Effects of Treated and Untreated Sludge Applications on Human Health, the Environment and Other Ecological Factors

Nur Azzalia Kamaruzaman, Mohd Hafiidz Jaafar, Mazlin Mohideen, and Sharon Fatinathan

Abstract The use of treated and untreated sewage sludge in agriculture has been a widespread practice due to its potential benefits. However, the presence of different contaminants in the composition of sludge such as microplastics, pharmaceutical active substances, heavy metals, organic pollutants and pathogens are eliciting various hazards. In relation to short-term and long-term impact on human health, there are reported adverse events which included toxicity, genotoxicity, mutagenicity and carcinogenicity. In addition, the environment is implicated by events of marine and freshwater eutrophication, potentially harmful nutrient leaching and emission of greenhouse gases which leads to climate change. Animals and marine life are also affected negatively by this practice such as abnormal growth, reproductive anomaly and accumulation of heavy metals and toxins, all of which ultimately affect mortality. Contradictory to its negative effects, sewage application is practised to improve soil productivity and fertility due to its high concentrations of organic matter and plant nutrients. This will increase plant yield, especially in fruit and vegetable production as well as dairy pasture and forestry. It is important to understand that despite the negative implications of sludge treatment in agriculture, it is still considered an excellent fertilizer and a soil conditioner to sustain an optimized growth. Therefore, appropriate sludge treatment is imperative to ensure its safe application to the land.

Keywords Agriculture · Fertilizer · Toxicity · Heavy metals · Microplastics · Sludge treatment

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M. Mohd Zaini Makhtar et al. (eds.), *Microbial Fuel Cell (MFC) Applications for Sludge Valorization*, Green Energy and Technology,
https://doi.org/10.1007/978-981-99-1083-0_2

1 Introduction

Sewage sludge is the inevitable by-product of wastewater treatment and a sludge management system treats the sludge to reduce its volume and for stabilization. Sludge (untreated and treated) is widely used in agricultural land, landfills and incineration [1, 2]. Its use in agricultural land can improve the physical property of poorly structured soil. Furthermore, in the European Union, 40% of the sludge produced is used to increase soil organic matter [3, 4]. In addition, sludge with high content of nitrogen and phosphorus is used as fertilizer. Apart from agriculture application, sludge with low organic matter and high organic substance is used in sanitary landfills. The sludge used in sanitary landfills must exhibit stability either with very slight or very slow degradation without emitting any putrefying odour [5]. In addition, sludge that is rich in carbon, hydrogen, and nitrogen can also be used as a fuel source via biogas degeneration or carbonization [6], whereby biogas produced can be used to generate electricity and heat [7].

Although many countries are using untreated and treated sewage sludge in several applications, there are concerns about the presence of various contaminants. According to Collivignarelli et al. [3], some of the adverse effects of sludge when used in various applications are the release of odour compounds, greenhouse gas emission and an increase in the level of persistent toxins [3]. Due to these concerns, there are regulations in many countries that require sufficient treatment to reduce the contaminants and to enhance the biological and physical stability of sludge [1].

The presence of different contaminants in sludge is largely dependent on the wastewater source, dewatering conditions, and treatment procedures employed to produce the treated sludge. Different sources of wastewater consist of different types of pollutants and need to be treated accordingly. Moreover, sludge generated from wastewater treatment plants should consist of a very minimal amount of pollutants. This is because many of the pollutants have the potential to cause mutagenic, teratogenic and carcinogenic effects in humans [8].

The usage of chemicals during the chemical conditioning process of sludge imposes environmental and human health risks. As an example, the usage of polyacrylamide (PAM) as a flocculent introduces acrylamide, a toxic monomer into the sludge. This increases the risk for agricultural application. Furthermore, the usage of chemical coagulants such as polymeric ferric chloride (PFC) and polymeric aluminium chloride (PACl) poses the risk of increasing dioxin concentration in the flue gas during the incineration of dewatered sludge [9]. Additionally, during chemical conditioning, toxic gases released during the chemical reactions at the wastewater treatment plant can pollute the air and disrupt human activities in the vicinity of the wastewater treatment plant [9].

The different technologies used to produce treated sludge can alter the sludge's structure, increase the nutrient release, and influence the speciation of heavy metals contained in the sludge [9]. Heavy metals were discovered to migrate and convert as a result of the sludge condition process. The leaching of heavy metals from dewatered sludge into the soil can be dangerous to humans when the amount of

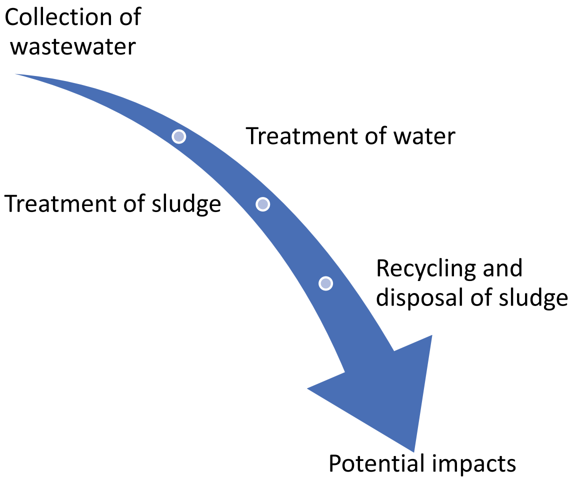

Fig. 1 Chronology of sludge, from origin to treatment, uses and potential impacts to humans and the ecology. Adapted from [11]

heavy metals entering the food chain is higher than the limit that the human body can metabolize [6].

Even though sludge brings benefits through its various applications, the composition of sludge has to be strictly monitored. Therefore it is important to understand the processes as depicted in Fig. 1, as various factors such as the origin of sludge, treatment of sludge and applications of sludge will ultimately determine the impacts imposed by the sludge [10]. This chapter outlines the possible toxic components present in the sludge, and the numerous implications of untreated and treated sludge on human health and ecology.

2 Potentially Toxic Composition of Sludge

The composition of sludge is ever-changing as the composition is highly dependent on the source of the wastewater and the treatment technologies used to produce the treated sludge. Many researchers have carried out analyses to identify the composition of sewage sludge and treated sludge. Regulations are in place in many countries to ensure that the composition of sludge used in different applications is safe for the environment and poses no harm to human health. The most commonly found toxic elements in sludge are microplastics, pharmaceutical active substances, heavy metals, organic pollutants and pathogens [12].

2.1 Microplastics

Microplastics are one of the emerging pollutants and the presence of microplastics in the environment is increasing rapidly due to the overuse of plastic materials in everyday life. Plastics are divided into primary plastics which are found in personal care products and clothes, and secondary plastics which are formed by the degradation of large plastics through mechanical erosion or photo-oxidative degradation. Microplastics in wastewater have been found to diffuse into the environment via sludge, as sludge tends to retain microplastics [13, 14]. Microplastics can also adsorb heavy metals and organic pollutants, allowing them to be transported into the aquatic environment [15]. Some of the commonly identified microplastics in sludge are polyproylene (PP), acrylic, polyamide (PA), polyester (PE), polycarbonate (PC), polystyrene (PS) and polyethylene terephthalate (PET) [15]. Although treated sludge is capable of trapping the microplastics, it is plausible for the trapped microplastics to be released into the environment over an extended time. This is confirmed by Keller et al. [14] who reported that microplastics were retained in the sludge, but nanosized plastics were still released from the sludge into the environment [14]. Therefore, further treatment of the sludge is required to ensure that the number of microplastics present in the sludge is kept at a very minimal level.

2.2 Pharmaceutical Active Substances

In recent years, the presence of pharmaceutical active substances in the environment has triggered concern because these substances possess ecotoxicological risks once present in the environment. Pharmaceutical active substances can leach from sludge into the soil and finally enter the surface water [4]. Plants can take up these pharmaceutical active substances and introduce these contaminants to humans via involuntary intake [16, 17]. Based on mass balance studies, it was found that antibiotics, antihypertensives, lipid-regulating agents and cardiovascular drugs removed from wastewater were absorbed by the sludge [18]. Ivanová et al. [4] reported that wastewaters also consisted of illicit drugs such as amphetamine, cocaine, benzoylecgonine [4]. In addition, Mejías et al. [18] reported that only selected pharmaceutical active substances and metabolites present in the sludge were reduced upon treatment [18]. Thus, the usage of untreated and treated sludge consisting of pharmaceutical active substances in agricultural land should be done with caution as studies have shown that some pharmaceutical active substances exhibited potential toxic effects on the soil [18, 19] (Fig. 2).

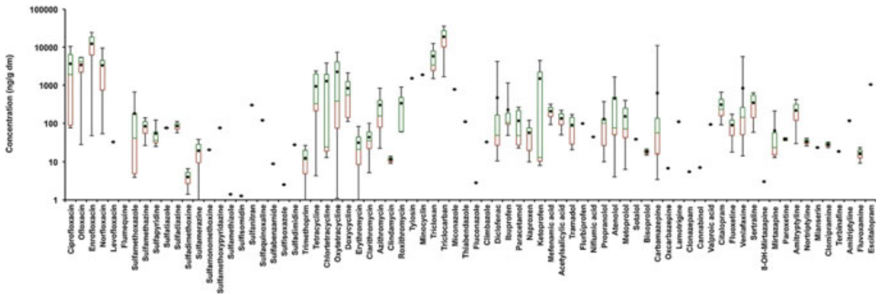

Fig. 2 Box-and-whisker plot on concentrations of pharmaceutical active substances in sludge [18] (CC by 4.0)

2.3 Heavy Metals

Researchers reported that sludge consists of high levels of heavy metals such as arsenic, cadmium, chromium, copper, lead and zinc. Currently, regulations in many countries require heavy metal testing to be carried out on sludge before it is used for various applications. Chen et al. [6] reported that dewatered sludge collected from 32 wastewater treatment plants in Japan had high concentrations of heavy metals especially copper, zinc and nickel [6]. Guo and Wen [20] stated that the usage of inorganic coagulants such as aluminium and iron salts to remove phosphorus and to increase dehydration during the dewatering process might inadvertently increase the presence of these elements in the dewatered sludge [20]. You et al. [21] emphasized that the toxicity of heavy metals was linked to the morphology of the heavy metal [21]. Heavy metals in the oxidizable and residual states are considered more stable and are less harmful because these heavy metals are not easily absorbed by organisms. However, heavy metals in the exchangeable, acid-soluble and reducible states are found to be unstable and are easily absorbed by organisms. Therefore, it is important to assess the presence of heavy metals in the sludge before utilization to prevent human and ecological risks.

2.4 Organic Pollutants

Organic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl (PCBs), and organochlorine pesticides (OCPs) are classified as persistent organic pollutants which are commonly found in sludge [5]. These pollutants which are similar to heavy metals can accumulate in the soil and pollute the crops. Different cities and countries have different distributions of persistent pollutants in sewage sludge. PAHs are most commonly found in wastewater, are reactive, and can transform into oxygenated PAHs (OPAHs) and nitrated PAHs (NPAHs). These substitutes are given prominence due to their high toxicity in comparison to the parent

PAHs [8]. Long-term exposure to PAHs can cause lung cancer risk [22]. PCBs, on other hand, have been banned worldwide for over twenty years. However, some products are found to produce PCBs such as paint, silicone-based rubber products and sealants in furniture [23]. Meanwhile, OCPs which are used for agricultural and non-agricultural purposes such as pest control has been demonstrated to be an endocrine disruptor [24]. In comparison to PAHs, PCBs and OCPs are seldom detected in landfill sludge. However, the impact of both PCBs and OCPs on humans and the environment is highly damaging.

2.5 Pathogens

Wastewater treatment plants use biological processes to produce a large amount of anaerobically digested sludge, which will be dewatered before being used in applications. The anaerobically digested sludge has the potential to emit odour and contain pathogens [25]. Pathogenic microorganisms such as protozoa, viruses and parasites can cause diseases if humans are exposed to them directly or indirectly. In addition to pathogens, antibiotic-resistant bacteria are also enriched after the anaerobic digestion of pre-treated sludge [26]. Therefore, this increases the risk of sludge spreading pathogens in the environment via landfill or agriculture application. Wang et al. [25] reported that coliforms and *E. coli* exhibited the highest regrowth rate during incubation after various treatment processes [25]. This is because *E. coli* can tolerate low water content than other bacteria, thereby *E. coli* was able to regrow in treated sludge. Therefore, effective treatment is required to reduce pathogens prior to sludge application.

3 Impact on Human Health

Due to various potentially toxic pollutants present in untreated and treated sludge, it is important to investigate the risks that sludge application may impose to humans. Health hazards in terms of short-term and long-term toxicities should be identified to ensure that the practice of utilizing sludge for various applications is safe, and adequate treatment of sludge is necessary for a sustainable agricultural practice and disposal method.

3.1 Toxicity Exposure

The risk of toxicity from sludge towards human health is a critical issue that needs to be addressed. Due to the content of the sludge, there are probabilities that it can be a toxic agent that may be harmful to public health through a few pathways, either directly or indirectly. Therefore, sludge management options and technologies are being applied to focus on managing human toxicity (non-carcinogenic and carcinogenic) as well as ecotoxicity [27]. There are many sludge treatment approaches being applied in the industry, such as dewatering of mixed sludge, lime stabilization of dewatered sludge, anaerobic digestion of mixed sludge, dewatering of anaerobically digested sludge, and incineration of dewatered anaerobically digested sludge. Dewatered sludge has the potential to be utilized in products that are beneficial to industries and communities. One of the examples is the utilization of dewatered sludge into fertilizers [28–30].

However, through the application of fertilizers, the content of heavy metals and organic compounds in dewatered sludge may expose humans to higher risks of hygiene and toxicity [30]. Due to the potential harmful risk to health and the environment, its marketability is lower than normal fertilizer [29]. Human toxicity is one of the significant indicators being itemized when conducting a life cycle assessment on sludge management [29]. The process of sludge toxicity impacting human health is discussed in this part of the chapter by looking from the perspectives of source, pathway and receptor.

In this process, sludge is the source of toxicity. Sludge produced by wastewater treatment contains heavy metals, putrescible content and pathogenic hazards which may be harmful to humans and the ecosystem [9, 31, 32]. The fate of pollutants depends on multiple factors including [33]:

i. plant operational parameters
ii. physicochemical parameters of pollutants
iii. biochemical sludge parameters.

The concept of a pathway leading to toxicity exposure to humans, in general, involves the chemical fate from an emission before being exposed to humans [34]. Human exposure can be divided into the following routes; inhalation, ingestion, dermal absorption or injection. In the case of sludge, the pathway to human toxicity involves toxic agents that have been emitted to the environment before being exposed to humans. The potential of human exposure could occur as the pollutants or toxic agents are released into the environment at the disposal stage and utilization of resources [29].

The final component is the receptor. For the receptor, which is humans, it is important to look at the vulnerability and the sensitivity factors when discussing this aspect. A receptor can be categorized as a group that requires protection, in this case, from toxicity. Different routes of exposure (dermal absorption, inhalation or ingestion) might affect different parts or organs of the body. Toxicity exposure may lead to carcinogenic and non-carcinogenic issues in humans. Moreover, the severity of toxicity exposure depends on toxicological potency (dose response). Detailed toxicological effects should be taken into consideration, as the following [35]:

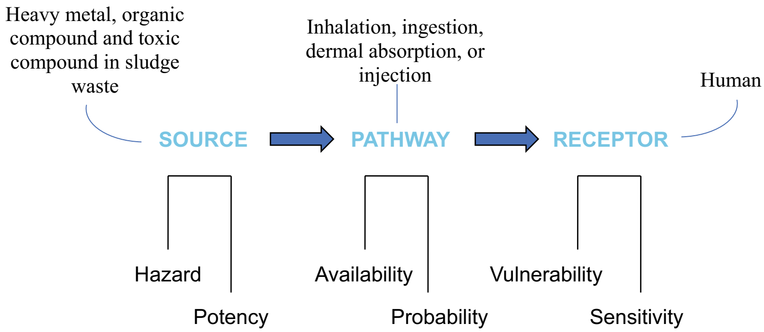

Fig. 3 Source-pathway-receptor model for sludge toxicity exposure in humans

i. Uptake, distribution, metabolism and excretion of the substance in the human
ii. The effects of the substance
iii. Dose-response relationships
iv. The biological mechanisms by which the substance exerts its effect.

A simple diagram model depicting the process of sludge toxicity in humans is shown in Fig. 3.

3.2 *Genotoxicity and Mutagenicity Effects*

Increasing world population and widespread urbanization lead to vast amounts of human waste. Thus, efficient wastewater treatment is required to produce sewage sludge, which requires further treatment. While treated sludge is applied on land, concerns arise about its effects on human health and the ecosystem [2]. Due to the possible toxic compositions of various types of untreated and treated sludge, many studies have looked into its potential to pose genotoxicity and mutagenicity effects on humans.

According to the World Health Organization (WHO), genotoxicity, also known as genetic toxicity, is a broader term that includes DNA damage, which may be reversible by DNA repair cellular processes, results in cell death, or may not result in permanent alterations in the content of surviving cell. Mutagenicity, a component of genotoxicity, is referred to as a process of inducing a permanent change in the genetic material (e.g. DNA, RNA) of an organism (e.g. human) which can lead to heritable changes to functions [36].

A study was looking into conventional activated sludge from different municipal wastewater treatment plants (WWTPs) in the north of Italy. For WWTP of domestic wastewater with agro-food industrial discharge, the samples showed no mutagenic activity in *Salmonella typhimurium* strains (with and without exogenous S9 metabolic activation), as shown from the Ames test. However, high toxicity was reported, which could potentially mask the effect of mutagenic activity due to a lack of bacterial growth. In addition, no genotoxicity was reported using the *Allium cepa* root test. On the other hand, the samples showed DNA damage of the exposed human leukocytes, as evaluated by the Comet test. Similarly, toxicity was observed, albeit at higher doses. For WWTP which treated winery effluents, slight mutagenic effect was reported for *Salmonella typhimurium* TA98 strain in the absence of S9 metabolic activation, thus indicating potentially detoxifying action of S9. While significant DNA damages were reported from the comet test, *Allium cepa* test showed no genotoxicity effect [37].

Another study which was conducted in Sao Paulo, Brazil was looking into the genotoxicity effects of decontaminated sewage sludge by monitored natural attenuation [38]. The natural processes in detoxifying sewage sludge included mainly degradation by on-site microorganisms as well as volatilization, transformation, dilution and dispersion [39]. It was found from the *Salmonella*/microsome assay that sludge samples after 12 months of treatment showed no mutagenic activity in *Salmonella typhimurium* strains TA98 and TA100, both in the absence and presence of S9 metabolic activation. However, mutagenic activity was observed for the sludge samples which were treated at 0, 2 and 6 months. Micronucleus test which was conducted on HepG2 cells (human-derived hepatoma) showed no significant genotoxic effects for sludge samples treated at 6 and 12 months, though a significant genotoxic effect was reported for sludge samples treated at 0 and 6 months. This indicated the importance of completing the detoxifying process of sludge samples and that natural attenuation at 6 months or longer was most optimized to ensure the safe release of sludge to the environment [38] (Fig. 4).

In addition to *in vitro* findings, an *in vivo* study was conducted whereby Wistar rats were utilized and the genotoxicity effects of treated sludge samples from a sewage treatment plant were observed through micronucleus test and comet assay. Results indicated that independent of rat gender and concentration of the treated sludge samples, no significant increase of micronucleated polychromatic erythrocytes (MNPCEs) in the femoral bone marrow and DNA damage in peripheral blood

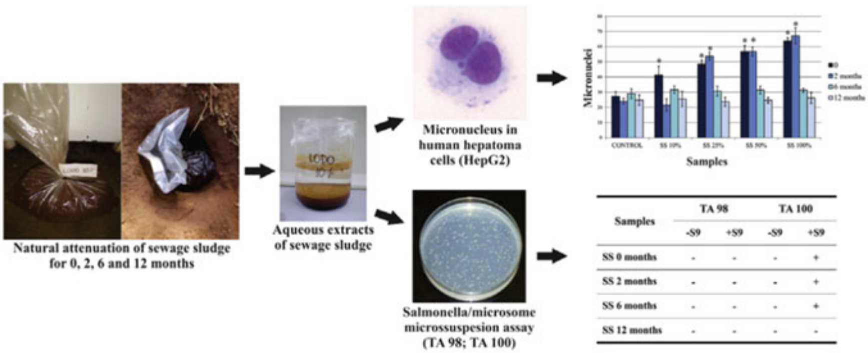

Fig. 4 Graphical representation of natural attenuation of sewage sludge for various time periods, which showed genotoxic and mutagenic effects in human hepatoma cells (HepG2) and *Salmonella typhimurium* respectively in different settings. Reprinted from [38], with permission from Elsevier

leucocytes was observed. Moreover, no influence on the proliferation of normal bone marrow erythroid was reported as the ratio of polychromatic erythrocytes (PCEs) and normochromatic erythrocytes (NCEs) for the treated sludge was not significantly different from the negative control. Further analysis of the metal levels showed below the standard levels [40].

A few other studies have highlighted the importance of treating sludge for the purpose of decontamination prior to disposal in the environment. The mutagenic effect was significantly reduced in treated sludge [41, 42], and was 2–3 times less toxic than its untreated counterpart [43]. Mutagenic substances may persist in soils for a long time, though different types of sludge have different genotoxic or mutagenic potentiality, which affects different degradation periods for which the toxic substances may decline to basal levels [38].

This section described various degrees of genotoxicity and mutagenicity findings for different types of untreated and treated sludge samples using varying test systems. It is therefore important to understand that the difference in results may depend on the type of influent of the sludge samples and the type of treatment that was conducted [10, 44]. In addition, with more than 150 assay systems developed to measure various endpoints of genotoxicity on a full spectrum of organism, from bacteria, to human cells and experimental animals, the complexity of these tests may affect the findings [45]. Therefore, studies so far have investigated these effects on a case-by-case basis [40].

3.3 Carcinogenic Potential

Carcinogenesis is the induction of cancer which originates from the accumulation of genomic alterations, whereby such alterations may be genotoxic or non-genotoxic [46]. It is another important element of long-term toxicity that needs to be investigated. Activated sludge from MWTPs from the Eastern Cape Province of South Africa, which were of suburban and agricultural origins were assessed for its potentially hazardous risks to humans. The levels of five metallic elements, iron, copper, cadmium, lead and zinc were shown to be at low concentrations and below the detection levels for hazards to human health. This followed the recommended limits of 1500 mg kg^{-1}, 39 mg kg^{-1}, 300 mg kg^{-1} and 2800 mg kg^{-1} for copper, cadmium, lead and zinc respectively as stated in the United States Environmental Protection Agency (USEPA) [47], as well as maximum permissible levels of 450 mg kg^{-1}, 5 mg kg^{-1}, 150 mg kg^{-1} and 700 mg kg^{-1} in South Africa [48]. Iron has no target limit due to its nature as an essential element [48]. Therefore, a risk assessment had indicated that all five metals did not pose any significant carcinogenic and non-carcinogenic health hazards to humans, either by oral or skin exposures. However, it is interesting to note that the metallic levels, though low, are higher than wastewater and river water samples. This is unsurprising as 80–90% of heavy metals are known to accumulate in sludge samples. In addition, as heavy metals bioaccumulate, efforts must be made into reducing their levels upon treatment at MWTPs prior to release into the environment to ensure long-term safety for all consumers [49].

Based on the study by Bertanza et al. [37], tumour potential of conventional activated sludge from WWTPs was tested on IAR203 hepatic cells. The sludge samples showed carcinogenic potential by significantly inhibiting gap junction-mediated intercellular communication. However, the carcinogenicity was not as marked as the positive control used, which was TPA, a reference tumour promoter. In *in vitro* cell transformation assay, a significant number of malignant foci or transformed cells were reported in comparison to negative control, though the mean values were significantly lower than positive control 3-MCA. This provided evidence of potentially carcinogenic characteristic of activated sludge [37].

4 Ecological Implications from Agricultural Use

Contradicting the presence of various hazardous agents in sludge as discussed earlier in this chapter, sludge also contains a myriad of beneficial substances that prompt its use in enhancing agriculture practice. The following sections described the effects of sludge application in agriculture and disposal from the perspective of ecology.

4.1 Environmental Factor

The environmental issue of sludge activities arises from wastewater treatment, solid waste and sludge management. The treated sewage water from sludge management is usually discharged to the nearest water ecosystem. Most of the treated sewage water regularly undergoes monitoring and assessment of water quality and is observed to be relatively clean. However, some studies still showed the long-term adverse effects of sewage water treatment [50–52] as not all of the applied water treatments managed to reduce the organic load that increased the nutrient compounds in the water ecosystem [27, 52]. This scenario will potentially cause marine and freshwater eutrophication.

Eutrophication is a condition whereby the environment is enriched with nutrients like phosphorus, nitrogen and other plants nutrients [53]. Freshwater eutrophication is usually associated with increasing nitrogen, while marine eutrophication is associated with increasing phosphorus content [50]. The gradual increase of plant nutrients will cause algae bloom that triggers the structural change of the water ecosystem [54]. Eutrophication is a serious environmental problem as it results in the deterioration of water quality. When there is a significant increase of algae surface of the water, sunlight is blocked from reaching the bottom of the water, thus significantly reducing the rate of photosynthesis [54]. This occurrence will reduce the oxygen concentration in the water, thereby causing environmental imbalance due to its negative impact on the water ecosystem. A simple diagram illustrating the eutrophication process caused by sludge (applied as fertilizer) is shown in Fig. 5.

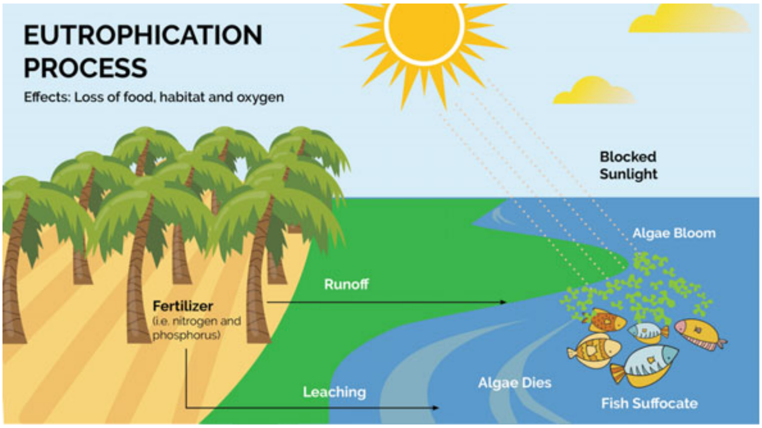

Fig. 5 Eutrophication process by fertilizer (from sludge). Algae bloom prevents sunlight from reaching the bottom of the water, thus reducing photosynthesis and subsequently decreasing oxygen levels. This ultimately kills plants and fish living in the water. Adapted from [55]

Apart from aquatic eutrophication, the rich organic matter in sludge has a risk of nutrient leaching, which can impact soil biodiversity [56]. The waste sludge is usually recycled as fertilizer in agriculture as the sludge is rich in nitrogen, phosphorus and total organic compound, which are suitable for plants [51]. The macronutrient in sewage sludge can increase the rate of growth of plant, however, in some cases, the sewage sludge might harm the soil. The two frequent toxic compounds that have been observed in the sludge is polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) [51]. These two compounds have mutagenic, carcinogenic and immunotoxin effects on living organisms and increase soil phytotoxicity. In addition, land application of sewage sludge may lead to the accumulation of pathogenic and parasitic organisms in the soil [57]. However, the number of these organisms can be significantly reduced with proper treatment of sludge prior to application to the land [58].

Furthermore, the disposal of solid waste in sludge contributes to the emission of greenhouse gases during the treatment and recycling processes [59]. The increase in greenhouse gas emissions contributes to global warming and climate change. Most studies reported that sewage sludge potentially emitted greenhouse gases, methane and nitrous oxide [59, 60]. Although methane and nitrous oxide emissions are relatively smaller than the emission of carbon dioxide, these two greenhouse gasses have multiplied potency for global warming and climate change [61, 62]. Methane is the second most abundant greenhouse gas with a shorter life span than carbon dioxide, and this gas has been found to be 100 times more extensive in warming the earth than carbon dioxide [62]. Additionally, nitrous oxide is 300 times more extensive than carbon dioxide in warming the atmosphere [61].

Climate change is a serious environmental problem as it affects the global ecosystem. Increasing global temperature causes a rise in sea levels, frequencies of droughts and forest fires and triggers extreme weather conditions [63, 64]. Subsequently, climate change disrupts food production, water supply, human health, human activity, natural resources and economics [65–67].

Contradictory to the negative implications of sludge application, it is also important to note that sludge is extensively used in agriculture as it may improve soil productivity and fertility due to its high concentrations of organic matter and plant nutrients. Studies have shown that sludge application also significantly increased microbial biomass in the soil as well as important soil enzymes such as arylsulfatase, acid phosphatase and alkaline phosphatase, albeit utilizing low metal sludge and at an appropriate rate. This is because the highest rate of sludge application (200 $t{\cdot}ha^{-1}$) caused a significant reduction of the soil's functional community diversity. Furthermore, the organic matter of sewage sludge is generally high at more than 50% dry matter. Therefore, this caused a profound positive impact on soil physical properties and soil conditioning effect by improving aeration and water infiltration as well as increasing soil aggregate formation stability [57, 68].

4.2 Plant Yield

Treated sludge from MWTP is usually disposed of, and one sustainable and economical method for the disposal is reusing the sludge in agriculture as an organic fertilizer. This method is widely practised by developing and developed countries worldwide [57]. Sewage sludge has been reported to contain nitrogen, phosphorus and organic matter, which are beneficial for plants. Dewatered sludge has been reported to release nitrogen slowly, thus benefiting crops over a relatively long period of time. Phosphorus content has also been shown to be available at 50% concentration in the year of application. In addition, liquid-anaerobically digested sludge was reported to possess a high content of ammonia nitrogen, which is readily available to plants and is particularly useful in grassland. Furthermore, organic matter from dewatered sludge was found to improve soil structure and its water-retaining capacity, thus improving the growth of plants [69].

In fruits and vegetable production, organic manure alone is insufficient to sustain optimized growth. A study in Jordan found that lettuce growth was increased when applied with 40 $tons{\cdot}ha^{-1}$ sewage sludge, which was a concentration equivalent to the recommended fertilizer rate. However, higher plant metal content was also reported [70]. Another study reported increased lettuce growth in terms of yield, head circle, plant height and leaf number as well as high nitrogen, phosphorus, potassium and magnesium levels when the soil was applied with 20, 40 and 80 $t{\cdot}ha^{-1}$ of sewage sludge [71]. In the Philippines, upland rice yield was increased when the land was applied with sewage sludge, whether alone or in combination with nitrogen fertilizer [72]. In Hawaii, maize biomass was increased when the land was treated with aerobically digested sludge, though the biomass was reduced when two undigested sludges were applied instead. This is because a higher rate of sludge caused phytotoxicity on the roots containing reducible manganese nodules [73]. In the UK, 26% of the crops treated with liquid sludge showed a significant increase in crop yield, through soil structure improvement. However, bed-dried sludge treated on clay soils caused 6–10% yield reduction of wheat grain, probably from excessive nitrogen content which caused crop lodging [58]. In Spain, sewage sludge use was a suitable replacement for chemical fertilizer, due to its potential benefits in fertilizing 3–4-year-old citrus trees. However, it was also reported that its use must be cautioned against horticultural crops such as soft fruits or vegetable crop [74]. It was revealed that cauliflower, cabbage and potato showed growth deficit and phytotoxicity in some parts of the plants when the soil was applied with sewage sludge for long period of time, most likely from high content of heavy metals (e.g. chromium accumulation in potato) [75].

Similarly, sewage sludge application has been found to be beneficial for the growth of dairy pasture and forestry. Sludge has valuable plant nutrients such as nitrogen, phosphorus, iron, calcium, magnesium and various other macro and micronutrients, which are important for cow's growth and milk production, though farmers should adhere to holding periods in which animals should be prevented from grazing sewage sludge-treated pasture to protect the animals from pathogens and risks of chemical contamination [57, 76, 77]. In forestry, sewage sludge application improved the soil's physical, chemical and biological properties as well as fertility, thus creating a favourable condition for improved vegetation in the existing forests [10]. Though sludge is valuable to enhance crop growth due to its high organic matter content and rich macro and micronutrients, caution must be practised to prevent the presence of heavy metals and organic compounds in the food chain, and these pollutant load can also be phytotoxic [57].

4.3 Effect to Animals and Marine Life

All animal species which are in contact with sewage sludge are somewhat affected negatively. The discharge of sewage sludge into tropical coastal seas releases hundreds of compounds, the most common ones included freshwater, inorganic nutrients (ammonium, nitrite, nitrate, and phosphate), pathogens, endocrine disrupters, suspended solids, sediments, heavy metals and toxins [78, 79]. Coral mortality is affected by the toxicity effects caused by coral diseases and coral bleaching. In addition, nutrient enrichment is enhancing algal growth and phytoplankton shading, which increase coral reefs' competitive ability for space and affect calcification rates, thereby destroying corals and removing the foundation species [80].

The presence of heavy metals in the water system leads to the accumulation of metals in plankton, algae and smaller prey, which are consumed by fish, leading to the build-up of heavy metals in fish tissues, in a process called biomagnification. Accumulation of toxic amounts of heavy metals can poison the fish. In addition, other animals, including humans may eat these fish with heavy metals, and the chain of heavy metal is transferred to the consumers. Furthermore, microplastics in sewage sludge are affecting marine life such as fish, mammals and crustaceans as these animals may eat them, living in or on them, or getting tangled in this litter [81].

Another study found that sewage sludge application to pasture caused significant spermatogenic abnormalities in adult male sheep when they were exposed to the sludge in utero and post-natal (until weaning and post-weaning). This was observed from their testes, as germ cell number reduced significantly, thus affecting sperm count and fertility among these sludge-exposed animals [82]. Reports have also revealed that DDT, one of the toxins contained in sewage sludge was affecting peregrine falcons in the US, causing thin eggshells that rendered incubation extremely difficult. In addition, amphibians were malformed due to the exposure of hormone-disrupting chemicals in sewage sludge. Toxins were also found to accumulate in worms and insects after prolonged exposure to sludge, whereby subsequently mammals and birds ingesting these animals would accumulate the toxins as well in their bodies [83].

5 Conclusion

This chapter described the various effects of untreated and treated sludge on human health, environment, plants and animals. Depending on a few factors, the effects of sludge can be negative and positive. The toxic composition of sludge consists of microplastics, heavy metals, organic pollutants, pharmaceutical active substances and pathogens, thus there were reports of toxicity, genotoxic, mutagenic and carcinogenic effects on human health. In addition, sludge application affected the environment in terms of aquatic eutrophication, soil phytotoxicity and climate change. Plants and animals were also affected in terms of phytotoxicity and mortality respectively. However, it is equally important to note that sludge also has profound beneficial properties, as it contains high content of nitrogen, phosphorus, organic matter and plant nutrients, which was the reason for its extensive use in agriculture. Plant growth was shown to be enhanced as sludge is an excellent fertilizer and a soil conditioner to sustain optimized growth and in some cases, no toxicity was reported among humans. Due to its potential, sludge application on land is part of a strategic and sustainable method of agricultural productivity. Therefore it is important to follow appropriate guidelines in treating sewage sludge prior to land application, either for agricultural use, disposal, or both, in order to maximize benefits and minimize health hazards to humans and the ecology. Lastly, understanding the effects of sludge application is imperative to ensure that sludge valorization can be optimized for a cost-effective and environmentally friendly sludge reduction and resource recovery method.

Acknowledgements This work is financially supported by APEX ERA Research Grant of Universiti Sains Malaysia (1001.PTEKIND.881006).

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