior as compared to other conventional bricks in many ways as when considering their water absorption rate, 5 bending strength, compression strength and abrasion strength. Keeping in mind these properties, SS bricks are well welcomed and widely used in public corridors and walkways however some other issues can be faced such as growth of moss, ice and whitening of bricks with the passage of time (Dharma and Boora 2019).

3.7 Pumice

Pumice is made in same way as the SS bricks are manufactured but along with some additional processes such as crushing and sieving with an immense focus on reuse of end-product in athletic fields. Usually, needs of athletic fields are met with natural raw materials such as volcanic gravel because it has properties of draining extra water meanwhile holding enough moisture content hence maintains the athletic fields condition when it rains (Zeyad et al. 2019). Conversely, volcanic gravel is not sufficiently available, so sewage pumice is the best alternative (Wang et al. 2018).

3.8 Slag

Slag is the promising solution when the basic aim of sewage sludge treatment is the reduction of volume and heavy metals immobilization as it drops the waste volume to 4% of its original mass. This process is energy efficient with less fuel demands and the rich fatty greasy content of raw material serves as heat for furnace but this whole process needs to be skillfully operated and efficient drying system at the end (Gao et al. 2020). If the maximum temperature of incinerator is kept at or below 800 °C, it results in the persistence of almost 80% of metal contents in ash available in raw SS as it is examined during operational date. Slag can be formed in two different ways; water cooled and air-dried slag. Both of these slags are translucent and can be used as raw crushed material for concrete but on the other hand the compression strength is not good as of natural gravel. Air-cooled slag can be a promising substitute for natural coarse aggregate such as back-filling material, concrete aggregate, roadbed raw materials, interlocking tiles, permeable pavement, and many other concrete products (Cong et al. 2020).

3.9 Artificial Lightweight Aggregate (ALWA)

The first ever treatment plant working on "artificial lightweight aggregate (ALWA) became functional at the Nambu plant in Tokyo in 1996 having production capacity of 500 kg of sludge/h (Spinosa 2004b). Ash after being incinerated is vigorously mixed with water content with a ratio of 23% w/w and along with a little quantity of binding agent such as alcohol distillation waste. This mixture is then forwarded to another processing unit called centrifugal pelletizer where these pallets are kept for maximum 10 min for drying purpose at a temperature of 270 °C and then moved to fluidized-bed kiln for quick heating at 1050 °C (Ramanathan 2015).

When heating is done, pallets are subjected to air for drying that makes a thin film and inside surface stays porous subsequently forming an end-product having specific gravity of 1.5 and spherical shape. This ALWA is having properties of higher spherical shape, low specific gravity and lesser compression strength as compared to other commercially lightweight aggregates. This artificial lightweight aggregate can be used as fillers for removal between kerosene storage tanks and room walls, flower vase additives, thermal insulator panel, planter soils, water-infiltrating pavements and as an alternative of anthracite material in rapid sand filters. In a survey, pedestrians appreciated the walkways that were paved by ALWA because they have more pleasant appearance, more elastic, and have less penetration or standing of rainwater (Okuno et al. 2004).

3.10 Portland Cement

Sludge can be used as an alternative raw material for "Portland cement" instead of some chief components like silicon dioxide (SiO_2), iron oxide (F_2O_3) and calcium oxide (CaO) that conventionally used as natural source of limestone and clay (Okuno 2001). The concentration of phosphorus pentoxide (P_2O_5) is the most critical factor that determines the use of SS as Portland cement as manufacturers take SS in any form be it dewatered sludge cake, dried sludge or incinerated ash. The maximum permissible limit for P_2O_5 is 0.4% and there is no standard value given by WHO or any other global institution. Incinerated ash comprises up to 15% of P_2O_5 content and this incinerated ash can be mixed about 2% of concrete raw material. Other relevant use is lime blending which involves blending of dewatered SS cake and lime in equal quantity. After vigorous mixing, the water contents are separated from SS cake using chemical reactions and some extra heating is done that subsequently forms a dry powder. This dried cake is an efficient raw material as well as fuel in Portland cement processing (Boniardi 2020).

3.11 Thermal Conversion

Thermal conversion is based on three chief conversion processes and they are; thermo-chemical conversion, thermo-chemical liquefaction and conversion or combustion. The process of thermal conversion of dewatered or dried SS into oil or low to medium temperature conversions resembles natural processes to those producing liquid hydrocarbons from organic raw materials, and it includes conversion by the means of thermal cracking and catalytic conversions being the chief processes making it more complex than an ordinary pyrolysis process. This conversion is carried out anaerobically (in the absence of oxygen) at temperature of about 400–500 °C and at atmospheric pressure. Upon the conversion of sewage sludge from an industrial source it produces 30–70% char, 15–40% oil, 10–15% reaction water, and 7–10% gaseous content. The oil generated through this process have properties similar as an ordinary fuel and have applications in electricity generation sector. As compared to biological conversion processes, thermo-chemical processes are less likely to be affected by organic or inorganic impurities persisting in the SS (Veluchamy 2018). This technology has many other pros such as availability of instantly usable and storable liquid fuels, production of greenhouse credits, total energy outputs facility, control over the heavy metal contents, destruction of hazardous compounds such as organochlorides, pathogens and viruses, more control over the gaseous emissions and odor, less footprint of processing unit, less volume to deal while disposal and dumping, as well as cost effective or economic. Major drawbacks of this process are the requirement of full-scale processing unit and complex methodology (Ronda et al. 2019).

The direct conversion of wet sludge into oil was firstly done at Batelle-Northwest Laboratories in the United States of America (USA) during 1980s at experimental scale using thermo-chemical liquefaction. In this process, wet sludge containing 20% total solids is directly subjected to heat at about 300 °C and 10 Mpa pressure for almost 90 minutes that starts the liquefaction process ultimately yielding char, heavy oil, gas and reaction water. This technology was later named as Sludge-to-Oil Reaction System (STORS) that usually produces up to 10–20% of oil and 5–30% char with respect to weight. Oil produced in this way has greater viscosity and behaves as solid at room temperature. Gas produces an average 14% of carbon dioxide (CO_2) and the reseals in this process are wastewater (reaction water). Wastewater has greatest biological oxygen demand being as high as 30,000 mg/L. This approach has many advantages over others such as production of reusable liquid fuel, less footprints for processing units, cost effective, more economic, probable degradation of viruses and pathogens, and minimization of waste needing transportation to dispose off-site.

On the other hand, this technology has many cons such as complex operation, complicated equipments, exertion in handling and separation of products, and additionally this process is only tested or operated at an experimental stage yet (Pawlak-Kruczek et al. 2019). During the combustion or conversion process, the combustion of gaseous products occurs rather than condensation eventually forming the liquid fuel. Most of the experiments have been carried out using organic waste with an addition or in absence of minor concentration of SS. First of all, SS is tattered and then mixed thoroughly with dewatered or dried SS and then subjected to high temperature of 450 °C anaerobically, subsequently it forms carbonized solid content and gases. Then, product segregation is done where liquid, solid, glass, metals and ceramics are removed from carbonized material and then incorporated into gaseous phases. In this phase, combustion of all products is done with a high temperature as 1300 °C that yields granulated slag and steam. This steam has two fates; i.e., can be converted into an electricity source using steam turbine or can act as heat source. Combusted-off gases are then subjected to further cleansing mechanism before being released to avoid any kind of atmospheric pollution by the use of wet scrubbers, dry scrubbers, fabric filters and electro-static precipitators (Chen et al. 2019).

It is reported in previous studies that the fate of all products is well-managed such as air emissions standards are followed, solid content is recycled but the gas cleansing residues are identified as hazardous waste. According to available data, it is stated that use of this technology can yield up to 1050 kWh/t of waste treated (Gao et al. 2020).

3.12 Deep-Shaft Wet Air Oxidation

The "deep shaft wet air oxidation" involves the use of air or oxygen (as an oxidant) to oxidize the organic waste content of SS in an aqueous phase that occurs at a standard temperature and pressure of 260 °C and 150 Mpa respectively. A distinctive characteristic of this approach is that the pressure is maintained or achieved using the suspension of reactor in a 1500 m deep shaft. The resultant aqueous stream consists up to 30% of SS organic contents and enough nitrogen gas (N) hence it is preferred to return it to wastewater treatment plant or disposed-off after basic treatment (Debellefontaine and Foussard 2000). Further, solid remains are passive substances with no potential hazards such as silicates, phosphates, carbonates and un-leachable heavy metal contents and additionally, resulting hot water can act as an energy source. This technique comes with multiple ecological benefits such as devastation of many viruses and pathogens, comparatively simpler operating method, lesser footprint, more control over heavy metal contents and odor, and less volume of waste to be dealt for final disposal and transportation. Disadvantages varies form manual shut-down of plant is needed to de-scale the reactor because of inorganic components and wide-spread treatment is required for large volume of wastewater (Tungler et al. 2015).

3.13 Gasification

The modified form of ravenous air combustion at minimum temperature of 900 °C is called "Gasification". Sludge is incorporated with sub-stoichiometric amount of oxygen to initiate the combustion of carbon content into carbon dioxide (CO_2) that further reacts with solid carbon content eventually producing carbon monoxide (CO). The chief components of gases produced by gasification process of SS are H_2, CO, CO_2, N_2, and hydrogen sulfide (H_2S). Typical process of SS gasification produces solid products (especially char) containing a certain amount of volatile compounds. It is not previously reported in data about what happens to heavy metals in gasification (Lin et al. 2021). An early experimental stage, advanced pressurized entrained flow gasifier is established in Germany. Pure oxygen is required as an oxidant as well as high temperature and pressure ranging from 1400–1700 °C and 0.6–2.6 Mpa respectively for the gasification process. At such a high temperature, molten slag from SS is formed that is sent to gasifier ultimately converted into granulated slag particle. High quality syn-gas is produced as a result of raw gas cleansing by the removal of ammonia, hydrogen sulfide, and carbon to nitrogen ratio. This vitrified gas is pure inert material and has application as a constituent of concrete mixtures. Wide-spread examination of this procedure has exposed that most of the heavy metals and organochlorides are totally under control. According to experimental stage testing, it is stated that gasification can result in high control over heavy metals such as mercury, degradation of organochlorides, control of odor, energy recovery, complete devastation of viruses and pathogens, reduction in probable greenhouse credits and decrease in volume of material for final disposal and off-site transportation. On the other hand, there are many cons of this technology such as unknown costs, comparatively complicated system to operate, and additionally it is not proven at full equipped stage (Parés Viader et al. 2017; Lin et al. 2019).

4 Conventional Management and Recycling Options

Conventional management and recycling options involves incineration, land application and land filling because of its proficiency to recover energy by biogas production.

4.1 Land Application

Sewage sludge has diverse application in agricultural sector and after biological treatment it can be directly applied on soil. This results into many advantages such as nutrients recycling and organic matter that indirectly benefits the soil structure by improving the stability of aggregate, water retention capacity, pH, porosity, and cation exchange capacity. Although, the land application results in many issues such as application of SS containing hazardous organic and inorganic phytotoxic contaminants, and pathogen. Though there are a number of technologies and processes claiming to be completely disinfecting, but there is no such steady approach that ensure the removal or neutralization of heavy metals hence authorities have set the permissible limit of heavy metals content in SS and soil (Usman et al. 2012). The annual demand of a specific nutrient varies from crop to crop. It is seen in many cases that SS being the source of primary plant nutrients such as nitrogen and phosphorus but if the quantity exceeds the required amount it may be the potential source of ground or surface water pollution. So it is essential to calculate and consider the potential nutrients amount that are bioavailable and will persist for the very next year. SS that is derived from small and medium wastewater works with a potential of land disposal and distributing in residential areas are suitable for land applications. On the other hand, direct application of sludge in field or land depends on many long-term factors such as crop type, and weather circumstances whilst the production of sludge is going on. Thus, sludge composting can be suitable option over sludge land filling because it generates the material with more simple storage, transportation needed from the production area to application site. Composting results in safer, environmentally friendly, and hygienic material (Yoshida et al. 2018).

4.2 Incineration

Incineration of sewage sludge needs proper evaluation of its costs, but it is an economical option to deal with waste in densely populated large urban zones where the vicinity between land application and disposal of waste is too far away for an economical disposal. Thermal treatment could be the possible solution for the waste that have minimum chances of yielding beneficial products upon recovery or recycling as well as it offers a permanent solution with confined space for storage in bad weather conditions (Werther and Ogada 1999).

The probable advantages of this high temperature treatment process are:

1. Significantly reduces the weight and volume of waste to be handled.
2. Degradation of hazardous organic substances.
3. Energy recovery

Incineration results in absolute oxidization of organic materials involving volatile matter and ultimately produces ash. Before the sludge incineration, an efficient dewatering or drying is needed because even if the enough water has been removed the organic material will still continue to combust. The major issue with incineration is the emission of potential toxic gases but meanwhile there are a large number of devices available that can significantly cut the emissions. As compared to dewatered sludge, the reduction in volume of SS incinerated is up to 90%. The ash produced by this process is pesticides, viruses and pathogens free plus the metal content is less soluble and oxidized form and hence less bioavailable. Efficiency of incineration plant is directly related to availability of proper supplementary machinery and equipments, such as receiving and storage system, preliminary treatment devices, heat recovery, feeding devices, flue gas cleaning, ash management, wastewater dumping and process examination (Donatello and Cheeseman 2013).

4.3 Landfilling

Landfilling is the viable solution to the waste in an area where there is sufficient room nearby available with cost effective manner and it is basic need for all other systems for disposing or dumping the waste with no more potential recycling or recovery options. It is casually thought to be a disposal solution because most of the organic matter content of SS is rationally lost but a specific amount of recovery might be another option to adopt by yielding the biogas. If this methane in the form of biogas is not captured it can potentially be a greenhouse effect source and methane is almost 20 times more hazardous as compared to carbon dioxide. Landfilling only supports SS that is well-dewatered; around 20–25% solid concentrations are typically required but it can exceed up to 30–35% to ensure an effective physical constancy to strengthen the cover material. Efficient biological management is also mandatory to avoid unpleasant odors and other emissions. Another issue with landfilling is the leaching that can be easily controlled naturally by the use of amendments as liners/covers, imported soils, membrane liners and collection and management. Use of imported clays or synthetic compounds such as high-density polyethylene (HDPE) can be effective to control or lower the natural permeability of soil. Right after few months of deposition, the biogas production typically starts and touches the peak points after 5–7 years and carry on for a period of many years at a declining rate (Spinosa 2007; Spinosa et al. 2007).

4.4 Conclusion and Future Perspectives

In the previous sections, it has been stated the capacity and potential of sewage sludge, even if containing some contaminants, can be act as a chief source of many products and substances as well as energy source, so as an alternative of waste, these chances offered by sludge should me acknowledged and more research should be done regarding its diverse applications and possibilities. Choosing an effective system for sludge management should have on priority basis i.e., (1) maximization of material and energy content recovery and, (2) minimization of total energy input and processing cost. Till date, there have been a variety of treatment options recommended, suggested and available in the market but selecting the appropriate system is directly affected by many other vital factors such as regional geography and local economy, weather and climatic conditions, regulatory restraints and many practices need public recognition as well. It is obvious that proper management and handling of sewage sludge demands extensive development of "multiple and diversified options" strategies, that is a joint challenge mutually for city administration, industries and citizens. It is recommended that these parties should focus on production of less sewage sludge for disposal on one hand and production of high-quality sludge on another hand. Hence, while deciding the best option for optimum sludge management, the local and site-specific considerations should also be considered as it is important for the optimization of the whole system that upon choosing an optimal disposal or reuse approach. It is also stated that sludge management varies from country to country according to many factors such as land area, population density, cost and public acceptance are the key factors. Developed nations have widespread legislative systems regarding sludge handling and management and in such countries major focus is on waste minimization and then recycling, meanwhile landfilling being the most undesirable solution. In less developed nations, more waste or sludge is disposed-off or landfilled directly without any primary treatment. Application of sludge in agricultural sector could be the potential future solution of waste as well as circular economy approach including recovery of phosphorus. Among all options, the most provocative approach is thermal treatment of sludge because of its high cost. The sewage sludge can be taken as impartial, when it comes to CO_2 emissions, a source of energy that makes it more valuable to some industrial processing units such as cement factories.

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