Chapter 2
Characterization of Sewage and Sludge

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Abstract Sewage and sludge characterisation is essential to comprehending their effects on the environment and improving treatment procedures. The physical, chemical, and biological characteristics of sewage and the accompanying sludge produced during wastewater treatment are the main subjects of this research. A number of parameters were examined, including pH, temperature, total suspended solids (TSS), chemical and biological oxygen demands (BOD and COD), nutrients (phosphorus and nitrogen), heavy metals, and microbial composition. The findings show that the composition varies significantly according on whether the sewage comes from a mixed, industrial, or residential source. The high organic content, nutritional richness, and possible pollutants, such as harmful metals and pathogenic bacteria, were noted during sludge characterisation. These results are essential for choosing the best treatment methods, guaranteeing secure disposal or reuse, and lowering environmental and public health hazards. The research emphasises how crucial thorough characterisation is to promoting resource recovery and sustainable wastewater treatment techniques.

Keywords Domestic sewage · Characterization · Mass spectrometry · Nutritional composition

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2.1 Introduction

Characterization of solid waste and sewage is an important step in understanding the public health and environmental hazards associated with them. The composition and type of wastes generated are changing with the change in our lifestyles (Gusiatin et al. 2024). This topic is very important for reducing public health risks, ensuring regulatory compliance, and improving recovery processes for sustainable waste treatment practices (Sava et al. 2024).

With this scenario, it is evident that the microplastics, hazardous chemicals, and carcinogenic elements in water, wastewater, sludges and sewage are growing day by day (Kumar and Gupta 2020; Gupta and Gupta 2016; Singh et al. 2018). Characterization of sewage and sludge types develops proper management strategies (Messaoudi et al. 2024). There is a wide range of pollutants found in various types of sewage, including organic matter, nutrients such as nitrogen and phosphorus, heavy metals, and emerging contaminants, along with pathogens (Brisolara and Ochoa 2016). Table 2.1 highlights different key components in sewage and sludge.

By systematically analyzing these components, researchers and wastewater treatment professionals can gain a clearer understanding of the potential risks linked to discharging treated effluent into natural water bodies. This understanding enables them to devise more effective treatment strategies tailored to specific waste streams (Abrahão Cezarini et al. 2024).

The sludge and sewage characterization process leads to the optimization of treatment processes (Mladenovič et al. 2017). There are several technologies available for contaminant removal from sewage and sludge, using physical, chemical, and biological methods. Proper understanding of the chemical and physical properties of these materials includes pH, biochemical oxygen demand (BOD), total suspended solids (TSS), total dissolved solids (TDS), and chemical oxygen demand (COD) that enable operators to select the correct treatment process in order to enhance

Table 2.1 Key components in sewage and sludge

Components	Potential risks	Examples	References
Organic matter	Increases BOD, eutrophication	Carbs, proteins, fats	Cezarini et al. (2024)
Heavy metals	Toxicity to human and as well as aquatic life	Lead, mercury, cadmium	Gusiatin et al. (2024)
Pathogens	Public health hazards	Bacteria, viruses, protozoa	Łomińska-Płatek et al. (2024)
Emerging components	Heavily persistent in the environment	Pharmaceuticals, microplastics, hormones	Raveendravarrier et al. (2025)
Hazardous chemicals	Carcinogenic and mutagenic effects	Pesticides, industrial chemicals	Yáñez-Hernández et al. (2024)

Table 2.2 Treatments for contamination removal

Treatments	Techniques involved	Target contaminants	Advantages	References
Physical treatment	Filtration, sedimentation	Suspended solids, large particles	Primary cost-effective method, can be easily operated	Soni et al. (2024)
Chemical treatment	Coagulation, precipitation, oxidation	Nutrients, toxins	Effective for specific contaminants	Jin et al. (2025),
Biological treatment	Activated sludge, Biofilm reactors	Pathogens and organic matter	Sustainable to reduce pollutants	Li (2025)

the desired contaminant removal while minimizing toxic sludge production, hence cost-effectiveness with energy-saving curated treatment mechanisms for optimum outcomes. Besides, sludge characterization is also an excellent approach in terms of sustainable downstream management and possible reuse as biosolids. These biosolids will be appropriate for repurposing in agriculture, landscaping, or even as a resource for energy generation (Li and Yuan 2024, Ghazali et al. 2024).

Another critical aspect of sewage and sludge characterization is regulatory compliance. Many environmental regulations put strong limits on the discharge of pollutants and the quality of biosolids (Kujawiak et al. 2024). The same can be made sure that the wastewater treatment facilities abide by these legal requirements through effective characterization studies and thus escape penalties while helping to contribute to national and local goals on the environment (Brisolara and Ochoa 2016; Kominko et al. 2024). Table 2.2 represents various methods for contamination removal.

The importance of characterizing sewage and sludge extends to public health. Pathogens and toxic substances in wastewater can pose risks to communities and ecosystems (Chen et al. 2024a, b) Characterization efforts focus on the identification and quantification of harmful agents to address them with appropriate treatment and disposal measures (Rezig et al. 2024). This becomes of particular importance with emerging contaminants, which may not be understood in their entirety but might have very critical health implications (Paffrath et al. 2024; Khalil et al. 2024). Figure 2.1 represents different stages of Sludge passing through the sewage treatment plant.

2.1.1 Types of Sewage and Sludge

Sewage and sludge may be classified according to origin, treatment processes, pathogen content, which define further uses and methods of disposal (Gusiatin et al. 2024).

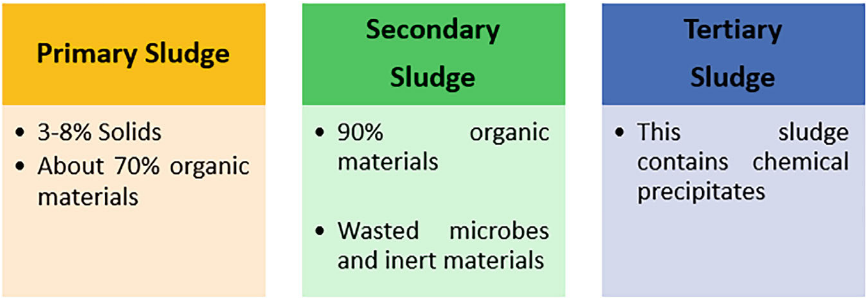

Fig. 2.1 Different stage of the sludge and their composition

2.1.1.1 Domestic Sewage

Domestic sewage is primarily wastewater originating from households, including human excreta, food residues, and many other trace chemicals. This type of sewage normally undergoes treatment in municipal wastewater treatment facilities to eliminate pathogens and pollutants before being discharged into the environment or being used again (Raveendravarrier et al. 2025).

2.1.1.2 Industrial Wastewater

Industrial sewage originates from manufacturing and industrial processes; it can contain a wide variety of pollutants such as heavy metals, micro-pollutants, and chemicals not normally present in domestic sewage. The treatment of this type of sewage often presents special challenges, as the normal methods used in municipal treatment may not effectively remove the pollutants (Li et al. 2023).

2.1.1.3 Class A Sludge

Class A sludge has been treated to kill specified pathogens, and therefore, it can be used without any restriction in agricultural uses and also freely sold to the public. Treatments to achieve Class A status may include pasteurization, heat drying, and thermophilic composting. This class of sludge poses the least risk to public health because of the undetectable presence of pathogens (Chang et al. 2023).

2.1.1.4 Class B Sludge

Class B sludge, on the other hand, may still contain some pathogen content, and thus its use is subject to more restrictions. This type of sludge is land-applied in such a manner that it does not present great risks either to human health or to the environment under controlled management (Madala 2025).

2.2 Overview of the Methods Used for Characterization of Sewage and Sludge

The characterization of sewage and sludge, in general, is a complex array of processes using diversified methodologies to assess their chemical, physical, and biological characteristics. Every characterization technique gives important information necessary for the management of wastewater and assessment of the environmental consequences apart from resource recovery. A summary of the main methods used in each of these categories is presented here (Alonso et al. 2023).

2.2.1 Chemical Characterization Techniques

Chemical characterization involves the analysis of the chemical composition of sewage and sludge with a view to determining the presence and concentrations of various substances, including both organic and inorganic contaminants (Facchini et al. 2021). Table 2.3 highlights the major chemical composition of sewage and sludge.

The main methodologies include:

Table 2.3 Different chemical components present in sewage and sludge

Components	Typical concentration range	Function/significance
Carbohydrates	10–20%	Energy source for microbial activity
Proteins	20–30%	Contribute to nutrient content (N Source)
Lipids	5–15%	Potential for biofuel production
Volatile fatty acids (VFAs)	1–5%	Precursors for bioplastics and bioenergy
Heavy metals	Variable concentrations	Environmental concerns, requires monitoring
Pathogens	Variable	Public health risk, necessitates treatment

2.2.1.1 Spectroscopic Techniques

Ultraviolet–visible spectroscopy is used to analyze the chromatic substances and organic components contained in wastewater. This method measures absorbance at specific wavelengths to assess dissolved organic material concentrations (Płonka et al. 2025). Infrared spectroscopy furnishes information regarding molecular structure and functional groups in organic materials by way of their characteristic absorption bands.

2.2.1.2 Chromatographic and Diffraction Methodologies

Gas Chromatography (GC) is applied for the volatile compounds. GC separates and quantifies organic pollutants like hydrocarbons, solvents, and pesticides (Ashekuzzaman et al. 2019). High-Performance Liquid Chromatography (HPLC) is in use for non-volatile compounds and polar, HPLC is quite effective for the detection of polycyclic organic substances in wastewater (Gupta 2018). X-ray diffraction (XRD) is the method of determining crystalline structures by the analysis of X-ray scattering.

2.2.1.3 Mass Spectrometry (MS)

Coupled with chromatography, mass spectrometry has been applied to the detailed molecular weight information and structural elucidation of organic compounds, thereby allowing for the identification of complicated mixtures present in sewage and sludge (Salva et al. 2025).

2.2.1.4 Elemental Analysis

ICP-MS and AAS are the techniques applied in the quantification of heavy metals and trace elements, which have a very significant role in the determination of toxicity levels and compliance with environmental regulations (Septiariva et al. 2022).

2.2.1.5 Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD)

COD measures the total amount of oxygen that can oxidize organic matter present in wastewater, while BOD measures the amount of oxygen that microorganisms in the water will use to degrade organic matter biologically. These parameters are very relevant for the determination of organic load and treatment efficiency (Wiercik et al. 2022).

Table 2.4 Different techniques for chemical characterization

Techniques	Method	Purpose/applications
Spectroscopic techniques	UV–Vis spectrophotometry	Analyzes chromatic substances and dissolved organic materials
	IR spectroscopy	Determines molecular structures and specified functional groups in organic/ inorganic constituents
	Mass spectrometry	Hyphenated technique, specifically coupled with different Gas Chromatographic techniques such as LC–MS, GC–MS, HPLC–MS, etc The techniques specifically identify molecular weight and charge to mass ratio of different analytes
	ICP-MS and AAS	Quantitation of heavy metals and trace elements to assess toxicity
Chromatographic techniques	Gas chromatography	Separates and quantifies volatile compounds (e.g., hydrocarbons)
	High-performance liquid chromatography	Detects non-volatile polar compounds (e.g., pharmaceutical dyes)
X-ray based techniques	X-Ray diffraction	Determines crystalline structures via X-ray scattering

Sewage treatment plants involve various stages and these stages thereby followed by different stages. The chemical characterisation techniques involve. An objective summary of different characterization techniques is presented in Table 2.4.

2.2.2 Physical Characterization Techniques

Physical characterization of sewage and sludge refers to the measurable and observable properties that may impact treatment processes. Key methods involved include:

2.2.2.1 Particle Size Distribution Analysis

Techniques like laser diffraction and sieving are used in the determination of the size distribution of the solid particles in sludge. The information is critical in optimizing processes like sedimentation and filtration (Domini et al. 2022). Figure 2.2 highlights different techniques associated to particle size distribution analysis.

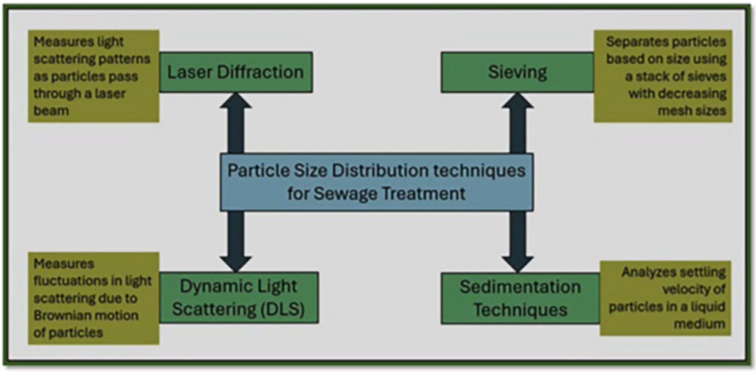

Fig. 2.2 Different particle size distribution techniques and their principles

2.2.2.2 TSS and VSS Measurement

Measurements of the Total Suspended Solids (TSS) and Volatile Suspended Solids (VSS) are useful for establishing the solids concentration of wastewater. The VSS, because it measures the organic material present, is particularly important to evaluate the efficiency of biological treatment operations (El Hayany et al. 2022).

2.2.2.3 Test for Density and Specific Gravity

Gravimetric procedures test and density gradient centrifugation types tests measure the density of sewage and sludge, parameters influencing settling behaviors and treatment systems design (van den Berg et al. 2020).

2.2.2.4 pH and Electrical Conductivity

The pH level is very important in establishing the level of acidity or alkalinity of the wastewater for microbial activity and chemical reactions. Electrical conductivity indicates ionic content, which affects the efficiency of the treatment process (Iticescu et al. 2018).

2.2.3 Biological Characterization Techniques

Biological characterization methodologies assess the presence and functionality of microorganisms in sewage and sludge, which are very essential in the processes of biological treatment (Yu et al. 2021). Main techniques include:

2.2.3.1 Microbial Community Analysis

Techniques such as Polymerase Chain Reaction (PCR) and next-generation sequencing (NGS) are used in the detection and quantification of microbial populations in sewage and sludge. This information is indispensable in understanding the processes occurring during biodegradation and assesses the effectiveness of biological treatment systems (El Houari et al. 2020).

2.2.3.2 Viable Cell Counts

Methods such as membrane filtration and culturing techniques allow for the quantification of viable bacteria and pathogens in wastewater, a crucial step in assessing public health risks (Michalska et al. 2022).

2.2.3.3 Enzyme Activity Assays

Measurements of the activity of specific enzymes, for example, dehydrogenase and cellulase, give very important information on the metabolic potential of microbial communities and their ability to decompose organic matter (Galintin et al. 2021).

2.2.3.4 Bioassays Used to Evaluate Toxicity

Bioassays use living organisms—such as algae and daphnia to determine the toxic impact of sewage and sludge on aquatic life. This helps determine the potential environmental impact of discharging treated effluent (Terekhin et al. 2024).

The examination of sewage and sludge using chemical, physical, and biological methods is very important for the effective management of wastewater and protection of the environment. Each of the adopted techniques provides unique information that is relevant in optimizing treatment processes, meeting regulatory standards, and safeguarding public health. By adopting these different techniques, wastewater treatment plants can obtain an overall understanding of their influent and effluent characteristics, thereby improve the outcome of treatment and create sustainable operating systems (Rangabhashiyam et al. 2022).

2.3 Environmental Implications

Sewage sludge, a residual byproduct of the treatment of wastewater, is a complex mixture of both organic and inorganic materials. Its composition varies depending on the characteristics of the influent and the treatment processes used. Its high content of nutrients, mainly nitrogen, phosphorus, and potassium, has resulted in its application as a soil amendment to increase the productivity of agriculture fields and soils. However, the application of sewage sludge raises serious concerns regarding soil quality and fertility, and environmental health because of the possible existence of harmful contaminants that include heavy metals, pathogens, and new pollutants like microplastics and pharmaceuticals (Brisolara and Ochoa 2016).

2.3.1 Composition of Sewage Sludge

Sewage sludge is a complex mixture of organic and inorganic materials that accumulates during the treatment of wastewater. The composition of the sludge varies considerably with the type of wastewater treated, the treatment processes used, and the peculiar characteristics of the influent.

2.3.1.1 Nutritional Composition

Sewage sludge contains essential plant nutrients, especially nitrogen (N), phosphorus (P), and potassium (K). The types and amounts of these nutrients determine their availability to crops. In sludge, nitrogen is found in many forms: organic nitrogen, ammonium (NH_4+), and nitrate (NO_3). While the plants can directly utilize ammonium and nitrate, the organic nitrogen must undergo mineralization, which slowly releases its nutrients. Phosphorus, usually found at lower concentrations in biosolids than nitrogen, is of special significance because of its importance in agriculture and the eventual depletion of traditional sources of phosphorus (Campo et al. 2022).

2.3.1.2 Pollutants and Contaminants

In addition to nutrients, sewage sludge is expected to carry a variety of pollutants, including heavy metals, pathogens, and organic micro-pollutants. The EPA of the United States has established pollutant limits for various constituents in sludge because these may pose risks to both human health and the environment.

Micro-pollutants, such as pharmaceuticals and endocrine-disrupting compounds, can be contained in dried sludge at levels up to hundreds of mg/kg, which calls for much concern about their possible ecological and health impacts once the sludge is used in agricultural practices (Jothinathan et al. 2023). Different sources of pollutants and contaminants are presented in Fig. 2.3.

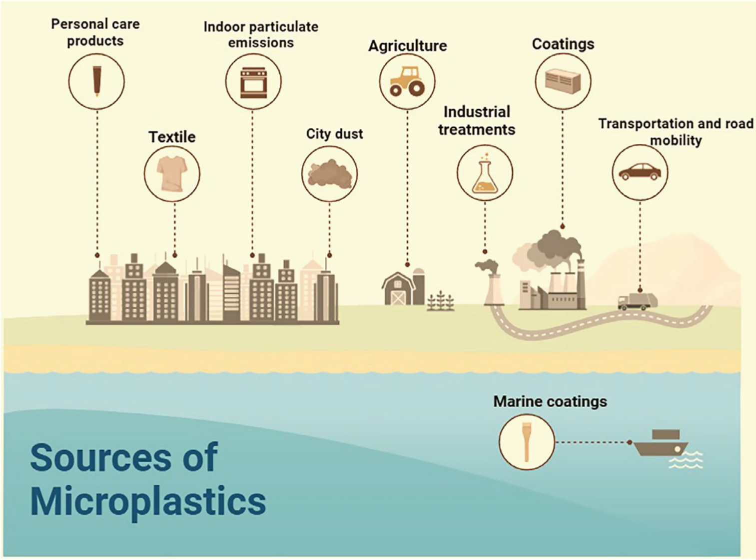

Fig. 2.3 Sources of microplastics as pollutants and contaminants

2.3.1.3 Pathogens

Pathogenic microorganisms are one of the major components making up sewage sludge. Pathogens such as *Salmonella*, as well as species of the genera *Cryptosporidium* and *Giardia*, can survive in untreated or improperly treated sludge and may pose a health risk unless properly inactivated. Various treatment methodologies, which include anaerobic digestion and alkaline stabilization, are used in an effort to reduce pathogen concentrations, hence improving the safety of the sludge for agricultural use (Appels et al. 2008).

2.3.2 Physical Characterisation of Sewage

The physical characteristics of sewage sludge, such as its water content, specific gravity, and size distribution, are important in handling, transportation, and agricultural application. In general, the sludge can be classified into primary sludge from physical treatment processes and secondary sludge generated during biological treatment processes. Good management of these characteristics is very vital in maximizing the beneficial uses of sewage sludge and minimizing all potential risks that may be associated with the application in the soil (Dramé et al. 2023).

2.3.3 *Impact of Sewage Sludge on Soil Quality*

This means that using sewage sludge, agriculture implies important changes regarding the quality of the soil itself, either by modifying nutrients levels, microbial populations, and sets of contaminants (Chang et al. 2023).

2.3.3.1 Nutrient Enhancement

Sewage sludge is believed to improve the fertility of soil by adding organic matter and essential nutrients. Another study showed that application of dehydrated sewage sludge significantly improved the amounts of soil organic matter and available major nutrients, such as nitrogen, phosphorus, and potassium, in upper layers within a short time period post-application; therefore, up to 20.6% of soil organic matter was obtained for a soil sample immediately following the operation. The study showed that, though it was most pronounced immediately after application, nutrient concentrations were still at significantly enhanced levels for the duration of the experiment a clear testimony to the ability of sewage sludge to enrich soil fertility with vital nutrients (Eid et al. 2020).

2.3.3.2 Soil Type and Toxicity

The toxicity associated with sewage sludge is contingent upon the type of soil, which profoundly influences its overall implications for soil quality. Empirical studies have demonstrated that diverse soil types, including sandy, loamy, and OECD artificial soil (OECD 207, 1984), display differing degrees of toxicity when subjected to sewage sludge treatment, particularly impacting the growth of plant roots and the viability of invertebrate species.

The EC(50) values for the inhibition of root growth in the different soils showed that OECD artificial soil was particularly sensitive to the application of sewage sludge, further underlining the need for consideration of the soil characteristics when assessing risks associated with sludge application (Domene et al. 2010a, b).

2.3.3.3 Pollutants and Monitoring

Notwithstanding its advantages, the use of insufficiently processed sewage sludge presents significant risks related to soil contamination, notably concerning heavy metals and pathogenic microorganisms. Ongoing assessment of sludge composition is crucial to minimize environmental hazards, especially considering the possible existence of toxic agents and heavy metals. The amalgamation of domestic, surface, and industrial wastewater can lead to the introduction of pollutants into the sludge, thereby requiring a comprehensive evaluation of its quality before application on land (Dramé et al. 2023).

2.3.3.4 Microbial Community and Soil Health

It has also been determined that sewage sludge may have a positive impact on the structure of the microbial community in soils, which will promote biological activity and improve soil health. Greater microbial biomass, resulting from the addition of biological solids, leads to better retention of moisture in the soil and reduced erosion, promoting better soil fertility over time. Long-term ecological effects due to heavy metals in sludge may alter microbial functions and overall soil health (Curci et al. 2020).

2.3.3.5 Fertility Enhancement

Using sewage sludge as fertilizer is known to offer great potential in enhancing the fertility of soils and further improving crop yield. Research shows that sewage sludge contributes organic matter to the soil, which is important in maintaining its health and fertility (Muter et al. 2022). In the following, the effects of different fertilization methods nitrogen and sewage sludge applications on soil organic matter quality and crop productivity were compared in five treatments established in a long-term field experiment initiated in 1993.

2.3.3.6 Nutrient Contribution and Organic Matter

Sewage sludge applies considerable amounts of organic matter to the soil. Annual carbon additions have been determined at 879 kg /ha year for the S120 treatment and 1758 kg /ha year for the S240 treatment. Despite these contributions, sewage sludge generally has a lower quality of organic matter compared to farmyard manure and thus may be less effective in improving CSOM (coarse-resolution soil organic matter) content than traditional organic fertilizers. For example, the S treatments did not exhibit a significant elevation in CSOM compared to the Con treatments, which might be explained by the relatively low C/N ratio of sewage sludge, stimulating rapid mineralization of organic matter. It is an end product of wastewater treatment, sewage sludge: that organic and inorganic mixture has a complex nature and varies with the influent characteristics and the treatment methods applied. Its high nutrient content, mainly nitrogen, phosphorus and potassium, has been used as an amendment to soil for increased agricultural productivity. There are concerns about soil quality and fertility, and environmental health that arise from using this material, as it is likely to contain hazardous contaminants such as heavy metals, pathogens, and emerging contaminants like microplastics and pharmaceuticals. The impact of

Table 2.5 Nutrient contribution and organic matter that contributes soil fertility

Aspects	Descriptions
Organic matter	879 kg/ha/year (S120), 1758 kg/ha/year (S240); lower quality than manure
CSOM impact	No Significant increase due to low C/N ratio causing rapid mineralization
Nutrient content	Rich in nitrogen, phosphorus, potassium; boosts crop productivity

sewage sludge on crop yield is considerable. In the mentioned study, the control treatment averaged 9.76 t DM/ha year while the other fertilization treatments, including those using sewage sludge, yielded an average of 12.3 t DM/ha year (Eyser et al. 2015). Table 2.5 represents different nutrient contribution and organic constituents establish soil fertility.

While there was no significant difference in yield from the fertilization treatments, the application of sewage sludge was associated with an increase in glomalin content, which is shown to correlate positively with levels of soil organic carbon. This would indicate that, though the yield improvement may not always be significantly greater in the short term, the future application of sewage sludge would well be worthwhile for soil health and productivity.

2.3.3.7 Quality of Soil Organic Matter

Soil organic matter quality parameters were evaluated using hot water and $CaCl_2$ extractions. Results showed that the mineral nitrogen treatment (N240) decreased soil organic matter quality as evidenced by lower mineralizable carbon and extractable carbon levels. S240 treatment has further presented significant increases in both hot water extractable organic matter and carbon content, which compares to those found in the control treatment, emphasizing the potential of sewage sludge for stabilizing organic matter in soil over time (Balík et al. 2022).

2.3.4 Evaluation of Toxicity from Sewage Sludge

The evaluation of sewage sludge toxicity is vital in understanding its environment-related ramifications, particularly in terms of soil quality and fertility. Sewage sludge, the solid residual produced by the wastewater treatment process, contains various toxic and hazardous materials that affect plant as well as animal life when applied to land as fertilizer.

Table 2.6 Toxicity of sewage sludge based on soil type

Type of soil	Test species	Toxicity indicator	EC (50)/LC (50) range	Observations
OCED artificial soil	*Lepidium sativum, Sorghum saccharatum*	EC (50) shows root growth	0.1–6.4%	Highest negative effects on root growth
Sandy soil	*Lepidium sativum, Sorghum saccharatum*	EC (50) shows root growth	0.03–9.4%	More tolerant compared to artificial soil
Loamy soil	*Lepidium sativum, Sorghum saccharatum*	EC (50) shows root growth	6.6–22.1%	Highest tolerance to sludge toxicity
Other soils	*Heterocypris incongruens*	LC (50) reprents survival rate	0.26–11.5%	Toxicity varies with sludge and soil

2.3.4.1 Influence of Soil Type on Toxicity of the Sludge

Some studies indicate that the toxicity level of sewage sludge is usually dependent on the soil type to which it is applied. In one such study, the effect of sandy, loamy, and OECD artificial soil on toxic sewage sludge was tested on three plant species, *Lepidium sativum*, *Sorghum saccharatum*, and *Sinapis alba*, and the invertebrate species *Heterocypris incongruens*. The OECD artificial soil proved to have the greatest negative effects on root growth, with EC(50) values ranging from 0.1 to 6.4%. Sandy soil had a more tolerant EC(50) value of 0.03–9.4%, while loamy soil also exhibited higher levels of tolerance, with EC(50) values of 6.6–22.1% aforementioned for OECD artificial soil. The highest LC(50) values for H. incongruencies range from 0.26–11.5%, depending on the sludge tested thus maintaining the idea of soil property in mediating sludge toxicity (Domene et al. 2010a, b).

Yet, research now points out that the toxic qualities of sewage sludge are sharply altered by the specific type of soil it is used in. Table 2.6 presents the toxicity of sewage sludge based on soil type.

2.3.4.2 Indicate the Unique Ways of Soil Type to Cause Toxicity

Some studies have shown that the soil application provides the necessary conditions for varying toxicity xenobiotics concerning sludge. One such study concerning sandy-loamy soil type and OECD artificial soil emphasizes the different toxic effects of sewage sludge across many plant species. According to the composition of contaminants, sewage sludge contains various contaminants, including heavy metals, organic compounds, and bacteria, which greatly vary in their toxic effects. According to the

EPA's 2009 Targeted National Sewage Sludge Survey, numerous toxic substances, including endocrine disrupters and metals, were found in sewage sludge- posing harmful effects for human and ecosystem health. According to the survey, 27 metals will end up in the mixture, depending on the concentration of semi volatile organics and polycyclic aromatic hydrocarbons. Because of the varying concentrations of bacteria, for instance, Salmonella, the health risks during the application of sludge on farmland grow exponentially (Domene et al. 2010a, b).

2.3.4.3 Emerging Pollutants and Microplastics

The emergence of new pollutants such as microplastics and per- and polyfluoroalkyl substances (PFAS) threatens to further complicate sewage sludge management. These contaminants pose an added risk due to their ability to build up in soils, leading to subsequent uptake by crops and raising the risk of inhalation and ingestion. Compounding the risk assessment for sludge application to agriculture is the variety of compounds and their synergistic interactions that may cause cumulative toxicological effects (Alvarenga et al. 2015).

2.3.5 Monitoring and Control

Sewage sludge toxicity risks will need to be effectively controlled and reduced. Wastewater treatment plants should put in place intermediate measures of control towards at-sources entry of toxic substances so as to improve and manage sludge quality before use. This is where the urgent need for new analytical methods to detect those contaminants emerges, since traditional approaches have failed to offer adequate data regarding the presence of hazardous substances, like microplastics. Continuous research on the impacts of sludge on soil ecosystems and food safety should be prioritized to guarantee everyone is protected from contracting diseases (Kulikowska et al. 2016).

2.3.6 Environmental Risks

The application of sewage sludge, generally called biosolids, to agricultural lands raises important issues about environmental health, mainly due to the presence of emerging pollutants and heavy metals that persist in the environment and impact soil quality and fertility. Land application is one practice adopted in the waste management of biosolids; approximately 40% of the six million dry metric tons of sewage sludge produced in a year in the United States are treated and applied on land, a practice that presents some dangers to the environment (Kirchmann et al. 2017).

2.3.7 *Emerging Pollutants*

Biosolids may act as a sink for a variety of emerging pollutants such as microplastics and other toxic substances. These pollutants impact not only the soil but also human health through bioaccumulation in the food chain. Evidence also suggests that the land application of biosolids may facilitate microplastic transfer to agricultural soils and ultimately into the greater environment. In addition, as systematic monitoring programs and standards pertaining to biosolid application are currently not in place, the hazards presented by biosolid application have amplified the need for more rigorous regulatory frameworks necessary to protect human health and the environment (Karlen et al. 2021).

2.3.7.1 Heavy Metal Contamination

Heavy metals, including lead, cadmium, and mercury, constitute a complex mixture of contaminants found in biosolids due to their prevalence in sewage. Some of these metals are regarded as essential at low doses, e.g., iron and nickel; yet others remain toxic and may cause metabolic defects in organisms that ingest crops cultivated in contaminated soils. Most heavy metals, once introduced into the soil, do not have quite the same shelf life biological or chemical degradation and remain on an environmental level as a persistent pollutant with a risk for bioaccumulation in the food chain. This is mainly alarming in developing countries, where the presence of insufficient control on landfill leachate stimulated the appearance of groundwater contamination that led to various health hazards threatening the community around (Saha et al. 2017).

2.3.8 *Recommendations for Mitigation*

To tackle these emerging environmental health threats, investments should ensue for continuous research on infrastructural changes toward wastewater treatment and proper land application of biosolids, as well as programs that raise public awareness about the dangers of the overuse of pharmaceuticals and plastics. Supportive regulations that consider the health of the environment and dispose of threats should be floated. The promotion of environmentally friendly products with better quality control in biosolids could minimize those risks (Nunes et al. 2021).

2.3.8.1 Mitigation Strategies

Treatment Processes

Effective treatment methods for municipal sewage sludge are critical to mitigating the potential health and environmental hazards associated with raw sewage sludge, which typically contains 1 to 4% solids and high levels of pathogens. Various treatment processes aim to stabilize sewage sludge, reduce pathogen content, and enhance solids concentration. These methods are often complex and require specific conditions such as holding time, temperature, pH, and solids content to be effective (Fusi et al. 2017).

Regulatory Framework

In addition to treatment processes, stringent regulations play a vital role in managing the risks associated with the land application of biosolids. In Pennsylvania, for instance, the biosolids regulations are more restrictive than federal guidelines, requiring adherence to additional risk-management measures. These include prohibitions on applying biosolids in environmentally sensitive areas, on steep slopes, and near water sources, as well as implementing soil conservation plans. Furthermore, mandatory training for personnel involved in land application programs ensures that practices comply with safety and environmental standards.

Public Communication and Awareness

Effective communication concerns the implications regarding the ingestion of pharmaceutical substances, or the environmental issues caused by agricultural runoff and their potential to start changing the entire scene. Raising public awareness will lead to a realization of the risk of such misuse of pharmaceuticals or plastics and may start exerting adequate pressure on decision-makers for the implementation of greener alternatives, finally finding ways to lessen the volumes of contaminants in the environment.

Innovative Technologies

Research continues into innovative degradation processes for persistent contaminants, such as perfluorinated compounds. Low-temperature mineralization methods, for example, are introduced as potential devices for breaking down perfluoro carboxylic acids through advanced chemical pathways. In building new technologies, it will also be crucial for future technologies to ensure dual benefits-they must be effective and environmentally friendly, catering to a wide range of emerging pollutants while minimizing energy consumption and capital expenditures (Ćwiertniewicz-Wojciechowska et al. 2023).

2.4 Potential of Circularity and Other Forms of Usage of Sewage and Sludge

Increased global concentration on sustainability and the circular economy means a change in the paradigm of sewage and sludge management. Once considered wastes, sewage and sludge are now gaining acknowledgment as alternative valuable resources for applications in many sectors. This review aims to summarize the current understanding of sewage and sludge composition, emphasizing their potential for circular uses. Chemical, physical, and biological characteristics of the two materials have been discussed with applications in energy, agriculture, and construction. Thereafter, the barriers and opportunities for the application of circular economy principles in sewage and sludge context are analyzed (Karlen et al. 2021).

The world is facing unprecedented environmental challenges, which include climate change, water scarcity, and waste management. The concept of circular economy has emerged as a promising solution, aiming to reduce waste and the consumption of resources by promoting the reuse and recycling of materials. Sewage and sludge, traditionally considered waste, are now seen as vital resources applicable in several sectors. The chemical characterization of sewage and sludge has led to the observation of the presence of different compounds, such as carbohydrates, proteins, lipids, and volatile fatty acids (VFAs). The details of the chemical composition of sewage and sludge can be found in various amid each other (Alvarenga et al. 2015).

2.4.1 Energy Production

Energy recovery is a process through which sewage and sludge can be converted into a useful product, including anaerobic digestion, gasification, and pyrolysis. Anaerobic digestion is a known technology for biogas production, which is a mixture of methane and carbon dioxide that can be used as a renewable energy source. Gasification and pyrolysis are thermal processes that convert organic matter into syngas and bio-oil, respectively, for use as fuels (Hidaka et al. 2016; Gahlot et al. 2022).

2.4.2 Agricultural Applications

Sewage and sludge can thus be seen as fertilizers and soil amendments in agriculture, providing nutrients to foster plant growth. The application of sewage sludge as fertilizers has been shown to improve soil fertility and promote crop yields sustainably. Nevertheless, the pollutants and pathogens in sewage and sludge introduce risks to human health and the natural environment; hence, effective treatment and management will be warranted to mitigate the risks (Zhang et al. 2022).

2.4.3 Construction Materials

Sewage and sludge can serve as raw materials in the production of construction materials, such as bricks, concrete, and cement. The incorporation of sewage sludge ash as an addition to cement is proposed to improve the mechanical properties of concrete (Chang et al. 2020).

2.4.4 Challenges and Opportunities

So many challenges, such as the presence of pollutants and pathogens, public perception, and the existing regulatory frameworks, face the implementation of circular economy principles into sewage and sludge management. The potential benefits of circular usage, including energy production, agricultural applications, and construction materials, present opportunities for sustainable development and economic growth (Shafii et al. 2019).

2.5 Conclusion

An essential part of efficiently treating and managing wastewater is characterising sewage and sludge. The complexity of sewage and sludge, which differ greatly based on their source and the procedures they go through, is highlighted by this research. Important details on their composition and possible effects on the environment are provided by key factors such nutrients, heavy metals, microbial content, chemical oxygen demand (COD), and biological oxygen demand (BOD). Although there are options for resource recovery, such as composting and biogas generation, because to the high organic matter and nutritional content, the presence of hazardous pollutants, such as heavy metals and pathogens, need rigorous monitoring and management to avoid environmental contamination and health hazards. All things considered, this research emphasises how crucial comprehensive sewage and sludge analysis is to satisfying environmental regulations, streamlining treatment procedures, and encouraging sustainable practices. In order to turn wastewater from a disposal issue into a useful resource, thorough characterisation will remain essential given the growing emphasis on waste reduction and resource recovery. Enhancing management plans and environmental results requires ongoing study and the use of cutting-edge analytical methods.

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