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Analysis of Properties of Municipal Sewage Sludge and its Application: A Short Review

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This paper analyses the geotechnical properties of municipal sewage sludge to assess its suitability for various engineering applications. A thorough review of research published between 2017 and 2024 focused on the physical, chemical, and mechanical characteristics of sewage sludge. The physical properties examined include particle size distribution, specific gravity, and moisture content, providing insights into its composition for potential uses. Chemical analyses identified key elements and contaminants, highlighting environmental impacts and compatibility with soil systems. Mechanical properties such as shear strength, compressibility, and consolidation behaviour were evaluated to understand the sludge's engineering behaviour under different loading conditions.

The review underscores the importance of site-specific studies that analyse the in-situ behaviour of sewage sludge and its interactions with existing soils. Long-term monitoring has been essential for assessing settlement, stability, and environmental impacts. The findings demonstrate that a wealth of data exists to inform responsible and sustainable utilization of municipal sewage sludge in geotechnical applications, supporting waste management practices and promoting circular economy principles. By understanding these properties, engineers can make informed decisions that advocate for environmental preservation while effectively managing municipal wastewater by-products.

Keywords: Geotechnical Properties, Municipal sewage sludge, Particle size distribution, Treatment Process

1. Introduction

The management of municipal wastewater is critical for safeguarding public health and protecting the environment. A significant byproduct of wastewater treatment facilities is municipal sewage sludge, a semi-solid residue containing a complex mixture of organic and inorganic constituents [Sharma et al., 2020]. This sludge is produced following either aerobic or anaerobic digestion processes and poses significant challenges for disposal due to its heterogeneous composition. Recent trends show a marked increase in sewage sludge production, driven by rapid urbanization, population growth, and industrial development [Liang et al., 2003]. Effective treatment and management of this sludge are essential to minimize its adverse effects during disposal and application.

An emerging area of research focuses on the geotechnical properties of municipal sewage sludge, which are critical for assessing its suitability for various engineering and environmental applications. This review aims to provide a comprehensive characterization of the geotechnical aspects of sewage sludge, detailing its physical, chemical, and mechanical properties influenced by treatment methods and regional variations [Bai et al., 2023].

Unlike previous reviews that may primarily discuss the composition and general treatment methods for sewage sludge, this paper emphasizes the nuanced geotechnical properties essential for practical applications, such as land reclamation, soil enhancement, and construction projects. We incorporate both laboratory experiments and field investigations, ensuring a holistic understanding of sludge behaviour under different environmental conditions.

Key physical properties, including particle size distribution, specific gravity, and moisture content, play pivotal roles in determining sludge suitability for various applications. Chemical analyses reveal beneficial elements as well as potential contaminants, guiding responsible usage. Furthermore, understanding mechanical properties—such as shear strength, compressibility, and consolidation behaviour—is crucial for evaluating the engineering performance of sewage sludge in diverse scenarios [Benítez et al., 2013].

In addition to traditional laboratory assessments, this review integrates findings from field investigations to capture the in-situ behaviour of municipal sewage sludge [Guo et al., 2006]. Such site-specific studies enhance our understanding of sludge interactions with existing soils and enable long-term monitoring of stability and environmental impacts [Clarkson et al., 2021].

By synthesizing current research and emphasizing the geotechnical properties of municipal sewage sludge, this review not only underscores the material's significance in sustainable engineering practices but also identifies gaps in existing literature, providing a roadmap for future research directions.

2. SEWAGE SLUDGE GENERATION

Rapid urbanization and population growth in India have led to an extraordinary increase in the generation of municipal sewage sludgeas a byproduct of wastewater treatment plants nationwide, this sludge presents notable obstacles to waste management and environmental sustainability. [Tejada et al., 2013]. Simultaneously, it presents an opportunity to explore innovative approaches for its beneficial use in various geotechnical applications. Various studies such as [Franz et al., 2008; Tejada et al., 2013;and Benítez et al., 2013]. have focused on investigating the geotechnical properties of sewage sludge. The increasing need for water and sanitation services in India has led to a rise in the volume of sewage sludge generated from wastewater treatment plants. In light of the country's commitment to sustainable development, there is a growing imperative to comprehensively understand the geotechnical characteristics of this sewage sludge so that its application can be done for the environment.

Furthermore, considering the diverse climatic conditions prevalent in India, long-term monitoring will contribute to understanding the resilience and environmental sustainability of sewage sludge applications over timeAccording to the Central Pollution Control Board of India, the production of wastewater, totalling around 38,354 million liters per day (MLD) in urban regions, stands as the predominant source of freshwater contamination in India. [El-Motaium. et al., 2007]. Only around half, approximately 11,786 MLD, Undergoes treatment at sewage treatment plants (STPs), while the remainder of the sewage is discharged untreated. [Yilmaz et al., 2018].Therefore, almost all water bodies such as ponds, lakes, rivers, etc are Contaminated as a result of the release of untreated sludge. The waste water treatment process is shown in Figure 1.

Figure 1. Sewage treatment.

In recent times, there has been an emphasis on adopting waste minimization, recycling, and reuse measures to decrease waste generation. Diverse management tactics are employed to alleviate the environmental consequences of waste handling [Bai et al., 2023]. While sewage sludge does provide a source of energy and nutrientsMoreover, it can also serve as a raw material for industrial production, energy generation, and land treatment. The type of distribution (on-site, off-site) and the degree of post-digestion are factors to consider .[Lund et al., 2004]. Fresh and untreated sludge contains many organisms; Most of the water has high (BOD) Biochemical Oxygen Demand, often putrid and malodorous. But sewage also contains nutrients that are important for plants (such as nitrogen and phosphorus) and can be an excellent fertilizer. Once the most important products such as carbon monoxide in sewage are reduced, this will improve the soil structure of the roots or it can change bio digestion or combustion for energy. Since sewage can absorb pollutants (such as heavy metals, and chemicals) Pollutants from industries and other activities can accumulate within the sludge [Benítezet al., 2013]. There are multiple methods by which sewage sludge can be transformed into valuable outputs. These include co-combustion and mono-combustion for energy recovery, anaerobic digestion with biogas production, aerobic composting, pyrolysis, gasification, and wet oxidation [Kumar et al., 2016].In which the process of gasification is shown in Figure 2. The selection of sewerage methods or sludge management techniques from available options should prioritize their environmental impact, favouring technologies with minimal environmental footprint. Public awareness of the environmental effects of management practices accepted for sludge of sewage treatment plants has increased.

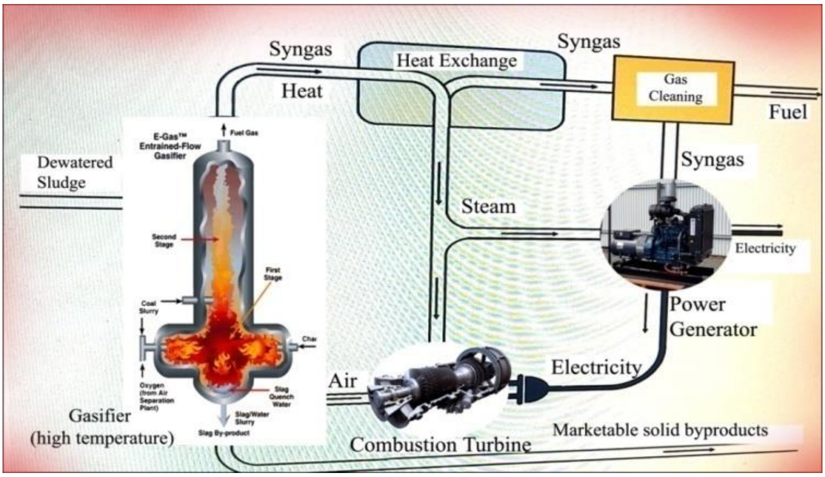

Figure 2. Process of gasification.

3. SEWAGE SLUDGE MANAGEMENT

Effective management of sewage sludge is crucial for minimizing environmental pollution resulting from its disposal. Sewage sludge management practices play a crucial role in addressing the challenges associated with its generation, treatment, and disposal. Geotechnical properties, which encompass physical, chemical, and mechanical characteristics,MSS can be treated and used as a soil conditioner or fertilizer. Research has shown that when properly processed, it can improve soil structure, increase nutrient content, and enhance microbial activity (Huang et al., 2024). However, concerns regarding heavy metal accumulation and pathogen transfer must be addressed. influence the potential applications of sewage sludge in various engineering and land management projects.

Source and pre-treatment of industrial and domestic wastewater can reduce the contamination levels in sewage sludge. Pre-treatment processes, such as primary and secondary sedimentation, help in removing solid particles and improving the overall quality of sewage sludge. Anaerobic digestion is a treatment process that not only stabilizes sewage sludge but also produces biogas as a by-product. Composting sewage sludge with organic materials can enhance its stabilization and reduce pathogens. The resulting compost can be utilized for soil improvement, with considerations for its geotechnical properties influencing application rates Utilizing pre-treated sludge in agriculture improves soil fertility and structure. Geotechnical properties such as texture, organic matter content, and nutrient composition influence the success of land application practices. Proper disposal in engineered landfills with the collection of leachate and liner systems is essential to prevent environmental contamination.

Geotechnical properties of sewage sludge impact its compaction, settlement, and potential for leachate generation. Energy Recovery incineration and thermal treatment can decrease the sludge volume of which is generated from sewage and recover energy. Residual ash from incineration may possess different geotechnical characteristics compared to raw sewage sludge. Regulatory Compliance and adherence to local and national regulations are critical for responsible sewage sludge management. Compliance Adhering to regulations ensures that geotechnical properties are integrated into a broader context of safeguarding both public health and the environment. Research and Innovation continued research on the geotechnical properties of sewage sludge can open up new avenues for its sustainable management. Innovations in treatment technologies and geotechnical applications contribute to more effective and environmentally friendly practices. But still performing or considering the biochar as catalyst for the treatment of heavy metals wastewater the lab testing needs to be performed before using it for the treatment so that it can assure that it can perform the proper treatment. A lot of efforts have been made for efficiency to enhance they're by the activation of chemicals or through the treatment of heat [Kaushal et al., 2017].In conclusion, integrating geotechnical considerations into sewage sludge management practices is essential for Maximizing the advantageous utilization of this resource while minimizing environmental hazards A holistic approach that combines scientific research, technological innovation, and regulatory compliance is necessary for achieving sustainable and responsible sewage sludge management.

Composting sewage sludge involves an aerobic decomposition process that enhances the organic content within the sludge.. The complete reaction of compost is as follows.

$C_{10}H_{19}O_8N + 12.5\ O_2 \rightarrow 10CO_2 + 8H_2O + NH_3$

Biological stabilization is essential during the composting process to mitigate pollution risks associated with the sludge. Another method of sewage sludge management involves its utilization in biogas production. It can also be harnessed for the generation of clean and renewable energy. It can also be utilized for clean and renewable energy generation. It serves as an optimal fuel for heating and electricity generationBiogas, produced via the anaerobic fermentation of bacteria or biodegradable substances, typically has a calorific value ranging from 21 to 25 MJ/m3, with an average methane concentration of around 65%, rendering it roughly 30 [Schillinger et al.,2012].Anaerobic digestion is a naturally occurring biological process of decomposition that occurs in the absence of oxygen. It breaks down organic waste to produce biogas, a blend of methane and carbon dioxide.. Methane has a calorific value comparable to carbon monoxide, rendering biogas a valuable energy source. [Halls et al., 2000].

4.GEOTECHNICAL PROPERTIES OF MUNICIPAL SEWAGE

Sewage sludge offers insights into the physical, chemical, and mechanical properties that influence its potential applications in geotechnical engineering. The physical properties of Indian municipal sewage sludge, including particle size distribution, density, and moisture content, are vital considerations for determining its suitability for diverse geotechnical applications [Viau et al., 2011]. Given the regional variations in industrial discharges and wastewater treatment processes, the chemical composition of sewage sludge in India is likely to exhibit unique characteristics. Understanding these properties is crucial for assessing the environmental impact and engineering feasibility of various reuse options. Mechanical properties, such as shear strength and compressibilityPlay a crucial role in assessing the stability and load-bearing capacity of sewage sludge when employed in geotechnical projects. The Indian scenario introduces additional complexities, including variations in climate, soil types, and land use practices, which may influence the performance of sewage sludge in different regions. Field investigations within the Indian context will provide site-specific insights into the behavior of municipal sewage sludge when integrated with local soils. The geotechnical properties of municipal sewage, encompass a range of physical, chemical, and mechanical characteristics that are important for assessing its suitability for various engineering applications. Here some key geotechnical properties of municipal sewage are discussed.

4.1 Physical Properties

Particle size distribution i.e., the distribution of particle sizes in sewage affects its texture and permeability. The density of sewage sludge influences its weight and compaction characteristics. Moisture Content i.e., the quantity of water present in sewage sludge affects its consistency and handling properties. The analysis demonstrated that variations in moisture content significantly affected the consistency and handling properties of sewage sludge, with higher moisture content leading to increased viscosity and difficulty in handling. Managing moisture content is essential for optimizing the processing and disposal of sewage sludge, as it directly impacts the energy requirements and costs associated with dewatering and treatment processes. Research revealed a direct correlation between sewage sludge density and compaction characteristics, with higher densities leading to greater compaction resistance. Understanding the density of sewage sludge is crucial for designing storage and transportation systems, as higher densities may require more robust infrastructure to prevent settling and structural damage. A holistic approach proposed integrates particle size distribution control, density management, and moisture content optimization to achieve sustainable sewage sludge management. This integrated approach emphasizes the importance of considering multiple factors simultaneously to enhance the overall efficiency, environmental sustainability, and The cost-effectiveness of sewage sludge treatment and disposal systems.

4.2 Chemical Properties

Sewage sludge comprises organic materials and nutrients, namely nitrogen, phosphorus, and potassium.. All these nutrients contribute to soil fertility.

The presence of heavy metals (e.g., copper, zinc, lead) needs to be monitored, as they can impact the environmental and human health aspects of land application.A study scrutinized the presence of heavy metals like copper, zinc, and lead in sewage sludge, as well as their potential impacts on soil quality and human health after being applied to land [Sikka et al., 2009]. Increased concentrations of heavy metals in sewage sludge can detrimentally impact soil health and may present hazards to human health via direct contact or through the food chain. Regular monitoring is essential to ensure compliance with regulatory limits and to prevent contamination of soil and groundwater.The analysis emphasized the importance of regulatory measures and monitoring programs to control heavy metal content in sewage sludge and mitigate associated environmental and health risks. Effective regulation and monitoring are essential to ensure the safe land application of sewage sludge. This includes setting stringent limits on heavy metal concentrations, implementing proper treatment techniques, and conducting regular assessments to prevent contamination of soil and water resources. The research conducted a risk assessment of heavy metal contamination in soil subsequent to sewage sludge application and suggested mitigation measures to mitigate adverse impacts on the environment and human health. Enforcing mitigation tactics like soil conditioning, phytoremediation, and appropriate sludge processing can mitigate the bioavailability and toxicity of heavy metals in soil, thus preserving both environmental and human health. A study examined the bioavailability and toxicity of heavy metals, such as copper, zinc, and lead, in soils amended with sewage sludge. Understanding the factors influencing the bioavailability and toxicity of heavy metals is crucial for assessing their environmental impacts and developing effective management strategies. Variables such as soil characteristics, metal speciation, and microbial function can impact the mobility and toxicity of heavy metals within soil.[Yilmaz et al., 2018].

4.3 Mechanical Properties

Shear Strength i.e., The ability of sewage sludge to resist deformation under applied forces is crucial for assessing its stability in landfills or when used as a soil amendment. Compressibility Understanding how sewage sludge compresses under load is essential for predicting settlement and deformation in engineered applications.

Consolidation behavior helps in assessing how sewage sludge consolidates over time, influencing its long-term behavior in different environments. The organic content of sewage sludge contributes to its beneficial effects on soil structure, water absorption, and nutrient frequency [Shrivastava et al., 2004].

pH and alkalinity The pH level of sewage sludge affect its chemical stability and potential impact on soil pH when applied to land. Pathogen Content Monitoring and managing the presence of pathogens in sewage sludge is crucial, especially when considering land application. Electrical Conductivity Electrical conductivity is the ability of sewage sludge to conduct electrical current, providing insights into its salinity and potential impact on soil quality. Settlement and Volume Changes Understanding the settlement characteristics and volume changes of sewage sludge is essential for predicting its behavior in landfills and engineered structures. Cation Exchange Capacity (CEC) plays a vital role in determining the capacity of sewage sludge to retain and exchange nutrients with the surrounding soil[Baloch et al., 2023].

Consistency and Rheological Properties Assessing the consistency and rheological behavior of sewage sludge helps in understanding its flow characteristics, which is important for handling and transportation. These geotechnical properties collectively determine the engineering feasibility and environmental impact of utilizing municipal sewage sludge in applications such as agricultural land improvement, landfill cover, and soil amendment. It's important to conduct thorough testing and analysis to tailor the use of sewage sludge to specific site conditions and regulatory requirements. There are several reasons back the generation of quantity of globalization of e-waste, technology transfer, big changes in technology, the price of affordable equipment that is new with more features than old ones, life span decreased lifespan.[Belhaj et.al., 2016]

5. APPLICATION OF MUNICIPAL SEWAGE

5.1 Sewage Sludge in Soil Amendment

Utilizing municipal sewage sludge as a soil amendment is a prevalent practice aimed at enhancing soil fertility, structure, and overall health. The geotechnical characteristics of sewage sludge are pivotal in assessing its suitability for such purposes. Expounding on its geotechnical aspects, sewage sludge can play a beneficial role in soil amendment.

5.1.1. Organic matter content benefit: Many authors reported [Lakhdar et al., 2011; Akwo et al., 2008; Alghobar et al., 2017;Dede et al., 2012; Mehta et al., 2015]. The advantages of sewage sludge include its organic matter content.. Sewage sludge is rich in organic matter, which upgrades the structure of soil, water absorption, and nutrient content. Consideration of the organic content influences the decomposition rate, affecting the long-term impact on soil properties.

5.1.2. Nutrient content benefit: Nutrient content benefits of sewage sludge are also important. There are many ingredients like nitrogen, phosphorus, and potassium, contributing to enhanced soil fertility. Consideration of proper nutrient management is essential to avoid over-application and potential environmental issues. The production process of sewage sludge has been very well explained in Figure 3.

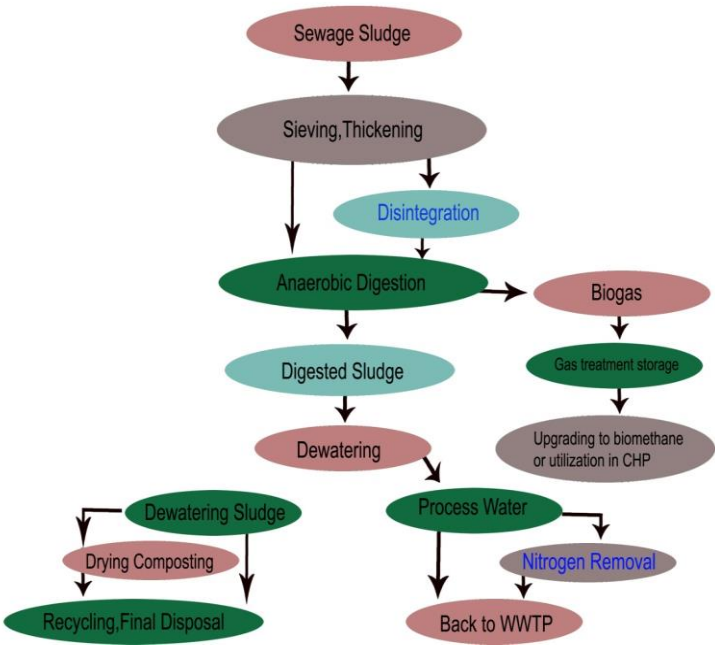

Figure 3. Production of sewage sludge and potential resource recuperation.

i. Nitrogen: This nutrient is crucial for plant growth, particularly for leafy vegetables. Sewage sludge typically contains a high percentage of nitrogen, which can improve plant health and yield.

ii. Phosphorus: Essential for root development and flowering, phosphorus from sewage sludge can help in establishing strong root systems, leading to better drought resistance and overall plant vigor.

iii. Potassium: Known for its role in photosynthesis and overall plant metabolism, potassium aids in water regulation and disease resistance. The presence of potassium in sewage sludge can enhance these processes in crops.

iv. Micronutrients: Beyond the primary nutrients, sewage sludge also contains valuable micronutrients like zinc, copper, and iron, which are often deficient in conventional fertilizers. These micronutrients support various physiological functions in plants.

5.1.3. pH Adjustment Benefit: Some sewage sludge may have a liming effect for helping in the adjusting of soil pH.Consideration of monitoring pH is crucial to prevent excessive alkalinity, which could negatively impact certain crops.

Microbial activity also plays an important role as Microbial of the organic matter in sewage sludge promotes microbial activity and fosters a healthier soil environment shown in Figure 4 Considerationof pathogen content in sewage sludge should be managed to prevent potential risks to human health. Various techniques are employed for pathogen reduction in sewage sludge, including aerobic digestion, air drying, anaerobic digestion, composting, and so forth.

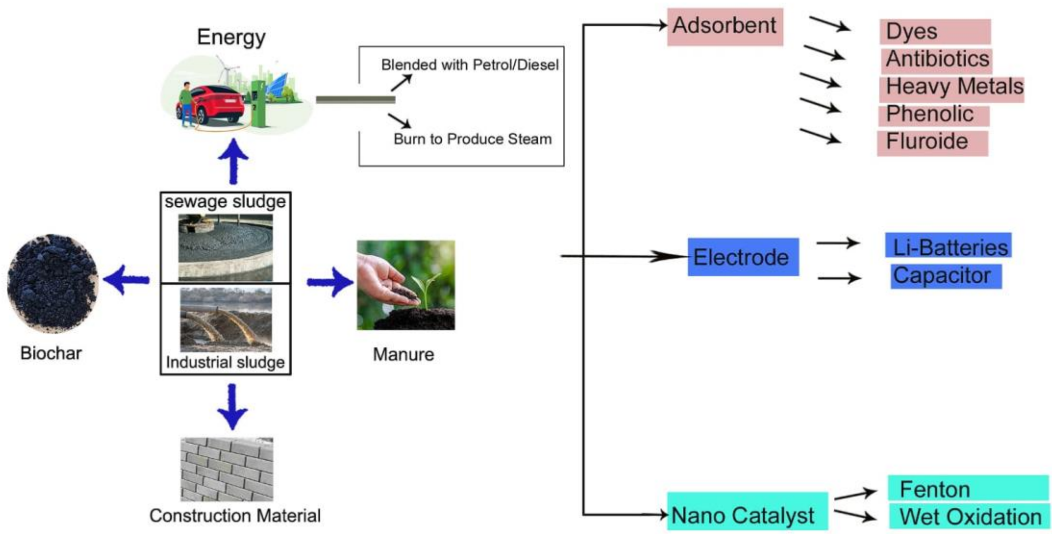

Figure 4. Various utilization methods of sewage sludge.

5.1.4. Water Retention and Drainage Benefit:Organic matter improves soil water retention, reducing water runoff and erosion. Consideration impact on drainage should be monitored, as excessive water retention could lead to waterlogged conditions. Soil Structure improvement benefits sewage sludge and enhances soil aggregation, improving soil structure etc.However, while the benefits of enhanced water retention are substantial, it is essential to monitor the impact on drainage. Excessive water retention can lead to waterlogged conditions, which can suffocate plant roots, create anaerobic environments, and promote the growth of root diseases. Therefore, balancing water retention with effective drainage is crucial. Careful management practices, such as monitoring soil moisture levels and adjusting the application rates of sewage sludge, can help mitigate these risks, ensuring that the soil remains adequately aerated while still benefiting from improved water-holding capacity.

In addition to water retention, the addition of sewage sludge enhances soil structure through improved aggregation. Organic matter promotes the formation of soil aggregates, which are clusters of soil particles that create larger spaces for air and water movement. This improved soil structure enhances drainage and aeration, allowing roots to penetrate more easily and access nutrients. Well-aggregated soil also increases resilience against erosion and compaction, which are significant concerns in agricultural systems. The benefits of enhanced soil structure extend beyond immediate plant health; they contribute to the long-term sustainability of agricultural practices by fostering a balanced ecosystem.

5.1.5. Cation Exchange Capacity (CEC) Benefit: sewage sludge can increase CEC, enhancing the soil's ability to retain and exchange essential nutrients. Monitoring CEC levels helps avoid nutrient imbalances and excessive nutrient leaching.As CEC levels rise, the soil's ability to retain nutrients improves, reducing the risk of nutrient leaching, especially in sandy or low-organic matter soils. Nutrient leaching occurs when rainwater or irrigation water washes away soluble nutrients, often resulting in lower crop yields and water pollution. By increasing CEC, sewage sludge helps to create a more stable nutrient environment, ensuring that essential elements remain available to plants over a longer period. This retention is particularly beneficial during dry periods when plants may struggle to access water and nutrients.

Moreover, a higher CEC can lead to better soil structure, which enhances aeration and root penetration. This improvement creates a healthier root zone, allowing plants to access nutrients more efficiently. Enhanced nutrient availability and retention also contribute to sustainable agricultural practices. Farmers can reduce reliance on synthetic fertilizers, lowering input costs and minimizing environmental impacts associated with fertilizer runoff.

Monitoring CEC levels is essential for managing soil health effectively. Regular assessments can help identify nutrient imbalances and inform adjustments in soil amendments, ensuring that plants receive the right balance of nutrients. Understanding CEC can also guide the application rates of sewage sludge, ensuring that its benefits are maximized without risking nutrient overload or toxicity.

5.1.6. Heavy Metal Contamination: Careful monitoring and management are crucial to prevent heavy metal contamination of soils, which could have adverse effects on plants and the environment. Settlement and compaction benefit of properly treated sewage sludge can contribute to reduced soil compaction and settlement. Consideration of the mechanical properties of sewage sludge, such as shear strength and compressibility, needs to be assessed for compatibility with specific soil types.

Regulatory Compliance Consideration adherence to regulations and guidelines for sewage sludge application is essential to ensure environmental and human health protection. The successful use of municipal sewage sludge as a soil amendment requires a thorough understanding of its geotechnical properties and careful consideration of local conditions and regulations. Proper testing, treatment, and monitoring are crucial to maximize the benefits of sewage sludge while mitigating potential risks. Different techniques can be used to treat sewage sludge to reduce the number of bacteria in sewage. In air drying method sewage sludge is dried in sand sludge drying beds or ponds with sludge-drying liners for several months or longer [Kumar et al., 2016].

The utilization of bio solids improves soil microbial biomass and specific soil enzyme functions such as urease, alkaline phosphatase, and beta-glucosidase, which are linked to the carbon, nitrogen, phosphorus, and sulfur soil cycles. Additionally, studies have indicated that supplementary soil amendments may stimulate dehydrogenase activity, while materials may harbor both intracellular and extracellular enzyme activity within the soil. [Tejada et al., 2013]. found that compost or sewage sludge was effective in treating the saline. Improved the physical and chemical properties of the soil, especially the carbon and nitrogen content. Thus, total enzyme activity increases significantly in both modifications, with higher enzyme activity (107% increase) at 13.3 Kg−1 urban waste.

5.2Sewage Sludge in Agriculture

Research indicates that the utilization of sewage sludge in crop production is advantageous. According to [Kumar et al., 2017]. report, incinerated sludge is rich in phosphorous and Phosphorus fertilizer can be obtained from sludge ash, ensuring an ample supply for agricultural use. Approximately 37% of sewage is used on agricultural lands; Other significant pathways, as reported by [Grobelak et al., 2019]. This includes land reclamation and restoration, accounting for 12%, and incineration, which constitutes 11% of the total waste management process.Both incineration and the direct application of sludge to agricultural soil encounter financial and environmental constraints.The advancement of technology has the potential to improve the environment and sustainable construction economics. Recently many researchers around the world have been publishing reports on the use of sewage in soil amendment and processing as shown in Table 1. Extensive research demonstrates that the use of sewage sludge improves overall development and crop yields while diminishing the reliance on chemicals or fertilizers.

Table 1.Presence of heavy metals in soils as a result of sewage sludge application.

Chemical components like heavy metals / other toxic elements.	**Plant variety/Terrain classification/Geographical soil positioning**	**References**
Cu, Zn	Chhatarpur and Badarpur	[Shrivastava et al., 2003]
K, Ca	South Florida, USA	[Sigua et al.,2005]
Fe, Pb	Fennel plants shoot	[El-Motaium et al.,2007]
Cd	Indian mustard,Cabbage and cauliflower,	[Sikka et al.,2009]
Cu, Zn, Ni, Cd, Cr, Pb	Brassica juncea (Root and shoot)	[Dede et al.,2012]
Cu, Fe, Mn, Zn	Tropical soils	[Nogueirol et al.,2013]
Fe, Zn, Cd, Cu, Pb, Cr	French Bean (Phaseolus vulgaris L.) (Shoot, root, leaves, fruit)	[Kumar et al.,2014]
Pb, Cr, Cd, Cu, Zn, Ni	Cabbage,	[Ullah et al.,2015]
Zn, Cu, Ni, Cr	Sunflower (Helianthus annuus) (Shoots and roots)	[Belhaj et al.,2016]
Cd, Pb	Shoots of Salix and Populus	[Kubátová et al.,2016]
Fe, Mn	Rice grain	[Meena et al.,2016]
N, P	Tomato	[Alghobar et al.,2017]
Cu,Ni	Clay loam and clay loam soil of Thessaloniki Plain (Greece)	[Tziachris et al., 2017]
Cu,Cd	Wheat plant (Triticumaestivum L.)	[Shahbazi et al.,2017]
Cu, Zn	Chhatarpur and Badarpur	[Shrivastava et al., 2003]

There is also a lack of information about the geotechnical properties of sewage sludge for civil engineering purposes in India. Most studies conducted in sewage sludge do not consider important geotechnical properties such as expansion pressure and free expansion index before being used in civil engineering using different methods products [Taki et al., 2007]. Additionally, other studies only show changes in geotechnical properties when sewage sludge is combined with other materials and do not discuss specific engineering applications.

5.3Sewage Sludge for Aqueous Contamination Removal

Almost all water sources, encompassing lakes, ponds, wetlands, streams, rivers, and their branches, are extensively polluted due to the existence of contaminated water [Arlt et al., 2002]. In addition, these conditions have led to the occurrence of many water and food-borne diseases in the surrounding region [Anas et al., 2021]. Likewise, the sludge formed during Wastewater treatment is dried in sludge beds, which are then employed in crop fertilization. Sewage in India, total nitrogen (15400-1920 mg Kg^{-1}) and phosphorous (44-60 mg Kg^{-1}) [Fytili et al., 2008].

Research on the use of sewage sludge for wastewater treatment and aqueous contamination removal has garnered significant attention in recent years. One notable study by investigated the application of sewage sludge-derived biochar for the removal of emerging contaminants from wastewater. The research demonstrated the biochar's ability to effectively adsorb pharmaceuticals and personal care products, highlighting its potential as a sustainable adsorbent material for wastewater treatment. Additionally, a study by examined the use of sewage sludge-derived hydrochar for the removal of heavy metals from wastewater. The study showcased the hydrochar's high adsorption capacity for heavy metals like lead, cadmium, and copper, indicating its potential as an efficient adsorbent for wastewater treatment processes. These studies collectively emphasize the promising role of sewage sludge-based materials in addressing aqueous contamination challenges in wastewater treatment, offering sustainable and cost-effective solutions for environmental remediation. Using adsorbents derived from sewage sludge for eliminating organic water pollutants is a promising approach [Otero et al., 2003]. These adsorbents can be effective due to their porous structure and high surface area, which allow them to trap pollutants. Additionally, repurposing sewage sludge in this way offers an environmentally friendly solution to waste management [Raheem et al., 2018]. However, it's important to ensure that the adsorbents are properly treated to remove any harmful contaminants before being used for water treatment. The sorption of arsenic onto sewage sludge is a well-studied method for removing arsenic from aqueous solutions[Kacprzak etal., 2017]. Sewage sludge contains various organic and inorganic materials that can effectively adsorb arsenic ions from water, thereby reducing its concentration. This method is often used in wastewater treatment plants as part of the overall treatment process to remove contaminants from water show in Table 2.

Table 2 Application of bio charfor removal of contaminant from aqueous solutions & Soil

Pollutant / Amendement	**Removal Efficiency/ Adsorption Capacity / Impact on soil**	**Type of Biochar**	**Reference**
Acidic Blue 210 (AB210), Acidic Blue 7 (AB7) azo dyes	99.32% of AB210 & 94.28% of AB7 azo dyes	Chemically activated sewage sludge biocha	[Ravindiran et al., 2023]
Methylene blue (MB	SSB: 54.23 mg/g SSMB: 55.6 mg/g of adsorption capacity	Sewage sludge biochar (SSB) Magnetic sewage sludge biochar (SSMB)	[Zeghioud et al., 2023]
Remazol Brilliant Blue R (RBBR)	8.56 to 80.6 mg/g with an increase in initial dye concentration from 10 to 100 mg/L	Sewage sludge biochar (SSB)	[Raj et al., 2021]

Malachite green (MG)	388.65 mg/g of MG was obtained with 500 mg/L of MG	Magnetic sludge biochar (MSBC)	[Zhang et al., 2022]
Malachite green (MG) and crystal violet (CV)	69.5 mg/g for MG 49.0 mg/g for CV	SSDB	[Sewu et al., 2021]
Phosphate uptake in ryegrass leaves	52 times higher retention of phosphate	Phosphatelanthanum coated SSDB	[Elkhlifi et al., 2021]
Removal of Lead (Pb), Copper (Cu), and Zinc (Zn)	28.6%, 50.1%, and 30.0% reduction in accumulation	Sewage sludge/cotton stalks (SCB)	[Wang et al., 2021]
Impact on Corn yield	33% more yield compared to control	SSDB	[De et al., 2019]
Leaching of Cu and Zn	~80% reduction in leaching	Sludge biocharceramsite (SBC)	[Li et al., 2018]
Pb, Zn and Cd availability in soi	Decreased availability of Pb, Zn, and Cd, by 85.3, 82.9 and 30.6%, respectively	Ultrasoundtreated SSDB	[Hazrati et al., 2021]

6. CONSTRAINTS ASSOCIATED WITH GEOTECHNICAL PROPERTIES OF SEWAGE SLUDGE

Limitations encountered during the application of municipal sewage sludge can be outweighed by numerous benefits, such as soil enhancement, increased fertility, and removal of contaminants from wastewater. These constraints need to be considered to ensure responsible and effective utilization. Here are some key constraints are discussed as follow.

Heavy metal-contaminated sewage sludge may contain elevated levels of metals which are heavy, such as cadmium, lead, and mercury, that can be collected in soils and pose risks to the health of humans and the environment. Mitigation are proper monitoring and treatment processes are essential to minimize heavy metal content and comply with regulatory limits[Lakhdar et al., 2011].Pathogens and microorganisms constrain sewage sludge harmful presenting risks to human health and ecosystems. Mitigation is adequate treatment, such as composting or anaerobic digestion, is necessary to reduce pathogenic content to safe level. Nutrient imbalance is also a problem. Improper application of sewage sludge can result in nutrient imbalances in the soil, impacting plant growth and potentially triggering environmental problems such as nutrient runoff. Mitigation are careful nutrient management, including soil testing and adjusting application rates, are crucial to prevent imbalances. Odor and aesthetics of the sludge is another big issues. The presence of sewage sludge can contribute to unpleasant odors and affect the aesthetic quality of the surrounding area. Proper handling, treatment, and application methods can help minimize odor issues, making sewage sludge more socially acceptable. Regulatory compliance constraints strict regulations control the application of the land of sewage sludge, including limits on heavy metals, pathogens, and other contaminants. Compliance with local, regional, and national regulations is essential to ensure the safe and responsible use of sewage sludge. It is also observing that the geotechnical properties of sewage sludge may not be compatible with certain soil types, leading to issues such as compaction or reduced drainage. Site-specific assessments and testing are necessary to find the compatibility of sludge from sewage with different soils. Public perception and acceptance constrain public resistance to the use of sludge from sewage for agriculture or land reclamation can hinder its widespread adoption. Community engagement, education, and transparent communication about the benefits and safety measures can help address public concerns. The transportation and handling of sewage sludge can be logistically challenging, particularly when dealing with large volumes. Efficient handling practices and proximity to treatment facilities or application sites can help minimize transportation challenges. Impact on water quality constraint runoff from fields where sewage sludge has been applied can potentially impact water quality through nutrient leaching. Mitigation proper application methods, considering factors like slope and soil type, can help minimize the risk of water quality degradation.

By acknowledging these constraints and implementing appropriate mitigation measures, municipalities, and agricultural practitioners can navigate the challenges associated with the geotechnical properties of municipal sewage sludge, ensuring its safe and effective use in various applications. Often, produced wastewater or bio solids are used, disposed of, and correlatedwithout adequate treatment. Therefore, it will have a serious impact on the environment and the health of the public [Liang et al., 2003]. Additionally, as the population continues to grow rapidly, the amount of sludge from sewage is expected in the future to increase. Sewage, in particular, Could potentially harbor pollutants and metals. [Artl et al., 2002].Additionally, researchers are different and Have documented the existence of hazardous substances in soil. And The use of bio solids in the field of agriculture in developing countries is tightly regulated but can be encouraged, such as Michigan bio solids and septic tank programs [Hong et al., 2009].Recycling aims to close the food cycle and return nutrients to agricultural land, increasing soil fertility and at the same time reducing pressure on landfills. However, in many developed and industrialized countries, the use of sewage or bio solids in agriculture is becoming increasingly controversial due to concerns that they may contain nasty and toxic pathogens. Like bacteria and heavy metals. Crucially, The utilization of sewage in soil aims to augment soil fertility and nourish crops, thereby positively impacting growth and yield, while conversely. , it introduces a significant portion of heavy metals and agricultural soil and crop constituents.

7. Future perspectives and recommendations.

Use of biochar for various application have been increased now a day however, still there is a gap for its production, characterization and application for the environmentally friendly use. As biochar is associated with the sewage therefore its concern related to the effectiveness and safety is still a barrier for the scientist community. Public awareness and outreach effort make sewage sludge a valuable solid waste for the different uses. Table 3 show the different barrier for the application of the biochar. Industrial application of biocharhas also not been reported in the literature. Proper industrial study of biochar will provide the way its use for the society. Therefore, for addressing the barriers collaboration require with industries, and regulatory agencies in order to develop the best practice for best application.

Table 3. Analysis and impact assessment of barriers of biochar for environmental application

Potential Barriers of SSDB	Impacts
Presence of PTEs	Risk of PTEs leaching into the environment and potentially causing harm to living organisms
Varying SSDB properties due to factors such as moisture content, pyrolysis temperature, and heating rate	Inconsistent biochar quality and performance may affect the biochar’s physical and chemical properties, such as porosity, surface area, and nutrient content.
Economic feasibility associated with the SSDB management.	High costs associated with the collection, transport, and processing of SS, which in turn may limit the potential for large-scale production of SSDB
Lack of standardized protocols for SSDB	This may lead to discrepancies in the reported data and hamper the

characterization and testing	comparability of results obtained from different studies. Difficulty in establishing consistent guidelines for SSDB production

8. CONCLUSIONS

In the present study, the analysis of the geotechnical properties of municipal sewage sludge and its application in different fields have been discussed. Advancements in treatment technologies, monitoring techniques, and sustainable applications will contribute to the continued improvement of sewage sludge management. The physical, chemical, and mechanical properties of municipal sludge are multifaceted and play a pivotal role in determining the suitability of this by-product for various applications. Understanding and managing geotechnical properties are crucial for responsible and effective use, whether in agriculture, soil improvement, or aqueous contaminant removal. Some challenges such as heavy metal contamination, pathogenic content, and public perception are still available to the widespread adoption of sewage sludge. Mitigation measures, including effective treatment processes and transparent communication, are essential to address these challenges. Environmental considerations, such as water quality impact and odor issues, need to be carefully managed to ensure the use of sewage sludge. Strategic management, continuous research, and adherence to best practices are essential for maximizing the benefits of sewage sludge while minimizing its potential negative impacts. The best sludge management strategies should focus primarily Considering economic, operational, and social limitations, evaluating the holistic sustainability of sludge management has become important for scientists, researchers, and policymakers. Therefore, there is a need for further research on various aspects of sewage so that it can be further utilized for sustainable development.

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