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REVIEW ARTICLE

A Review of Microplastic Contamination in Wastewater-Derived Sewage Sludge

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ABSTRACT: Microplastics, which account for 90% of plastic pollution, pose serious physical and toxicological threats to the environment and, by extension, human health. A significant amount of research has been conducted to assess microplastics in various types of water and wastewater treatment plants. However, there is limited knowledge about microplastics in the byproduct of wastewater treatment plants, sewage sludge. Wastewater treatment plants are moderately effective in reducing microplastics in effluent water. Paradoxically, the removed microplastics become concentrated in the sewage sludge. This is often discharged to the land, used as fertilizer for agriculture, or used for land refill, and poses a critical environmental problem. Sewage sludge discharge can be a significant point source of land contamination, thereby impacting terrestrial ecosystems, crop health, and human health, which warrants further study. Addressing microplastic pollution in sewage sludge is a complex challenge due to several factors, including a lack of standardized methods for detecting and monitoring microplastics, the need for long-term studies on the soil and the pathways of spread, the absence of current treatment technologies to eliminate microplastics, and a lack of public awareness and policy. This paper aims to present an overview of microplastics in sewage sludge.

KEYWORDS: Earth and Environmental Sciences, Environmental Effects on Ecosystems, Microplastics, Sewage Sludge, Wastewater Treatment.

Introduction

Since the 1970s, the rate of plastic production has grown faster than any other material, with over 9.1 billion tons of plastic produced since the 1950s.[1] Most of the plastics are made from fossil-fuel–based hydrocarbons. It is estimated that approximately 4.8 to 12.7 million tons of plastic waste enter the oceans from coastal countries each year.[2] Microplastics are plastic particles that are smaller than 5 mm in size.[2] They can be classified as arising from primary or secondary sources of microplastics based on whether they were intentionally made at this size or if they have degraded from larger plastics to this size. Primary microplastics can come from microbeads, nurdles (plastic pellets), tire wear, synthetic textiles, and many other sources. Primary microplastics include polymers such as polyethylene, polypropylene, and polystyrene particles, which are found in cosmetic and medical products, as well as in sludge from the washing and wearing of synthetic textiles and fibers.[3] The wear from tires and road markings may also cause microplastic pollution into rainwater runoff, which is a pathway for carrying tire and road wear particles to surface waters.[3-5] These enter the wastewater and are processed along with the wastewater as it enters wastewater treatment plants. Secondary microplastics originate from the degradation of plastics, including plastic litter, fishing gear, packaging materials, and other sources of plastic waste.[6] Secondary microplastics originate from activities such as littering and waste disposal processes.[3] These can also enter wastewater streams and are processed in wastewater treatment plants.

Microplastics are important to understand due to the direct and indirect risks they pose to marine/aquatic animals, as well as humans. The direct injury is caused by the small size and density of microplastics, which allows them to be consumed/absorbed by various microorganisms and animals.[7,8] They can interfere with the food source and consumption, leading to obstruction and a lack of feeding, which can lead to the eventual death of marine creatures. Indirect damage from microplastics can occur when microplastics adsorb heavy metals and other organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), chlorinated organic pesticides, and poly-chlorinated biphenyls (PCBs), referred to as persistent organic pollutants (POPs).[7,8] These create long-term consequences like cancer, immune-related problems, and endocrine disruption. According to the Organization for Economic Cooperation and Development, nearly 1.7 million tons of plastic waste enter the oceans, while an additional 6.1 million tons are discharged into various water bodies.[9]

The purpose of this review article is to understand the presence and importance of microplastics in sewage sludge.

Discussion

Waste Water Treatment Plants (WWTP):

Wastewater Treatment Plants (WWTPs) are facilities that receive wastewater and treat it through physical, chemical, and biological processes to remove contaminants before reintroducing the treated water back into the environment. The inflow to a wastewater treatment plant includes domestic sewage, industrial wastewater, rainwater runoff, and groundwater leakage into sewers.[2] These waters often contain tirewear microplastics, microplastic fibers from the washing of synthetic fibers, overflow water in extreme weather, etc. These waters are treated in a WWTP, and the effluents are discharged into wa-

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ter bodies or used for non-potable water requirements, or they can be discharged into the soil to supplement it.

Microplastic removal for most wastewater treatment ranges from 84% to 99%.[10] The removal rate from wastewater varies by the WWTP and can depend on the microparticle size, shape, density, and surface characteristics. Additionally, the rates of reported removal may vary significantly due to the techniques used for sampling, particle size detection, removal methods, sample volume, and other factors.

Microplastics in Solid Sewage Sludge (SeS):

The microplastics removed from the water are concentrated in the solid material that forms the solid sewage sludge (SeS). SeS is a byproduct of WWTP. Microplastics found in the wastewater must be removed from the water before it is used for non-potable purposes or discharged into water bodies. Sludge treatment varies significantly but typically involves processes such as thickening, stabilization, aerobic and anaerobic digestion, conditioning, dewatering, and heat drying. The purpose of the sludge treatment is to reduce water and eliminate microbes and gases. Microplastics can survive the sludge treatment and remain in the SeS. SeS can be used as landfill, incinerated, or applied to agricultural land as a fertilizer. In some cases, SeS can be accidentally disposed of on the land.[11] Since microplastic removal from SeS is not the aim of the sludge treatment, microplastics will be present and can become concentrated in this sludge, and can persist in the soil for long periods.[12] SeS can be a significant source of microplastic contamination into soil, soil animals, microbes, and plants.

Importance of Microplastics in Sewage Sludge:

Despite the high number of microplastics in the wastewater influent to WWTP, most of the wastewater treatment processes are effective in removing 84 to 99% of microplastics from the wastewater.[13,14]

This relatively high efficiency of removal necessitates that these "removed" microplastics concentrate in sludge, a byproduct of wastewater treatment. Sludge consists of primary sludge (fecal matter) and post-treated activated secondary sludge (biosolids).

20% to 60% of a WWTP's total operating costs are related to sludge management, which is disproportionately high considering that sludge accounts for only 1 to 2% of the effluent volume.[15] SeS is rich in organic material, phosphorus, and nitrogen, and can be very effective in improving soil quality. The most common method used to handle sludge is its application to agricultural lands.[16]

Utilizing SeS as a soil fertilizer or in landfills is one way to recycle waste materials in a circular manner. Due to the presence of microplastics in SeS, the use of SeS in agricultural lands can introduce microplastics into the soil, contaminating terrestrial ecosystems. These particles may also be transported into nearby water bodies through surface water runoff and can also impact aquatic environments. These microplastics can also be ingested by animals in the soil and introduced into the food chain, potentially affecting crop production, crop health, and human health.

They can create long-lasting contamination of agricultural lands, reducing the overall productivity of these lands in growing crops and raising concerns about maintaining agricultural growth and food security.

Treatment of Sewage Sludge:

Several processes can be used to treat sewage sludge, including stabilizing, thickening, drying, dewatering, composting, anaerobic digestion, lime treatment, and thermal treatment. Conventional sludge treatment methods have not demonstrated a reduction in microplastic concentration. Composting has been shown to alter the surface structure and reduce the number of microplastics in sewage sludge in China.[17] Composting is aerobic biodegradation of organic material, which is exothermic. This raises the temperature in the sludge to over 70°C, which can cause degradation and fragmentation of microplastics within the sludge.

Concentration of Microplastics:

It is proposed that the concentration of microplastics in the influent to a WWTP determines the concentration of microplastics in the SeS.[18]

In recent review articles on this topic, a wide range of concentrations has been observed, varying by country of origin and specific WWTP (Table 1). Microplastics can range anywhere between 0.37 and 495,000 microplastic particles per gram of SeS. Since the weight of microplastics can be difficult to measure, a quantitative method of counting particles per fixed weight of the sewage sludge is used and is described as MP/g (number of microplastics/gram of sewage sludge). Other reasons for microplastics concentration variability in wastewater and SeS include differences in urbanization, population density, plastic use, and the number of surrounding industries. Regions with advanced waste management practices have lower microplastic loads compared with regions with inadequate waste management practices. Warm seasons are associated with higher concentrations of microplastics in influent water and, consequently, in sewage sludge.[19]

Repeated sludge applications are associated with higher concentrations of microplastics in agricultural soil, which persist over time.[20]

In addition to these reasons, the variability in microplastics in sewage sludge may be related to improper or inconsistent sampling and differences in testing methods.[21] There is a need for standardized procedures for collecting, pretreating, and testing microplastics in SeS.

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Table 1: Concentration of reported microplastics as the number of Microplastics per gram of sewage sludge from review articles showing the range of microplastic concentration detected.

Author	Title	Journal	Minimum MP/g	Maximum MP/g	Number of sites
Charles Rolsky *et al.* [22]	Municipal sewage sludge as a source of microplastics in the environment	Current Opinions in Environmental Science and Health	0.45	113	67
Maliheh Arab *et al.* [23]	Microplastics in Sludges and Soils: A Comprehensive Review on Distribution, Characteristics, and Effects	Chemical Engineering	510	495,000	22
Sarra Hechmi *et al.* [24]	Soil contamination with microplastics (MPs) from treated wastewater and sewage sludge: risks and sustainable mitigation strategies	Discover Environment	18	240,300	23
Fahir Hassan *et al.* [25]	Microplastic contamination in sewage sludge: Abundance, characteristics, and impacts on the environment and human health	Environmental Technology & Innovation	0.37	169,000	13
Daisy Harley Nyang *et al.* [26]	Investigation and analysis of microplastics in sewage sludge and biosolids: A case study from one wastewater treatment works in the UK	Science of the Total Environment	0.51	169,000	65

Size and shape of microplastics:

As shown in Table 2, more than 80% of microplastics in sewage sludge are less than 500 micrometers in size.[27] It is thought to be related to the quick adsorption of small microplastics onto sewage. Larger microplastics can interfere with flocculation and sludge dewatering.[28]

Conesa and Ortuno classified the types of microplastics into different shapes, including microfibers, fragments, spheres, and granules.[29]

The most common types were microfibers, followed by fragments and films. These account for 60 to 85% of all microplastics in sewage sludge.[23]

Table 2: The size and shape of microplastics in sewage sludge.

Author	Title	Journal	Year	Purpose	Size Distribution Findings	Type (Fiber/Fragment)
H Kang *et al.* [30]	Occurrence of microplastics in municipal wastewater treatment plants	Environmental Health and Toxicology	2018	Assess microplastic presence in WWTPs' sludge	>80% of microplastics <500 µm; most commonly detected: 20–300 µm	Fragments are dominant; some fibers
X Li *et al.* [31]	Microplastics in sewage sludge from wastewater treatment plants in China	Water Research	2018	Study microplastic occurrence and risks in sewage sludge	60–90% <500 µm; particles <100 µm dominated sludge samples	Fibers are dominant, followed by fragments
Corradini *et al.* [20]	Evidence of microplastic accumulation in agricultural soils from sewage	Science of the Total Environment	2019	Examine microplastic transfer via sludge to soil	Peak particle size range: 100–300 µm; particles <1 mm comprised >90%	Fibers and fragments were both found; fibers are more prevalent
NB Turan *et al.* [32]	Microplastics in wastewater treatment plants: Occurrence, fate, and identification	Process Safety and Environmental Protection	2021	Review detection methods and fate of microplastics in WWTPs	~70–85% of detected microplastics in sludge <500 µm	Fibers standard; fragments also observed
Ziajahromi *et al.* [33]	Wastewater treatment plant effluent as a source of microplastics: review of the fate, chemical interactions, and potential risks to aquatic organisms	Water Science & Technology	2016	Review WWTPs as microplastic sources	The majority of microplastics in sludge are <1 mm; fine particles are prevalent.	Fragments and fibers both reported
Liu *et al.* [34]	Effects of microplastics on the properties of different types of sewage sludge and strategies to overcome the	Science of the Total Environment	2023	Characterize sludge microplastics and assess removal strategies	>50% of microplastics were <300 µm; larger particles (>1 mm) were rare	Fragments are slightly more common; some films and fibers
Gatidou *et al.* [35]	Review on the occurrence and fate of microplastics in Sewage Treatment Plants	Journal of Hazardous Materials	2019	Review the distribution, fate, and management of microplastics in WWTPs	75–95% of particles <500 µm; distribution varies based on treatment technology	Fibers are dominant in most samples

Microplastics Polymer Composition in Sewage Sludge:

The most common type of polymers seen were the polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyamide (PA), followed by polyester, polystyrene (PS) and polyvinyl chloride (PVC) as shown in Table 3.[23] This maybe because polyethylene and polypropylene are the most

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used plastics, and polyester and polyamide are frequently released with washing synthetic clothes.[27]

Table 3: Polymer composition of microplastics seen in sewage sludge on different articles.

Author(s)	Title	Journal	Year	Polymer Composition Findings
H Kang *et al.* [30]	Occurrence of microplastics in municipal wastewater treatment plants	Environmental Health and Toxicology	2018	PE, PP, and PS are the most common; some PET and PVC
X Li *et al.* [31]	Microplastics in sewage sludge from wastewater treatment plants in China	Water Research	2018	PET, PE, PP dominant; trace PS and PA
Corradini *et al.* [20]	Evidence of microplastic accumulation in agricultural soils from sewage	Science of the Total Environment	2019	PET and PE are prevalent; also detected are PP and PS
NB Turan *et al.* [32]	Microplastics in wastewater treatment plants: Occurrence, fate, and identification	Process Safety and Environmental Protection	2021	PE and PP are dominant in sludge; PET is also found
P Kay *et al.* [36]	Wastewater treatment plants as a source of microplastics in river catchments	Environmental Science & Pollution Research	2018	Varied: PE, PP, PET, PS, PVC in different proportions
Liu *et al.* [34]	Effects of microplastics on the properties of different types of sewage sludge and strategies to overcome the inhibition: A review	Science of The Total Environment	2023	PP and PE major types; some PS, PET, PA
Hu *et al.* [37]	Current research trends on microplastic pollution from wastewater systems: a critical review	Environmental Science and Technology	2019	PET and PE are the most reported; regional differences affect composition

*PET = polyethylene terephthalate, PE = polyethylene, PP = polypropylene, PS = polystyrene, PVC =polyvinylchloride, PA = polyamide

Surface morphology of microplastics in sewage sludge:

The surface of microplastics in sludge demonstrates varying degrees of deterioration.[28] This may be the result of the sludge treatment process and causes these microplastics to have scratches, folds, and aggregated structures.[31] These are thought to be areas where microplastics can readily trap heavy metals and other organic pollutants. Eventually, these microplastics will fragment along the folds or scratches, forming even smaller microplastics.

Effects of microplastics on soil and plant growth:

Microplastics have been shown to decrease soil bulk density and increase the water-holding capacity of soils. These changes mimic the effects of waterlogging, which can result in increased susceptibility to pests/diseases, root decay, and a reduction in soil oxygen levels.[38] Microplastics can also increase microbial activity in the soil, which can have long-term consequences on the soil.

Research indicates that the effect on plants is complex, with an increase in root length and root surface area but a decrease in shoot length and shoot biomass.[39] The increased root growth may be due to altered soil porosity and increased water in the soil due to the presence of microplastics. These findings suggest an adverse effect on overall plant health due to the negative impact on shoot growth, which indicates a decrease in nutrition to the shoots.

Microplastics have also been shown to absorb persistent organic pollutants (POPs) such as pesticides and dioxins and furans (byproducts of combustion and incineration). These are carried by microplastics from the soil to the plants, where they desorb and get deposited in the plants. In addition, polycyclic aromatic hydrocarbons can be absorbed by microplastics, increasing their bioavailability to plants and other organisms. This process of bioavailability and bioaccumulation of chemicals such as POPs and PAHs can threaten our entire ecosystem by affecting both plant life and animal life. [40]

Conclusion

Wastewater treatment plants have improved their efficiency in removing microplastics from wastewater. This efficiency has paradoxically shifted the burden of microplastics onto one of its byproducts, sewage sludge. Sewage sludge is routinely applied to agricultural land and landfills and can be accidentally discharged into the environment, introducing microplastics into both soil-based and aquatic ecosystems. Most microplastics are fine fibers less than 500 μm in size, as discussed earlier. Microfibers may get concentrated in sludge due to their long and thin shape, which allows them to bypass some filters. Commonly found microplastics in sewage sludge include polyethylene, polypropylene, and polyethylene terephthalate. Sewage sludge is an often-overlooked source of microplastic contamination in agricultural lands, which can impact the soil, soil animals, crop growth, and human health. The number of microplastics in agricultural lands increases with the number of sludge applications. It can be reasonably surmised that microplastic concentrations in agricultural lands are and will become an even more serious problem. Microplastics have a myriad of adverse effects, including their impact on plants and their ingestion by microorganisms and other animals, and their profound effect on the health of animals and humans. This underscores the need for standardizing global methods for detection and quantification, implementing mandatory regulations related to microplastics monitoring in WWTPs and sewage sludge output, improving existing treatment of sewage sludge with proper disposal procedures to reduce and prevent microplastics' entry into the environment, and investing in innovative technologies to degrade and minimize microplastics in sewage sludge.

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