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Recent Research on Municipal Sludge as Soil Fertilizer in China: a Review

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Abstract Due to the annual increase in wastewater treatment in most Chinese cities, a major environmental issue has arisen: safe treatment, disposal, and recycling of municipal sludge. Municipal sludge has a high content of carbon and essential nutrients for plant growth; hence, it has gained interest among researchers as a soil fertilizer. This study discusses the potential usage of municipal sludge as soil fertilizer (indicators include nitrogen (N), phosphorus (P), and trace elements) along with its shortcomings and drawbacks (potentially toxic elements (PTEs), organic matter (OM), pathogens, etc.) as well as reviews the latest reports on the role of municipal sludge in land use. The use of municipal sludge as a soil fertilizer is a sustainable management practice and a single application of sludge does not harm the environment. However, repeated use of sludge may result in the accumulation of harmful chemicals and pathogens that can enter the food chain and endanger human health. Therefore, long-term field studies are needed to develop ways to eliminate these adverse effects and make municipal sludge available for agricultural use.

Keywords Municipal sludge · Resource utilization · Nutrient cycling · Recycled fertilizer

Bo Zhang and Xingxing Zhou contributed equally to this study.

Highlights
- China's municipal sewage and sludge volumes are increasing by the day.
- The nutrients in municipal sludge have potential as soil fertilizer.
- Treatment of municipal sludge can improve its land application.
- Municipal sludge may contain organic pollutants and potentially toxic elements.
- Using municipal sludge for soil improvement is a promising technology for nutrient recovery.

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1 Introduction

Herein, data were collected from the 2011 to 2020 annual reports by the Ministry of Ecology and Environment of the People's Republic of China (Fig. 1). According to these statistics, China's annual wastewater treatment volume increased from 40.29 billion tons in 2011 to 81.13 billion tons in 2020. The municipal domestic wastewater discharge volume increased from 34.97 billion tons in 2011 to 71.39 billion tons in 2020, and the municipal domestic wastewater discharge volume accounted for 86.20–88.40% of the total annual wastewater treatment volume, with little change over time. Thus, municipal wastewater accounts for a large proportion of the total volume of wastewater. The most intuitive data on the number of municipal wastewater treatment plants show a significant increase in them, from 3974 in 2011 to 11,055 in 2020. Moreover, this demonstrates that the proper disposal or recycling of municipal wastewater is a pressing environmental issue in China. The annual increase in the volume of municipal wastewater treatment presents a major environmental problem: the treatment and disposal of municipal sludge. The term "municipal sludge" refers to a glutinous, aqueous substance produced during the aerobic or anaerobic biological treatment of municipal wastewater (Luo et al., 2021; Stefanakis et al., 2014).

Municipal sludge is a solid or semisolid byproduct of the aerobic or anaerobic digestion of the domestic wastewater, storm water, plant debris, and manure treated in municipal wastewater treatment plants (Saleh Bairq et al., 2018; Seleiman et al., 2020). By the end of 2020, China generated an estimated 36.984 million tons of municipal sludge. Approximately 60 megatons (Mt) of raw wastewater sludge was generated in 2019, and this number is predicted to exceed 90 Mt in 2025 (calculated at a water content of 80%) (Guo et al., 2021). Municipal sludge typically has a water content of more than 80%, which leads to complications in its safe handling and disposal (Kacprzak et al., 2017). The disposal of such large quantities of sludge in a safe manner has become an environmental concern (Li et al., 2011; Luo et al., 2021).

Conventional disposal methods for municipal sludge include sludge landfills, agricultural applications, incineration, and construction material applications (Jiang et al., 2021). In recent years, a number of

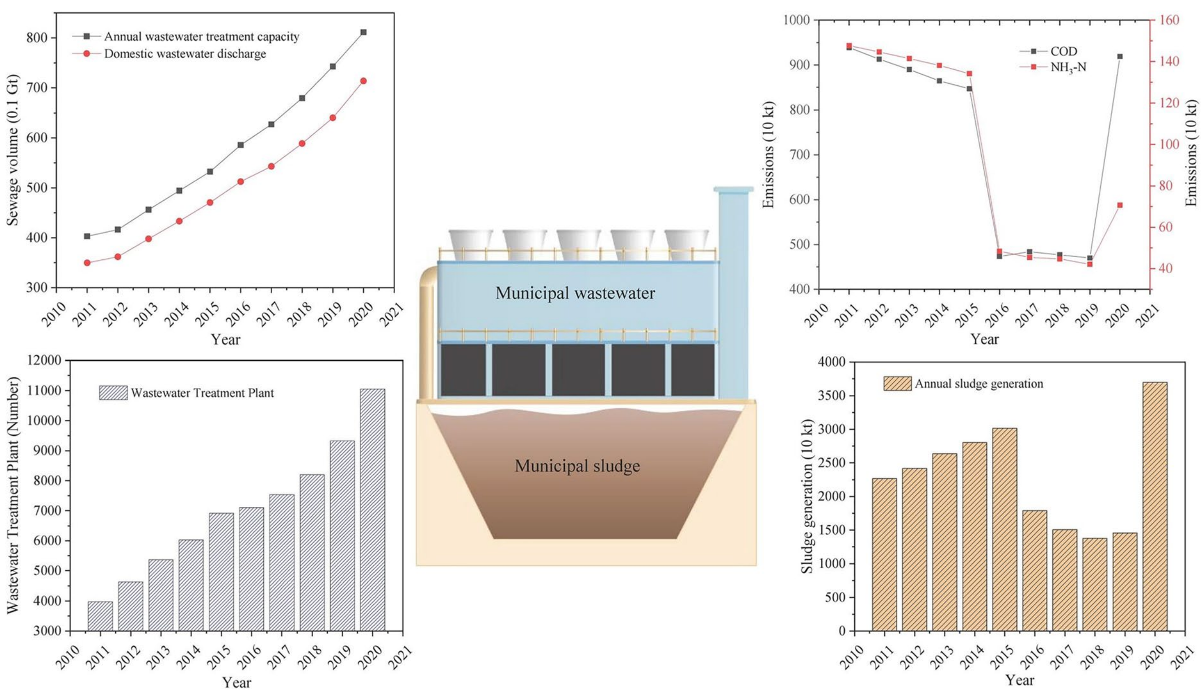

Fig. 1 Summary data for municipal wastewater sludge in China, 2011–2020. Note: Data from the Ministry of Ecology and Environment of the People's Republic of China

high-tech disposal technologies have been developed, including thermochemical conversion, anaerobic digestion, and hydrothermal liquefaction (Han et al., 2021). Landfilling is the most convenient but lowest-rated disposal method because it is the least environmentally efficient option in the long run and is now banned in many developed countries (Kacprzak et al., 2017). In recent years, some scholars have suggested that incineration is an effective method for treating sludge (Zhao et al., 2017, 2020) because incineration enables the conversion of sludge into thermal energy, reducing its volume (Zhai et al., 2017) and toxicity (Liu et al., 2006) as well as increasing its resource value (Shen & Qinlei, 2006). However, the ash produced after incineration of municipal sludge must be disposed of in landfills, which may result in secondary pollution through the release of heavy metals (Wu et al., 2021). Municipal sludge contains 20–30% inorganic materials (mainly silicon, aluminum, iron, and calcium), which is similar to the composition of many raw materials commonly used in construction materials; hence, municipal sludge can be used in brick making, cement, ceramic granules, activated carbon, molten lightweight materials, and biochemical fiberboard production (He & Wang, 2019; Wang et al., 2021). Municipal sludge is rich in organic matter, N, P, K, and other mineral elements and can be used as an effective fertilizer and soil conditioner. Many countries use treated sludge for soil improvement (Yakamercan et al., 2021). The utilization of municipal sludge in China in 2019 was as follows: land use, 29.24%; incineration, 26.69%; sludge landfills, 20.10%; and building material utilization, 15.88% (Fig. 2).

Municipal sludge contains many valuable nutrients (e.g., OM, N, P, and K). Studies show that the total dry solids of municipal sludge contain 20.5–40.3% organic carbon (C), 2.8–4.9% total nitrogen (TN), 1.2–3% total phosphorus, and < 1% total potassium (Collivignarelli et al., 2019). Therefore, the use of municipal sludge as a soil fertilizer makes sense from environmental and economic points of view. However, caution is required when attempting to maximize the value of municipal sludge because it can contain potentially toxic elements (PTEs), organic pollutants, and antibiotic-resistant microorganisms (Rivier et al., 2019), which pose a serious threat to ecosystems and human health when they enter the food chain untreated (Hoang et al., 2022).

Therefore, gaining insights into the feasibility, economics, and dynamic cycling of contaminants in municipal sludge is necessary before using it as a soil fertilizer. Several review articles have been published on the integrated use of municipal sludge, but they have mostly focused on ceramic pellet preparation, environmental pollution after incineration, recovery of nitrogen and phosphorous elements, and so on (Cheng et al., 2022a, b; Hoang et al., 2022; Nancharaiah & Sarvajith, 2019; Wang et al., 2021; Zhao et al., 2022). Information on the disposal and comprehensive use of municipal sludge as a soil fertilizer is scarce. This study aims to fill this knowledge gap by focusing on the potential use of municipal sludge as a soil fertilizer as well as reporting on the constraints in using it as a soil fertilizer, recent research progress, and future research trends.

2 The Potential of Municipal Sludge as a Soil Fertilizer

The accelerated municipalization and increased environmental protection efforts by the Chinese government have increased the number of domestic wastewater treatment plants in operation and require existing facilities to be upgraded. These plants will inevitably produce a large amount of municipal sludge, posing a serious threat to the environment (Deepesh et al., 2016). Large-scale generation of municipal sludge is unavoidable. Hence, we must find an economical, environmentally friendly, and viable path for utilizing municipal sludge. The process of converting waste into a useful product is known as waste value addition, and one waste value addition option for municipal sludge is to use it as soil fertilizer (Arancon et al., 2016). Municipal sludge consists of nutrient-rich organic material, such as the C, N, P, and K elements that are important for plant growth (Ilker Angin et al., 2017).

The OM in soil plays an important role in promoting crop growth and development, improving soil structure, promoting the activity of soil microorganisms, and enhancing soil nutrient properties (Pedra et al., 2007; Zheng et al., 2022). Municipal sludge is rich in the OM (40–70% organic carbon and dry matter) and nutrient content required for plant growth, making it a potential soil fertilizer. Studies by Sciubba et al. (2013) and Dhanker et al. (2021) on the addition of municipal sludge to agricultural soils

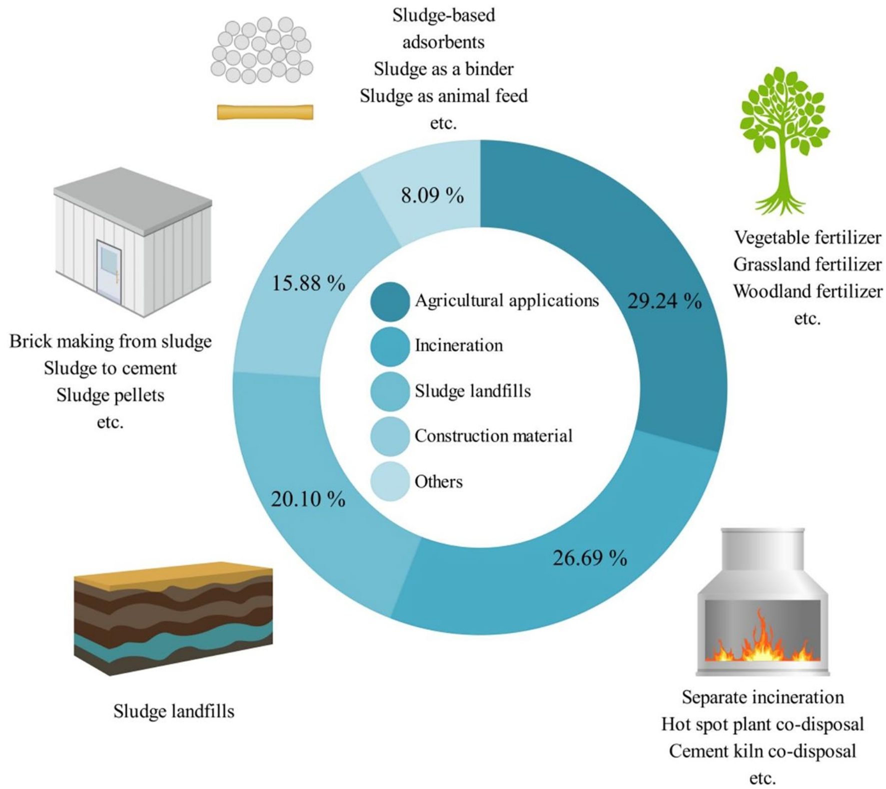

Fig. 2 Sludge disposal methods in China, 2019

reported that OM increases considerably with the addition of wastewater sludge (up to 1.05% compared to the control), and this observation has been confirmed by numerous studies (Ding et al., 2020; No et al., 2022). Hamdi et al. (2018) investigated the effect of adding municipal sludge to sandy loam and sandy soil, respectively, on OM and found that the addition of 120 $t \cdot ha^{-1} \cdot year^{-1}$ of municipal sludge led to an increase in OM content of 2.92% and 2.64% in sandy loam and sandy soil, respectively, after three amendments as compared to the control. This difference was due to the high clay fraction and high sorption capacity of sandy loam (Hamdi et al., 2018).

Municipal sludge contains nitrogenous plant-promoting nutrients and plant growth biostimulants, which have received immense attention in recent years because of their innate fertilization effects and characteristics (Tang et al., 2022). Studies have shown that the use of municipal sludge can replace up to 30% of nitrogenous fertilizers when fully applied (Raheem et al., 2018). Nitrogen is an essential macronutrient for plant growth, and the high N content in municipal sludge, municipal sludge cake, and filtrate, especially after dewatering with $(NH_4)_2SO_4$, makes them potential sources of N for promoting plant growth; Koutroubas et al. (2014) and Wu et al. (2020) showed that the application of municipal sludge had a positive impact on wheat crops, with increased early dry matter and nitrogen accumulation compared to the control. Koutroubas et al. (2020) also explored the effects of municipal sludge application on N accumulation, distribution, transfer, and utilization in sunflower and found that municipal sludge increased early crop growth rates and N uptake levels compared to inorganic N fertilizers. Moreover, municipal sludge application also increased soil OM and fast-acting phosphorous levels compared to the control (Koutroubas et al., 2020).

The looming crisis of phosphate rock depletion has driven the development of various solid waste–derived P fertilizers (Qian et al., 2022). This led to the idea of recovering and using P from municipal sludge. The main forms of P present in the municipal sludge are orthophosphate and pyrophosphate (Tqa et al., 2019). Over 85% of P in municipal wastewater enters the sludge (Qin et al., 2022). Moreover, if P in municipal sludge were fully utilized, it could replace 13% of the phosphate fertilizer used in German ore production. Furthermore, given the volume of municipal sludge, its potential for use as an agricultural fertilizer is enormous (Krüger & Adam, 2015). Current research focuses on the application of purified phosphate fertilizer from municipal sludge. For example, Qin et al. (2022) used CaO and MgO to vitrify municipal sludge in order to obtain a glass phosphate fertilizer with a high proportion of phosphorus (approximately 99.3%) and PTE content in line with current regulations for agricultural use. Schambeck et al. (2021) successfully used alginate-like exopolymer hydrogels to recover phosphate from municipal wastewater, with high selectivity for phosphate adsorption (up to 90.8% recovery) even in the presence of competing ions. Rehman and Qayyum (2020) explored the possibility of replacing the phosphate fertilizer in rice–wheat cropping systems with a combined compost of municipal sludge, farmyard manure, and rock phosphate. Moreover, Rehman and Qayyum (2020) determined that compost containing a combination of municipal sludge (25%), farmyard manure (25%), and rock phosphate (50%) is an environmentally friendly fertilizer suitable for rice–wheat cropping systems and that industrial recycling of wastewater sludge by composting with phosphate helps to meet the P requirements of crops.

In addition to the nutrients in municipal sludge that promote plant growth and development, its high water content and water retention are also useful features (Koutroubas et al., 2014). The high water content in municipal sludge is a viable solution to the problem of low and unreliable crop yields in arid and semi-arid regions which lack fresh water resources (Badza et al., 2020; Černe et al., 2019). Municipal sludge as fertilizer can improve soil structure (soil porosity, field capacity, and plant wilting point), fertility (OM, N, and P), and crop yield. In summary, municipal sludge is an excellent soil addition to deal with the challenges of water scarcity and soil fertility loss.

3 Constraints in the Use of Municipal Sludge as Soil Fertilizer

3.1 Threat of PTEs in Municipal Sludge

The biggest concern in using municipal sludge as soil fertilizer is PTEs. Municipal sludge is a distribution point source of PTE contamination (Cheng et al., 2022a, b). The PTEs tend to accumulate in the sludge, and when applied to soil as fertilizer, they are absorbed by herbs, shrubs, and crops in the ecosystem; enriched; and eventually accumulated in the food chain (Yakamercan et al., 2021). Once PTEs enter the ecosystem, they may pose significant health risks to humans through ingestion, inhalation, and dermal contact. They are a key environmental pollutant because their compounds are nonbiodegradable, aggregated, and stable, and exposure to PTEs can have detrimental effects on humans, such as neurological problems; kidney complications; and liver, cardiovascular, and bone disease. Moreover, PTEs have teratogenic, mutagenic, and carcinogenic properties (Raissy et al., 2022). Contamination due to PTEs has become a major obstacle in the use of municipal sludge as soil fertilizer. Therefore, municipal sludge must meet certain regulatory requirements before it can be used as a soil fertilizer.

Table 1 lists the PTE content of dry sludge from selected municipal wastewater treatment plants in China. According to the statistical data, the PTE content in the sludge from various cities is lower than the limit standards in the Control Standard for Agricultural Sludge Pollutants (GB 4282–2018), Sludge Disposal for Land Improvement in Municipal Wastewater Treatment Plants (GB/T 24,600–2009), and Sludge Disposal for Land Improvement in Municipal Wastewater Treatment Plants (GB/T 23,486–2009) documents. The concern for most researchers is that when municipal sludge is applied to agricultural land as a fertilizer year after year, the PTEs in the sludge are not used by the crops. Instead, PTEs accumulate in agricultural soil and eventually enter the food chain, causing irreversible harm to human health (Adamu et al., 1989; Y. Zhang et al., 2022a, b, 2022c). Therefore, municipal sludge is not suitable for long-term application as soil fertilizer because of the ecological risk posed by the PTEs in it. However, its application for sandy soil improvement at an early stage and reliance on natural ecological restoration of the environment at later stages has potential.

3.2 Threat of Pathogens in Municipal Sludge

In addition to PTEs, pathogens in municipal sludge are a major barrier to its use as a soil fertilizer. This is because fecal-contaminated wastewater enters the municipal wastewater system, where most of the fecal pathogens are adsorbed on the activated sludge

Table 1 PTE content in various municipal sludges, unit: mg·kg^{-1} (dry mass)

Authors	Cu	Zn	Cr	Ni	Pb	Cd	Hg	As	Data sources
(Huang et al., 2022)	102.0	296.0	113.0	23.2	29.5	1.6	—	—	Shandong wastewater treatment plant, China
(L. Zhang et al., 2022a, b, c)	99.5	995.0	169.0	29.1	22.8	2.3	—	20.9	Nanjing wastewater treatment plant, China
(Y. Zhang et al., 2022a, b, c)	192.1	706.3	152.9	50.7	54.7	1.4	—	9.8	Beijing wastewater treatment plant, China
(Yue et al., 2017)	99.9	868.3	53.9	—	25.2	3.5	—	26.3	Beijing wastewater treatment plant, China
(Xiao et al., 2016)	146.7	263.0	441.1	30.4	62.2	0.2	—	8.2	Guangdong wastewater treatment plant, China
(Cai et al., 2018)	139.7	901.9	102.5	26.3	15.0	2.2	1.3	—	Shandong wastewater treatment plant, China
(Jin et al., 2017)	75.5	296.0	—	—	—	2.1	—	—	Gansu wastewater treatment plant, China
(Liu et al., 2019)	98.6	347.1	53.7	—	26.6	0.7	—	18.1	Beijing Xiaotangshan wastewater treatment plant
(Cheng et al., 2022a, b)	188.7	577.5	107.3	38.6	60.3	2.6	2.1	17.6	City wastewater treatment plant in China
Grade A	500	1200	500	100	300	3	3	30	Control Standard for Agricultural Sludge Pollutants (GB 4282–2018)
Grade B	1500	3000	1000	200	1000	15	15	75	
Soil pH < 6.5	800	2000	600	100	300	5	5	75	Sludge Disposal for Land Improvement in Municipal Wastewater Treatment Plants (GB/T 24,600–2009)
Soil pH ≧ 6.5	1500	4000	1000	200	1000	20	15	75	
Soil pH < 6.5	800	2000	600	100	300	5	5	75	Sludge Disposal for Land Improvement in Municipal Wastewater Treatment Plants (GB/T 23,486–2009)
Soil pH ≧ 6.5	1500	4000	1000	200	1000	20	15	75	

"—" indicates that data are unavailable

(Clarke et al., 2017). With the global outbreak of new coronaviruses, attention has been drawn to human pathogens and their serious threat to public health (Zhang et al., 2022a, b, c). Researchers have identified 83 pathogenic microorganisms from the macrogenomes of 20 municipal wastewater sludge samples, including 15 pathogenic microorganisms with specific functions (Ju et al., 2016). Pathogenic *Escherichia coli* is a well-known foodborne pathogen present in municipal sludge that can cause severe diarrhea and other serious illnesses (Zhang et al., 2022a, b, c). Pathogen inactivation is one of the main strategies for addressing this issue, and its efficacy depends on various physical, chemical, and biological processes. This strategy can be used to reduce the pathogen load of sludge by optimizing conditions, such as temperature, pH, and residence time, minimizing the potential risk to human health (Li et al., 2021). There is a risk that any pathogens in municipal sludge applied to land as fertilizer may enter the ecosystem, so it is important to consider the pathogens in municipal sludge in order to reduce the health risk to humans. Studies on pathogens in municipal sludge in recent years are listed in Table 2.

3.3 Threat of Persistent Organic Pollutants in Municipal Sludge

Currently, researchers have a growing concern about persistent organic pollutants (POPs) in municipal sludge. The main sources of POPs in municipal sludge are food waste cleaners, household chemicals (such as monosodium glutamate), personal hygiene products, pharmaceuticals, and various other products or wastes entering the municipal wastewater system (Rivier et al., 2019). During the global COVID-19 epidemic, disinfectants were widely detected in municipal wastewater plants, suggesting that the byproducts of disinfectants are also present in municipal sludge (Guo et al., 2021). Current studies confirm that microplastics have been found in municipal sewage sludge around the world. Once microplastics enter the environment, local microbial populations can ingest them, which in turn can pose health threats to humans and even negatively affect factors such as species growth and reproduction (Rolsky et al., 2020). Advanced technologies in wastewater treatment, such as ultrafiltration, nanofiltration, reverse osmosis, and membrane bioreactor processes, can partially eliminate these POPs. However, these technologies are expensive, and these chemicals are difficult to remove from the municipal wastewater system. Hence, most of these chemicals are concentrated in the municipal sludge (Sarkar et al., 2019). Therefore, some researchers consider the POPs in sludge as a potential barrier to its use as a soil fertilizer (Oleszczuk, 2008; Sun et al., 2019).

Researchers from the Harbin Institute of Technology assessed and summarized the risk of polycyclic aromatic hydrocarbons (PAHs) in the municipal sludge from various cities in China and found that the average value of $\sum_{16}$PAHs in municipal sludge is 9340 ng·g^{-1}, which is in the midlevel range compared to the average value of $\sum_{16}$PAHs in municipal sludge worldwide. Moreover, automobile exhaust, coal combustion, and burning natural gas are the main sources of POPs in China. The EU, French, US, and Chinese legal regulations show that municipal sludge can be used for land application with low environmental risk (Sun et al., 2019). In recent years, some researchers have also explored ways to reduce the POP content in municipal sludge; for example, Guo et al. (2021) proposed a sludge anaerobic digestion-solar drying method to reduce its POP content. After this method was used, the PTEs, nutrients (N, P, K), and POPs in municipal sludge were in compliance with the relevant standards for land remediation and sludge greening in China (GB 24,600–2009. CJ 248–2007), while maintaining the high nutritional value of the sludge. Lu et al. (2021) summarized the effects of composting on the POPs in municipal sludge in recent years and reported that significant research progress has been made on the removal and dissipation mechanism of organic pollutants, optimizing composting methods and the processes to promote the removal and dissipation of organic pollutants. The composted sludge still contains a variety of organic pollutants but generally meets the criteria for land use standards. Sludge composting can effectively remove some organic pollutants, such as phthalic acid esters and polycyclic aromatic hydrocarbon compounds.

4 Recent Research Progress on Municipal Sludge as Fertilizer

The use of municipal sludge as soil fertilizer owing to its relatively high content of OM and nutrients has been recognized by many scholars (Collivignarelli et al., 2019). Numerous experiments have confirmed the use of municipal sludge as soil fertilizer, and this study summarizes the research progress on this concept in recent years.

The most common way of using municipal sludge as a soil fertilizer is to apply it directly to agricultural fields, mines, municipal green spaces, and so on. Koutroubas et al. (2014) conducted a 2-year experiment to investigate the effects of municipal sludge on wheat growth, grain yield, nitrogen accumulation, and trace element concentrations and found that the dry matter, grain yield, and soil N concentrations increased considerably after the application of municipal sludge. Moreover, the concentrations of PTEs such as Cu, Mn, and Zn in wheat grains did not exceed the standard limits. In addition to wheat, germination experiments were conducted on rape, maize, and sunflower, demonstrating moderate to low phytotoxic effects of municipal sludge dosing at 0.10%, 0.25%, and 0.50% on the tested plants. From the biomass point of view, municipal sludge could provide sufficient nutrients for normal plant growth, but increasing the fertilizer dose could lead to the accumulation of PTEs in plants and soil, especially Cd and Ni (Li et al., 2013). For plants not grown under laboratory conditions, the effect of municipal sludge on soil quality was explored after a specific period of time, and the following conclusions were reached: the addition of municipal sludge decreases the pH of the substrate, the EC value of the substrate increases, the OM and N content of the substrate increases considerably, and the tendency for the substrate to degrade during the experimental period is absent. The bad news is that as the pH of the substrate decreases, the availability of PTE increased (Dhanker et al., 2021). Similar conclusions were observed during the revegetation of a mine site, where the application of municipal sludge resulted in considerable increase in the biomass of all herbaceous plants compared with the control. After 100 days of growth, the application of municipal sludge had considerable effect on the biomass of Kentucky bluegrass (17.54-fold increases in aboveground production, and 13.94-fold increases

Table 2 Recent studies on pathogens in municipal sludge

Authors	City	Research content	Main conclusions
(Wang et al., 2022)	Nanjing, China	The effect of typical chemical conditioning methods on the abundance of pathogens in sludge solids and sludge supernatant was investigated	Phage, JCPyV, HF183, BKPyV, HAdV, and EC can be detected in sludge from local wastewater treatment plants. Chemical conditioning with Fenton's reagent is most effective for removing fecal markers from supernatant and solids of conditioned wastewater sludge
(Zhang et al., 2022a, b, c)	Hangzhou and Shanghai, China	To study the survival potential of multidrug-resistant EAEC strains isolated from sludge by heat treatment. Predicts their ability to kill pathogenic bacteria	Municipal sludge contains pathogenic bacteria, and it is confirmed that pathogenic bacteria will have a dormant state, and that state cannot be completely killed during the sludge heat treatment, meaning that even if the sludge is heat treated, sludge application to the land is risky
(Khalil et al., 2011)	Alexandria, Egypt	To investigate the effect of turning frequency on the changes in physical, chemical, and microbiological (pathogenic) parameters of municipal wastewater sludge during composting	The compost products were negative for pathogens. This indicates that composting is a safe treatment and that the hygienic quality of the composting process is satisfactory when viruses, bacteria, and parasites are subjected to intensive control procedures
(Deepesh et al., 2016)	Bangalore, India	The feasibility of municipal sludge and assessment of the quality of organic soil conditioners. To assess the suitability based on heavy metal content, pesticide residues, microbial quality, and phytotoxicity	Indicative bacterial densities for both composts were below the standard limits for organic compost. *Salmonella* was not detected in the final product. The indicative bacterial densities justify the method and can be used as a high-quality organic compost
(Ju et al., 2016)	Hong Kong, China	Based on municipal sludge data, broad-spectrum detection of antibiotic resistance genes (ARG) and antibiotic resistance genes (HBP) was performed. ARG-ARG, ARG-HBP, and HBP species co-occurrence patterns were also explored	The inability of anaerobic digestion to remove ARG and HBP confirms the potential for anaerobic digestion of sludge to propagate antibiotic resistance and pathogenicity, as well as the existence of coexistence patterns between ARG types, which involves a synergistic effect of antibiotic selection pressure and resistance cluster formation
(Carraturo et al., 2022)	North of Italy	The regrowth of *Salmonella typhimurium* and *Escherichia coli* artificially inoculated on mature digestate was tested under anaerobic and aerobic conditions to assess the effectiveness of mature digestate as a microbial growth medium	High-solid anaerobic digestion under thermophilic conditions ensures the absence of pathogens in fresh and stored digests. Anaerobic conditions resulted in a rapid and complete reduction in the microbial load of *S. typhimurium*, confirming that it is a low environmental risk after 24 h in the digestate

Table 2 (continued)

Authors	City	Research content	Main conclusions
(Liu et al., 2022)	Jilin, Lhasa, Shenzhen, Yili, China	To investigate the distribution, physiological-ecological characteristics, and potential environmental risks of bacterial pathogens in municipal sludge in four regions of China	Pathogens were present in all four municipal sludge, representing 57 microbial species groups but dominated by the genus *Fusobacterium*. Some pathogens were also found to survive antibiotics and could be completely inactivated by chlorine disinfection, but conventional UV disinfectants did not work well
(Estrada et al., 2004)	—	To monitor the effect of the application of treated sludge on the behavior of Enterobacteriaceae in the soil and study their evolution over time after application	After 80 days of testing, fecal coliforms and *E. coli* were greatly reduced or undetectable, but during the same period, there was a significant increase in the number of microorganisms studied in the mixture containing fertilizer (calcium ammonium nitrate)
(Selambakkannu et al., 2022)	Klang Valley, Malaysia	The aim of this study was to verify the efficiency of electron beam irradiation treatment on the inactivation of *Salmonella enterica, Salmonella brucei*, *Enterococcus*, and *Escherichia coli*	Electron beam irradiation treatment was effective for inactivation of municipal sludge pathogens. Higher inactivation efficiency was observed at lower dose rates and higher energies. No bacterial regrowth was observed after 60 days of storage
(Leroy-Freitas et al., 2022)	Minas Gerais, Brazil	The abundance of pathogens in three municipal sludges was investigated using different wastewater treatment methods: conventional activated sludge, post-UASB biological trickling, and modified activated sludge with an ultraviolet disinfection stage	The genetic markers studied in this paper showed associations with abundant genera and potentially pathogenic groups, indicating their close symbiosis in WWTP. In addition, potentially pathogenic genera were evident in both raw and treated wastewater samples and experienced considerable reduction after treatment

"—" indicates that data were unavailable in belowground production compared to the control) and in alfalfa-ryegrass mixtures (5.34-fold and 7.20-fold, respectively) (Li et al., 2013). Zhao et al. (2020) explored the effect of bituminous ash, biomass ash, and municipal sewage sludge on the quantity and quality of grass bean mixtures and confirmed that biomass ash had the highest P, K, and Mg content; bituminous ash had the highest sodium content; and sewage sludge had the highest organic matter N and Ca content. Analysis of the chemical composition of the sludge showed that its heavy metal content did not exceed the standard limit values and that it could be applied to the soil, used for agriculture, or for reclamation.

Municipal sludge improves soil fertility in terms of nutrients, promotes plant growth, and improves soil structure. However, the presence of PTEs in municipal sludge poses a threat to human health. Two methods are suggested to eliminate the threat due to the presence of PTEs in municipal sludge: controlling the concentration of PTEs in the available state of municipal sludge in combination with other technologies and using municipal sludge directly in areas far from the biological food chain, such as desert environments.

The direct utilization of municipal sludge as a soil fertilizer is limited by putrescible OM, pathogenic organisms, PTEs, etc. (Tang et al., 2022). Therefore, in recent years, controlling the limiting factors of sludge before its use as soil fertilizer using techniques such as anaerobic digestion, aerobic composting, and pyrolysis has been proposed (Hoang et al., 2022). Černe et al. (2019) previously evaluated the potential of aerobic and anaerobic composting of municipal sludge for use as a soil fertilizer based on the physicochemical characteristics, nutrient status, and concentrations of PTEs and radionuclides. Although eight of the nine experimental municipal sludge species had residues within local agricultural use limits and had potential as soil fertilizer, anaerobically composted municipal sludge was considered unsuitable for agricultural use because of its high content of PTEs and radionuclides compared to aerobic compost and the original municipal sludge. The combination of fly ash, ammonium sulfate, and manure with municipal sludge has also been proposed, with the core of this process including the dewatering of municipal sludge to reduce its volume and enhance its nutrient utilization (Pei et al., 2020; Tsadilas et al., 2018).

In addition to the direct application of municipal sludge to soil, technologies for extracting useful substances (N, P, etc.) from municipal sludge have emerged in recent years. Phosphorus is a nonrenewable and irreplaceable resource, and the currently detected global reserves of P may be depleted within a few generations (Steckenmesser et al., 2017). Hence, technologies for the recovery of P from municipal sludge have been developed. These technologies include chemical precipitation of P during anaerobic digestion to form calcium stannate and calcium caseinate, wet chemical extraction, and thermal treatment of sludge (Oliveira et al., 2016; Qian et al., 2022). Tang et al. (2022) developed alkaline, a thermal hydrolysis technology, to produce dewatered liquid municipal sludge for use as a fertilizer. The advantage of this technology is that the resulting liquid sludge fertilizer has a high pH level and may produce more nitrogenous plant growth-promoting nutrients and precursors of nitrogenous plant growth-promoting biostimulants for the production of high-liquid fertilizers.

5 Conclusions

Municipal sludge is a valuable soil fertilizer, and this study summarizes and analyzes recent studies that demonstrate sustainable management methods for the use of municipal sludge as a soil fertilizer. However, contamination of the sludge with PTEs, organic pollutants, and pathogens cannot be avoided. Moreover, a large number of current experimental studies are short term. In addition, municipal sludge is not used continuously every year; hence, conclusions are drawn to meet local control limits. This shows that municipal sludge should be used in areas far from human activities (e.g., deserts, mine recovery of vegetation) to improve soil fertility and accelerate the growth of plants. Moreover, long-term and valuable experimental data on the effective, nontoxic, and environment-friendly use of municipal sludge as a soil fertilizer can be obtained from further research in this field.

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Author Contribution Bo Zhang: formal analysis, writing—original draft, data curation, writing—review and editing.

Xingxing Zhou: review, manuscript preparation.

Xupicheng Ren: data curation.

Xiaomin Hu: review and supervision, project administration.

Borui Ji: data curation.

Data Availability The data will be made available on request.

Declarations

Competing Interests The authors declare no competing interests.

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