REVIEW

Municipal sewage sludge management in a changing world: Trends and safe resource recovery

Gestión de lodos municipales en un mundo cambiante: tendencias y recuperación segura de recursos

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ABSTRACT

In this review, we examine municipal sewage sludge management and resource recovery in relation to United Nations Sustainable Development Goal 6 (SDG 6: Clean Water and Sanitation), circular economy goals and public health protection. Major management alternatives, including agricultural land application, energy recovery, use in construction materials, land reclamation and biofuel production are assessed, along with their technical, regulatory, environmental and social constraints. Based on studies and case examples from diverse global regions, in this review we facilitate comparison of sludge management options and identify context-appropriate strategies amid rapid changes in current regulatory requirements and climatic conditions. The reviewed literature indicates that there is no single optimal pathway for sludge management; rather, the most suitable options are dependent upon sludge characteristics, treatment infrastructure, costs, monitoring capacity, local environmental conditions and relevant legal requirements. Resource recovery pathways can reduce environmental burdens and generate value by recovering energy, nutrients or useful materials, but in many cases they require pre-treatment, reliable process control and adequate monitoring. Although land application can improve soil fertility and organic matter content, it requires careful control of pathogens, heavy metals and other contaminants, in order to protect ecosystems and human health. In this study, we conclude that decision-making processes should take into account life-cycle assessments of sludge management alternatives, comprehensive comparisons of technical, environmental, economic and social aspects, environmental justice considerations, sustainability, governance, and integrated water resources management (IWRM). Such an integrated approach can support safer and more locally appropriate resource recovery pathways, while taking into account factors associated with regional conditions and regulatory frameworks.

Keywords: *sanitation, biosolids, sewage sludge, resource recovery, circular economy, public health*

RESUMEN

Esta revisión analiza la gestión y recuperación de recursos de los lodos de aguas residuales municipales en relación con el objetivo de desarrollo sostenible 6 (ODS 6: Agua limpia y saneamiento), los objetivos de economía circular y la protección de la salud pública. Se evalúan las principales alternativas de gestión, incluidas la aplicación agrícola, la recuperación de energía, el uso en materiales de construcción, la recuperación de tierras y la producción de biocombustibles, junto con sus limitaciones técnicas, regulatorias y sociales. Basada en estudios y casos de distintas regiones del mundo, esta revisión facilita la comparación de opciones de gestión e identifica estrategias adecuadas según el contexto, considerando los rápidos cambios en las condiciones regulatorias y climáticas actuales. La bibliografía analizada indica que no existe una vía óptima única para la gestión de lodos; las opciones más adecuadas dependen de las características del lodo, la infraestructura de tratamiento, los costos, la capacidad de monitoreo y los requisitos legales. Las vías de recuperación de recursos pueden reducir cargas ambientales y generar valor, pero requieren pretratamiento, control confiable del proceso y monitoreo adecuado. La aplicación al suelo puede mejorar la fertilidad y el contenido de materia orgánica, aunque exige controlar patógenos, metales pesados y otros contaminantes. Se concluye que la toma de decisiones debe integrar evaluación de ciclo de vida, comparación técnica, ambiental, económica y social, justicia ambiental, sostenibilidad, gobernanza y gestión integrada de los recursos hídricos (GIRH), tomando en cuenta el contexto regional y regulatorio.

Palabras clave: *saneamiento, biosólidos, lodos de aguas residuales, recuperación de recursos, economía circular, salud pública*

1. Introduction

Water and sanitation systems are crucial for protecting public health, maintaining ecosystem stability and supporting urban productivity. However, they face growing pressure from rapid urbanization, increasing resource demands and climate-driven fluctuations in water availability and quality (Cosgrove and Loucks, 2015; Ghosh *et al*., 2024; Musie and Gonfa, 2023). While the development of wastewater collection and treatment is essential for reducing disease burdens and protecting receiving waters, it also increases the generation of sewage sludge, a heterogeneous by-product containing organic matter, nutrients, pathogens, heavy metals and, increasingly, contaminants of concern (Huang *et al*., 2016; Hušek *et al*., 2022; Salgot and Folch, 2018). As wastewater treatment coverage increases under United Nations Sustainable Development Goal 6 (SDG 6: Clean Water and Sanitation), sludge management should no longer be regarded as a secondary concern, but rather as a central factor determining the overall sustainability of sanitation systems.

Historically, sludge management has been regarded principally as a disposal problem. Increasingly, however, more recent literature has treated sludge as a potential resource stream within a circular economy, offering opportunities for nutrient recovery, energy generation and material reuse (Di Giacomo and Romano, 2022; Peccia and Westerhoff, 2015; Raheem *et al*., 2018) Although this shift is significant, persistent risks should not be overlooked. Poorly managed sludge can transfer metals, pathogens and organic micropollutants to soil, air and water, and generate social conflict when communities perceive inequitable exposure to environmental burdens (Lowman *et al*., 2013; Tytła and Widziewicz-Rzońca, 2023; Yakamercan *et al*., 2021). Therefore, the key challenge is not simply the recovery of resources from sludge, but rather the identification of management pathways that are technically robust, protective of human health, economically realistic and socially legitimate. In addition to these concerns, the literature has increasingly emphasized the presence of emerging contaminants in sewage sludge, including pharmaceuticals, personal care products, endocrine-disrupting compounds and other persistent organic micropollutants (Hušek *et al*., 2022; Peña-Guzmán *et al*., 2019). Because in many cases conventional wastewater treatment does not fully remove these compounds, they may re-enter the environment through sludge reuse or disposal (Hušek *et al*., 2022; Peccia and Westerhoff, 2015; Peña-Guzmán *et al*., 2019). Consequently, sludge management systems should not be evaluated solely in terms of their resource recovery potential (Di Giacomo and Romano, 2022; Raheem *et al*., 2018). Instead, it is critical that it be determined whether a given treatment process destroys or transforms these contaminants, or primarily transfers and concentrates them into other by-products, such as biosolids, ash and leachate (Hušek *et al*., 2022; Peccia and Westerhoff, 2015; Yoshida *et al*., 2018). This «destruction versus transfer» perspective is essential for effective risk governance and provides the basis for the pathway comparison presented later in this review.

With these goals in mind, in this review we examine the principal municipal sewage sludge management and resource recovery routes, including agricultural use, energy recovery, use in construction materials, land reclamation and biofuel production, as well as conventional disposal options, such as landfilling and incineration. In addition to summarizing current practices, we address key issues requiring further attention, including the mismatches between treatment requirements and implementation capacity, regulatory fragmentation and regional inequities, particularly in Latin America and other regions with limited wastewater-treatment infrastructures, as well as the need for decision-making frameworks that integrate factors associated with risk, sustainability and governance.

While there is extensive literature on sewage sludge management, previous reviews have tended to focus narrowly either on technological performance or sustainability assessment, while often neglecting to integrate technological maturity, risk governance and regional disparities into a unified decision-making framework. This shortcoming limits their applicability in real-world decision-making scenarios across diverse socio-technical contexts (Christodoulou and Stamatelatou, 2016; Mahlknecht *et al*., 2020; Ren *et al*., 2017).

This gap illustrates the need for an updated review for several reasons. Firstly, recent life cycle studies have shown that sludge treatment and final disposal contribute significantly to the climate footprint of wastewater systems. These studies have also shown that the relative performance of management options may shift as electricity grids are decarbonized and controls for nitrous-oxide emissions and energy recovery are improved (H. Chang *et al*., 2023; El Abbadi *et al*., 2025; Yu *et al*., 2023). Secondly, emerging technologies and operational improvements, including advanced thermal systems, decarbonization strategies and land-based carbon sequestration pathways, are evolving, but their performance and trade-offs are strongly dependent upon regional conditions (Chen *et al*., 2026; Kacprzak *et al*., 2025; Takaoka *et al*., 2025). Thirdly, growing attention at policy level to contaminants of concern, particularly per- and polyfluoroalkyl substances (PFAS), underscores the need to address risk management alongside resource recovery (Ismail and Tizaoui, 2025; Saliu and Sauvé, 2024). Finally, global differences in infrastructure, financing and governance mean that evidence from high-income countries cannot always be directly applied to regions such as Latin America, where treatment coverage, enforcement capacity and markets for recovered products

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vary considerably (Ganesapillai *et al*., 2026). Japan's recent experience illustrates how thermal treatment of sewage sludge is being discussed increasingly, not only as a disposal option, but also as part of broader strategies for carbon neutrality, destruction of organic micropollutants and energy recovery (Takaoka *et al*., 2025). In order to address these concerns, in this review we considered emerging contaminants as a primary limiting factor for resource recovery, rather than as a secondary issue (Hušek *et al*., 2022; Peccia and Westerhoff, 2015). We determined whether each sludge management pathway permanently destroys priority contaminants or transfers them to secondary streams, such as biosolids, digestate or ash (Hušek *et al*., 2022; Yoshida *et al*., 2018). This is a crucial distinction, because technologies that successfully reduce sludge volume or recover energy may still pose environmental risks if they redistribute persistent compounds (Peccia and Westerhoff, 2015; Yoshida *et al*., 2018). Therefore, the syntheses in Sections 5-8 and Table 3 specifically evaluate sludge pathways by balancing circular economy benefits with contaminant fate and risk governance.

2. Methodology

For our study, we employed a structured scoping review approach to summarize the current knowledge regarding municipal sewage sludge management and resource recovery pathways. The work is presented as a PRISMA-informed scoping review (rather than as a fully systematic review), with the objective of mapping evidence and comparing pathways across contexts, rather than exhaustively capturing all available records. The literature search was conducted between January and March 2026, using Google Scholar as the primary search engine, due to its broad interdisciplinary coverage. To strengthen our review, we complemented database searching with backward and forward citation tracking, in order to identify additional relevant studies, including recent and highly cited publications not found during the initial search. The search utilized combinations of the following keywords: «sewage sludge», «biosolids management», «energy recovery», «agricultural reuse», «construction materials», «land reclamation» and «biofuels». All the searches were executed within the established time window (January-March 2026) and reported using explicit search strings. The core search string was («sewage sludge» OR biosolids OR «wastewater sludge») AND (management OR treatment OR disposal OR valorization OR «resource recovery»). To improve the coverage of pathway-specific literature, we applied targeted extensions of the core string using key pathway terms (e.g., anaerobic digestion/biogas/thermal treatment; land application/composting; construction materials/cement/brick) and an emerging contaminant extension (e.g., PFAS/micropollutants/microplastics). Because Google Scholar returns a very high number of search results and ranks them by relevance, we screened the results in ranked order and reviewed the first 100 records for each query string, including core and pathway-focused queries. This threshold was defined *a priori*, in order to improve transparency and manageability. The records were then combined, and duplicates were removed. Backward and forward citation chaining was used to identify additional foundational and recent studies that might not have appeared among the top-ranked results. The inclusion criteria were as follows: (i) studies published between 2016 and March 2026, with earlier foundational studies included when identified through citation tracking and considered essential for contextual or methodological relevance; (ii) peer-reviewed articles written in English or Spanish; (iii) studies addressing technological, environmental or regulatory aspects of municipal sludge management; and (iv) studies directly relevant to sludge resource recovery or disposal pathways. The exclusion criteria included the following: (i) duplicate records; (ii) studies focused exclusively on industrial sludge; and (iii) publications lacking sufficient technical detail. The review process followed a structured screening approach based on PRISMA guidelines, comprising identification, title and abstract screening, full-text assessment, and final inclusion. From an initial pool of 423 records, 148 were retained after title and abstract screening, and 87 were selected after full-text assessment (Figure 1). The selected studies were organized into thematic categories based on the following criteria: resource recovery pathway, geographic context, technology readiness level, environmental and health risk indicators, and implementation barriers. For each included study, we recorded the sludge/system context (where reported), treatment sequence (process steps) and management pathway, geographic setting and scale, evidence maturity/technology readiness level (TRL; from laboratory to full scale), performance outcomes (e.g., volume reduction, energy yield, nutrient recovery and material performance), reported risk indicators (pathogens, metals and emerging contaminants, where available), and implementation barriers (economic, regulatory, operational and social). Given the heterogeneity in study designs, TRLs and system boundaries, comparisons are presented as a qualitative, context-based synthesis, rather than as a quantitative meta-analysis.

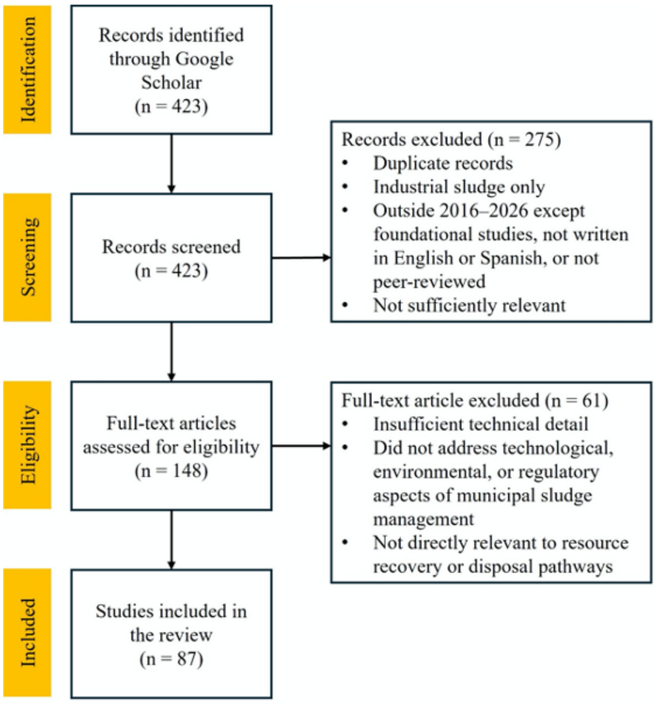

Figure 1. Flow diagram of the study selection process following a structured scoping-review approach based on PRISMA principles (final n = 87)

3. Urban water cycle and integrated management

The urban water cycle (UWC) encompasses the interaction between natural hydrological processes and human-made systems for water intake, treatment, distribution, use, drainage, wastewater collection and discharge or reuse (Peña-Guzmán *et al.*, 2019). In reality, many cities still manage drinking water, wastewater and stormwater as separate sectors, a practice that can lead to inefficiencies, pollutant transfers and missed opportunities for water reuse and resource recovery (Howard and Gerber, 2018; Sosa-Rodríguez *et al.*, 2020). This lack of integration is particularly problematic when sludge management is treated as an isolated end-of-pipe issue, rather than as an integral part of urban water management and broader resource flows.

Integrated water resources management (IWRM) provides a useful conceptual and governance framework for reintegrating these sectors by emphasizing coordinated planning, stakeholder participation and adaptive decision-making across water, land and related resources (Cosgrove and Loucks, 2015; Loucks and Van Beek, 2017; Meran *et al.*, 2021), as shown in Figure 2. In the context of sludge management, an IWRM perspective helps to clarify trade-offs that are often overlooked in purely technology-centered reviews. For example, a sludge management route that performs well at the wastewater-treatment-plant scale may be less sustainable on a city scale if it increases transport emissions, requires imported additives, or shifts risks to peri-urban communities. Similarly, investments in water saving, decentralized drainage and source control can indirectly influence sludge quantity and quality, thereby affecting downstream treatment options (Marinoski *et al.*, 2018; Northey *et al.*, 2016; Silva, 2023).

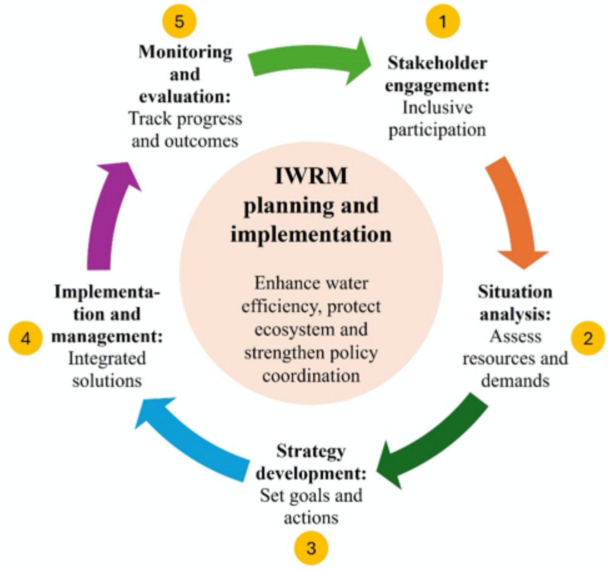

Figure 2. Integrated water resources management (IWRM) planning and implementation

A stronger link between UWC planning and sludge management becomes increasingly critical under climate and urbanization pressures. Population growth (Figure 3) and changing consumption patterns drive increased wastewater volumes and solids loads, while extreme rainfall and drought can destabilize sewer systems, alter pollutant concentrations, and compromise treatment performance (Liu *et al.*, 2023; United Nations, 2022; Varady *et al.*, 2016). Therefore, sludge management should be planned as part of comprehensive and resilient urban water strategies, rather than merely as a disposal operation. This approach enhances the flow of decision-making from sanitation service goals to treatment selection, valorization pathways and long-term public health outcomes.

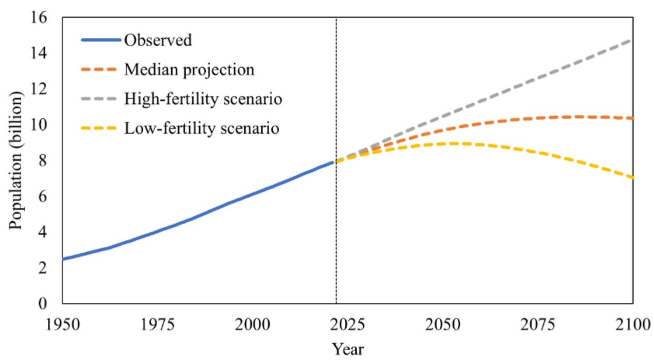

Figure 3. Historical (solid line) and projected (dotted lines) world population to 2100, according to the United Nations (United Nations, 2022)

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4. Household-centered environmental sanitation and community-led total sanitation

To contextualize this section, it is important to clarify the distinction between fecal sludge and sewage sludge (Lüthi *et al*., 2009). In this review, we focus primarily on municipal sewage sludge generated in formal wastewater treatment plants (WWTPs). Fecal sludge from onsite sanitation systems (e.g., pit latrines and septic tanks) differs from municipal sewage sludge in typical organic loading patterns, rheology, dilution and contaminant profiles; most notably, municipal systems are subject to urban runoff and industrial inputs, which result in higher heavy metal and persistent chemicals concentrations. Consequently, household-centered environmental sanitation (HCES) and community-led total sanitation (CLTS) are discussed here not as direct sludge management pathways, but as upstream sanitation planning and service delivery frameworks that shape the containment, collection and routing of excreta into formal services (Kyessi, 2005; Lüthi *et al*., 2009). However, they directly influence sludge management by shaping excreta flows, containment practices, user behavior and the practical feasibility of downstream treatment and resource recovery systems (Harter *et al*., 2020; Harter *et al*., 2019; Lüthi *et al*., 2009). Specifically, HCES emphasizes household-level facilities and safe management close to the point of generation, whereas CLTS prioritizes community mobilization and behavioral change to end open defecation and improve sanitation practices (Kar and Chambers, 2008; Zuin *et al*., 2019). In Table 1, we summarize the main advantages and disadvantages of each approach.

The strengths of HCES include privacy, potential health benefits and the opportunity to integrate household investments with municipal support mechanisms, although challenges remain to implementation in dense urban settings where land, maintenance capacity and service chains are constrained (Asrate *et al*., 2022; Kyessi, 2005). CLTS can drive behavioral change and community ownership, and yet outcomes often prove fragile where technical support, financing and institutional follow-through are lacking (Al'Afghani *et al*., 2019; Harter *et al*., 2020). In our review, we found that a key implication is that sanitation models directly influence the quantity and characteristics of solids entering municipal systems. In contexts where service chains are incomplete, sludge management burdens may shift to informal dumping, unsafe reuse or poorly controlled disposal. Thus, sanitation planning must connect household and community approaches with municipal sludge treatment capacity. A common policy mistake is to evaluate sanitation success solely through access indicators (e.g., toilet coverage) while failing to consider investment in safe transport, treatment and end-use regulation. This disconnect partly explains why gains in sanitation access do not always yield comparable gains in environmental quality or public health protection (Budge *et al*., 2022; Obaideen *et al*., 2022).

Table 1. Comparative summary of HCES and CLTS [adapted from Al'Afghani *et al*. (2019); Kyessi (2005)]

Approach	Main strengths	Main limitations / implications
HCES	Improves household privacy and potentially reduces disease transmission when facilities are properly maintained; aligns with local funding schemes.	Presents space and maintenance constraints in dense areas; household systems can generate secondary waste streams that require safe municipal management.
CLTS	Promotes community mobilization, behavioral change, and reduction in open defecation; has relatively low initial infrastructure cost.	Outcomes are dependent on long-term technical support, governance, and resources; proves insufficient where infrastructure and service chains are weak.

5. Municipal sewage sludge management: characteristics, treatment logic and valorization pathways

Municipal sewage sludge (MSS) constitutes the main solid by-product of wastewater treatment and is generated in all treatment plants, although its quantity and composition vary in accordance with influent characteristics, treatment configuration and local industrial contributions (Demirbas *et al*., 2017; Di Giacomo and Romano, 2022; Zhang *et al*., 2017). Key challenges include high moisture content, heterogeneity, odor, pathogen loads and variable concentrations of nutrients, metals and organic micropollutants. This variability partially explains why sludge management remains difficult to standardize and why technology transfer between countries often fails when local sludge characteristics are not adequately considered (Hušek *et al*., 2022; Mansor and Fatehah, 2022).

Due to these characteristics, sludge processing typically must address several objectives simultaneously, including volume reduction, stabilization, pathogen reduction, odor control, enhanced dewaterability, energy recovery and resource recovery. Pre-treatment has grown increasingly important as it can enhance anaerobic digestion performance and achieve solids reduction, though it may also elevate operating costs and system complexity (Ćwiertniewicz-Wojciechowska *et al*., 2023; Shrestha *et al*., 2020). Consequently, the sustainability for any sludge management pathway should be evaluated across the entire treatment process, rather than being solely based on the final product.

As shown in Figure 4, within this context the resource recovery pathways most commonly discussed in the literature include agricultural use, energy recovery, utilization in construction materials, land reclamation and biofuel production (Z. Chang *et al*., 2020; Hušek *et al*., 2022; Raheem *et al*., 2018). In order to facilitate comparison among sludge management strategies, the main resource recovery pathways examined in this review have been classified according to technological maturity, potential benefits and associated risks. Table 2 summarizes the key characteristics of each pathway, based on the reviewed literature.

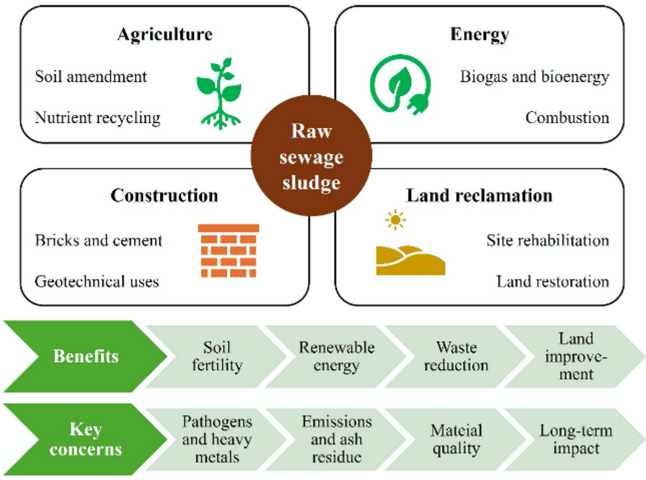

Figure 4. Possible uses of sewage sludge: benefits and key concerns

As shown in Table 2, these pathways differ significantly, not only in technological maturity but also in their benefits, limitations and risk profiles. Established options such as anaerobic digestion and land application demonstrate high readiness levels, while emerging pathways such as biofuel production remain less mature and encounter economic and operational challenges. Thus, technology selection must not rely solely on theoretical benefits, but rather on feasibility, regulatory acceptance and potential risks. For instance, agricultural use may recover nutrients directly but is increasingly challenged by contaminant concerns, while thermal routes offer volume reduction and energy recovery at the cost of capital-intensive emissions control. Material applications may immobilize contaminants, although long-term leaching and performance validation continue to require further attention (Boudjabi and Chenchouni, 2021; Liang *et al.*, 2021; Wu *et al.*, 2021).

Agricultural use continues to be one of the most studied reuse options, due to the fact that stabilized sludge can supplement soils with organic matter, nitrogen, phosphorus and micronutrients, thereby potentially improving soil fertility, structure and crop productivity (Boudjabi and Chenchouni, 2021; Lamastra *et al.*, 2018; Marin and Rusănescu, 2023). Nevertheless, the discussion must extend beyond nutrient benefits. Risks are determined by sludge origin, treatment quality, application rates, soil properties, crop type and long-term accumulation. Specifically, heavy metals and other contaminants can restrict safe application, regardless of short-term agronomic performance (Hušek *et al.*, 2022; Tytła and Widziewicz-Rzońca, 2023; Yoshida *et al.*, 2018). Therefore, agricultural reuse requires evaluation as a monitored management strategy, as opposed to a low-cost disposal option.

Energy recovery encompasses anaerobic digestion, incineration, co-combustion and various emerging thermochemical routes. Anaerobic digestion remains widely implemented and yields biogas while reducing volatile solids, although digester performance is sensitive to feed characteristics, pre-treatment and process control (Grando *et al.*, 2017; Richard *et al.*, 2019; Shah *et al.*, 2021). Recent evidence also indicates that anaerobic co-digestion can improve the energy-recovery potential of sewage sludge when it is combined with suitable organic co-substrates. For example, González *et al.* (2026) reported that the co-digestion of sewage sludge with animal manures, particularly poultry manure, can enhance methane production under optimized conditions, although performance is strongly dependent upon the C/N ratio, substrate proportion, temperature, reactor type and pre-treatment strategy. Thermal options, including incineration, gasification, pyrolysis and either hydrothermal carbonization or liquefaction, are often proposed for enhanced volume reduction and energy/material recovery, although their comparative sustainability is dependent upon moisture content, energy balance, flue-gas treatment, ash handling and market outlets for by-products (Bora *et al.*, 2020; Poblete *et al.*, 2022; Samolada and Zabaniotou, 2014; Zarandi *et al.*, 2023).

Construction-material applications (e.g., bricks, ceramics, cementitious systems, lightweight aggregates) constitute a promising valorization route as they can immobilize certain contaminants while reducing demand for virgin raw materials (Z. Chang *et al.*, 2020; Świerczek *et al.*, 2018; Wu *et al.*, 2021). Nevertheless, this pathway is occasionally presented with excessive optimism. Product performance, firing energy requirements, ash/sludge composition variability and compliance with building standards ultimately determine whether these applications prove to be genuinely scalable and environmentally beneficial. While the literature increasingly supports this approach, standardization, long-term durability and leaching assessments remain critical research and regulatory priorities.

Land reclamation and soil restoration offer benefits in degraded sites, since sludge-derived amendments can enhance organic matter content and water retention, particularly in poor or disturbed soils (Larney and Angers, 2012; Song and Lee, 2010). However, the suitability of this pathway varies by site and is contingent upon contaminant profiles, treatment level, land-use goals and post-application monitoring. In contaminated or abandoned industrial areas, sludge use requires evaluation as part of a comprehensive remediation plan, not merely as a disposal option.

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Table 2. Comparative framework of sewage sludge valorization pathways. TRL = technology readiness level; PFAS = per- and polyfluoroalkyl substances; HTL = hydrothermal liquefaction

Valorization pathway	Main technologies	TRL	Key benefits	Major risks/limitations	Representative references
Agricultural use	Land application, composting, digestate reuse	7-9	Nutrient recycling (N, P, K); enhanced soil fertility/ structure; organic matter input.	Heavy metal accumulation; pathogen transmission; emerging contaminants (PFAS, microplastics pollution).	Hušek *et al*. (2022); Lucia *et al*. (2025); Saliu and Sauvé (2024); Singh and Agrawal (2008)
Energy recovery	Anaerobic digestion, incineration, pyrolysis	7-9	Renewable energy generation (biogas/heat); volume reduction (up to 90%); pathogen destruction.	Air-emission control requirements; ash management; methane leakage risks	Liang *et al*. (2021); Muñiz *et al*. (2025); Raheem *et al*. (2018); Takaoka *et al*. (2025)
Construction materials	Bricks, cement clinker, lightweight aggregates	6-8	Resource circularity; heavy metals immobilization; reduced demand for raw materials.	Leaching risks; sludge composition variability; lack of long-term standardization.	Z. Chang *et al*. (2020); Świerczek *et al*. (2018); Wu *et al*. (2021)
Land reclamation	Soil restoration, land rehabilitation	6-8	Enhanced soil structure and water retention; ecosystem recovery in degraded sites.	Site-specific constraints; contaminant accumulation; stringent monitoring requirements.	Larney and Angers (2012); Rincon Tamanini *et al*. (2008); Saliu and Sauvé (2024)
Biofuel production	Transesterification, HTL, pyrolysis bio-oil	3-6	High-value energy carriers (biodiesel, bio-oil); fossil fuels substitution.	High moisture content (energy penalty); complex chemical processing; limited economic feasibility.	(Bora *et al*., 2020); Ganesapillai *et al*. (2026); Samolada and Zabaniotou (2014); Shah *et al*. (2021)

6. Sewage sludge disposal and risk management

While the circular economy emphasizes resource recovery, disposal continues to be unavoidable for a significant fraction of sludge and process residues. Even in recovery-oriented systems, contaminants may become concentrated in reject streams, ash or leachates, thus requiring secure management (Hušek *et al*., 2022; Poblete *et al*., 2022). Consequently, in integrated sludge systems disposal must not be treated as a failure but instead as a necessary component of risk management. The critical policy question is centered on how to minimize final disposal while simultaneously preventing risks being transferred to communities or ecosystems.

Consequently, sludge management pathways must be evaluated based not only on technological performance but also on potential risks to human health and the environment. Table 3 summarizes the main contaminants, exposure pathways and associated impacts across the principal sludge management routes, and the key mitigation strategies identified in the literature. The risk patterns presented in Table 3 indicate that sludge management pathways often redistribute contaminants across environmental compartments, rather than fully eliminating them. This redistribution principle can be interpreted by distinguishing whether a given pathway is expected to destroy priority compounds or primarily transfer and concentrate them in other residual streams. For example, land-based applications may shift risks to soil and food systems, whereas thermal processes concentrate contaminants in air emissions and ash residues. Land-based reuse can shift contaminants to soil–plant–water pathways, meaning that safe implementation is dependent upon treatment quality, regulatory limits and monitoring, rather than on agronomic benefits alone (Lamastra *et al*., 2018; Peccia and Westerhoff, 2015). This underscores the need for pathway-specific risk management strategies, as opposed to broad, generalized regulatory approaches.

This redistribution is particularly important in the case of persistent emerging contaminants that are resistant to conventional biological treatments, including anaerobic digestion. PFAS exemplify this issue; conventional biological processes leave these compounds largely intact, shifting them between biosolids, centrate/reject water and soils or receiving waters, depending on the management route utilized (Ismail and Tizaoui, 2025). This underscores how resource recovery strategies must be evaluated alongside contaminant fate, monitoring capabilities and governance safeguards, rather than being assumed to eliminate environmental risks by default.

Historically, due to its relative operational simplicity, landfilling has been a common practice. However, this practice is inconsistent with circular economy principles and presents significant environmental limitations. The primary risks include leachate generation, groundwater contamination, methane emissions, odors, vector attraction and long-term land occupation, particularly in the context of poorly engineered facilities (Abdel-Shafy *et al*., 2024; Bello *et al*., 2022; Samolada and Zabaniotou, 2014; Siddiqua *et al*., 2022). Such impacts can be both technical and social, with the potential for landfill location and expansion to affect vulnerable communities. As a consequence, many jurisdictions prioritize diversion from landfills, promoting sludge stabilization and resource recovery before final disposal.

Incineration is a mature technology providing considerable volume reduction and pathogen destruction and supporting energy recovery when utilized with combined heat and power systems (Liang *et al*., 2021; Lin *et al*., 2018). However, its sustainability should be evaluated through consideration of full system boundaries, including drying requirements, air pollution control, residue management and the local energy context (Abuşoğlu *et al*., 2017; Ren *et al*., 2017). Co-combustion in existing facilities, such as cement kilns and other combustion systems, may improve feasibility in some contexts, but system performance is dependent upon feed blending, emission standards and ash quality (Lasek *et al*., 2021; Liang *et al*., 2021). Therefore, in addition to comparing incineration with landfilling in terms of volume reduction, policy discussions must also consider capital costs, technical expertise and regulatory capacity. In contrast, high temperature thermal routes can achieve effective destruction of biological hazards and many organic compounds, but they may also generate air-emission control demands and concentrate metals and other residual risks in ash streams, requiring robust governance and residue management (Fytili and Zabaniotou, 2008; Werther and Ogada, 1999).

Land application presents a distinct set of challenges when managed primarily as a disposal route, rather than as a controlled reuse strategy. Although nutrient recovery and soil improvement benefits are significant, they do not mitigate the risks associated with pathogens, heavy metals or micropollutants, where treatment and monitoring are insufficient (Hušek *et al*., 2022; Lamastra *et al*., 2018; Yakamercan *et al*., 2021). Furthermore, environmental justice concerns are critical because communities near wastewater infrastructure may experience disproportionate exposure to environmental hazards and nuisance burdens, especially when public participation and transparency are limited (Lowman *et al*., 2013). Consequently, risk communication, monitoring and community engagement must be integrated as core components of sludge management planning, rather than as optional social measures. Similarly, construction material valorization can immobilize some contaminants through sintering or binding, and long-term leaching performance and standardization remain crucial for determining whether this strategy effectively mitigates environmental risks or merely shifts them to the product's lifecycle and end-of-life stages (Z. Chang *et al*., 2020; Świerczek *et al*., 2018; Wu *et al*., 2021).

Taken together, the literature supports a hierarchy-based approach: preventing contamination at source whenever possible, enhancing sludge quality through treatment and pre-treatment, prioritizing safe resource recovery, and reserving secure disposal for unavoidable residuals. This comprehensive framework is far more consistent with public health protection than the mere promotion of technology alone.

Table 3. Risk profile and mitigation strategies across sewage sludge valorization pathways. PFAS = per- and polyfluoroalkyl substances; PPCPs = pharmaceuticals and personal care products; ARGs = antibiotic resistance genes; GHG = greenhouse gases; APC = advanced air pollution control; TCLP = toxicity characteristic leaching procedure

Valorization pathway	Critical contaminants	Exposure pathway	Potential impacts	Risk management / mitigation strategies	Representative reference
Agricultural use	Heavy metals (Cd, Pb, Cu, Zn), pathogens, PFAS, microplastics, and PPCPs.	Plant uptake (food chain), groundwater leaching, and atmospheric transport (dust/aerosols).	Bioaccumulation in crops, chronic toxicity, and spread of ARGs.	Strict regulatory limits, stabilization (composting/digestion), lime addition, and soil/crop monitoring.	Espinoza-Guillen *et al*. (2022); Ismail and Tizaoui (2025); Lucia *et al*. (2025); Saliu and Sauvé (2024); Viau *et al*. (2011); Yakamercan *et al*. (2021)
Energy recovery (Incineration)	Flue gas emissions (NOx, SO_2, CO_2, Hg), dioxins, furans, and contaminated ash.	Inhalation of flue gases and leaching from landfilled incineration ash.	Air pollution, respiratory issues, and contribution to GHG emissions.	APC, optimized combustion conditions, and ash immobilization/vitrification.	Fytili and Zabaniotou (2008); Liang *et al*. (2021); Muñiz *et al*. (2025); Raheem *et al*. (2018); Takaoka *et al*. (2025); Werther and Ogada (1999)
Construction materials	Leachable heavy metals (Pb, Cr, Cd) and soluble salts (Cl−).	Leaching during product service life or post-demolition disposal.	Secondary soil/water pollution and potential structural instability resulting from composition variability.	High-temperature sintering (chemical immobilization), limiting sludge substitution rates, and TCLP leaching tests.	Z. Chang *et al*. (2020); Lin *et al*. (2018); Świerczek *et al*. (2018); Wu *et al*. (2021)
Land reclamation	Excess nutrients (N, P), metals, and persistent pathogens.	Surface runoff to water bodies and percolation to deep soil layers.	Eutrophication of nearby aquatic ecosystems and long-term soil toxicity.	Judicious application rates, buffer zones, site-specific monitoring, and ensuring sludge maturity.	Larney and Angers (2012); Lin *et al*. (2018); Rincon Tamanini *et al*. (2008); Saliu and Sauvé (2024)
Biofuel production	Volatile organic compounds, methane leakage, and acidic process effluents.	Accidental spills during transport and fugitive GHG emissions during processing.	Climate impact from methane release and toxicity of process by-products.	Closed-loop processing, biogas upgrading/purification, and proper management of reject water/digestate.	Bora *et al*. (2020); El Abbadi *et al*. (2025); Ganesapillai *et al*. (2026); Raheem *et al*. (2018); Richard *et al*. (2019)

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7. Global trends and regional disparities in municipal sewage sludge management

Global trends in sewage sludge management are irregular, making broad generalizations misleading. High-income regions with long-established sewerage and treatment infrastructure (particularly in much of Europe and Japan) increasingly manage sludge within stricter regulatory and data-reporting frameworks. Consequently, these areas place greater emphasis on contaminant reduction, energy generation and phosphorus recovery (Di Giacomo and Romano, 2022; Hušek *et al*., 2022; Sotelo *et al*., 2019). In these contexts, policy debates have shifted away from simple disposal capacity toward optimizing treatment trains, life-cycle burdens, alignment with circular economy principles, and the managing of residual risks from metals and emerging contaminants (Z. Chang *et al*., 2020; Hušek *et al*., 2022; Zarandi *et al*., 2023).

Latin America and the Caribbean require more attention because the region combines relatively high rates of urbanization with inequalities in sanitation coverage, treatment performance and operational continuity. Consequently, in many cases sludge management challenges are not merely technical, but also institutional: utilities may operate under conditions of fragmented governance, uneven financing and variable monitoring capacity, while peri-urban expansion may outpace sewerage and treatment upgrades (Di Giacomo and Romano, 2022; Silva, 2023; Sosa-Rodriguez *et al*., 2020). At the same time, water scarcity, drought pressure and climate variability in parts of the region strengthen the case for integrated wastewater reuse and resource recovery planning. However, these strategies require improved risk management and cross-sectoral coordination, in order to avoid shifting environmental burdens from water services to agriculture or vulnerable communities (Mahlknecht *et al*., 2020; Silva, 2023; Varady *et al*., 2016).

A useful global comparison involves examining regions according to their primary limitations, rather than solely by income category. In parts of East and Southeast Asia, rapid urbanization has been accompanied by wastewater infrastructure expansion. Nevertheless, differences in treatment access and performance remain, and sludge management capacity does not always keep pace with wastewater treatment growth (Di Giacomo and Romano, 2022; Shi *et al*., 2022). In many parts of Sub-Saharan Africa and South Asia, centralized sewer systems coexist with large non-sewered populations. In these contexts, fecal sludge management, gradual service improvements and locally maintainable treatment pathways may be more appropriate than the direct transfer of capital-intensive models from Europe or North America (Nhapi and Gijzen, 2005; Oladoja, 2017; Richard *et al*., 2019; Zuin *et al*., 2019).

Globally, the «state of the art» is best understood as a set of context-specific pathways, rather than as a single technological endpoint. For some cities, the priority is advanced thermal treatment with nutrient recovery and strict emissions controls. For others, the most critical improvements involve reliable waste collection, stabilization, dewatering, pathogen reduction and safe final disposal or controlled reuse, supported by monitoring and governance reform (Hušek *et al*., 2022; Shah *et al*., 2021; Siddiqua *et al*., 2022; Silva, 2023). Approaching regional disparities this way avoids deficit narratives, highlighting instead transition pathways, institutional readiness and the necessity of cross-sectoral coordination among the water, sanitation, waste, agriculture and energy sectors (Cosgrove and Loucks, 2015; Gleick, 1996; Zuin *et al*., 2019).

8. Discussion

The comparative analysis presented in Table 2 and the risk profiles summarized in Table 3 provide a basis for interpreting current sludge management strategies. Together, they demonstrate that differences in technological maturity are closely related to differences in risk distribution and governance needs across various options. The studies reviewed in this manuscript suggest that a primary weakness in many sewage sludge policies is not the lack of technical options, but the lack of integrated decision-making frameworks that compare options under local conditions. Technologies are often promoted in isolation, including anaerobic digestion, incineration, land application or material reuse, without fully considering sludge composition, pre-treatment needs, monitoring capacity, social acceptance and market stability for recovered products. This narrow approach can create an implementation gap, in which advanced strategies do not always deliver the expected environmental or public health benefits (Hušek *et al*., 2022; Raheem *et al*., 2018; Ren *et al*., 2017).

A broader interpretation of the literature also reveals a continuing tension between circular economy goals and public health management. As indicated in Table 3, resource recovery pathways may reduce disposal burdens and recover energy, nutrients or materials, but they can also shift environmental risks across soil, air, ash, leachate and residual streams if risk control measures are insufficient. For example, agricultural application can improve soils while raising concerns about heavy metals and emerging pollutants; thermal routes can reduce sludge volume while concentrating contaminants in ash and requiring advanced emission controls; and the use of construction materials may immobilize contaminants but still require long-term performance validation (Liang *et al*., 2021; Tytła and Widziewicz-Rzońca, 2023; Wu *et al*., 2021; Yoshida *et al*., 2018). Rather than undermining the argument for resource recovery, these points underscore the necessity for pathway-specific risk governance.

A cross-cutting interpretation of the literature reveals that many resource recovery technologies do not eliminate contaminants, but instead shift them between environmental compartments, unless strict controls are applied (Peccia and Westerhoff, 2015). For instance, although land application and composting recover valuable nutrients, without rigorous monitoring they risk long-term metal and micropollutants accumulation (Lamastra *et al.*, 2018). Similarly, anaerobic digestion successfully recovers energy but often does not fully degrade persistent micropollutants, resulting in unresolved governance challenges (Hušek *et al.*, 2022; Peccia and Westerhoff, 2015). Thermal routes destroy many hazards and reduce volume, but require advanced emission and ash management to prevent secondary pollution (Fytili and Zabaniotou, 2008; Werther and Ogada, 1999). Ultimately, this “destruction versus transfer” dynamic underscores that resource recovery is not unconditionally sustainable; it must be evaluated alongside institutional and technical capacity for risk governance.

Another important issue is scale. The literature supports city- and region-specific planning, but many reviews still present management routes as if they were widely transferable. In practice, feasibility is dependent upon plant scale, energy prices, transport distances, institutional coordination, laboratory capacity and regulatory enforcement. These factors are particularly important in Latin America and other regions where, although wastewater treatment coverage continues to expand, sludge management systems may remain underdeveloped (Mahlknecht *et al.*, 2020; Silva, 2023). In such contexts, phased strategies that improve stabilization, dewatering and safe intermediate disposal may provide greater short-term public health benefits than the adoption of complex resource recovery technologies that cannot be sustainably maintained.

In future studies and policy design, social acceptance and environmental justice will require greater attention. Community concerns associated with odors, transport, perceived contamination and unequal exposure are often treated as secondary issues, but they directly affect project viability and legitimacy (Lowman *et al.*, 2013). Therefore, stakeholder participation, transparent monitoring and risk communication should be integrated into sludge management planning. Such strategies are consistent with IWRM principles and help shift the focus of the field from technology selection alone to the achieving of socially robust sanitation transitions (Cosgrove and Loucks, 2015; Meran *et al.*, 2021).

The findings of this review indicate that the priorities of research should include region-specific life-cycle assessments and multi-criteria decision-making assessments, harmonized monitoring of emerging contaminants and pathogen indicators, long-term field studies on land application and construction materials, evaluation of phosphorus and nutrient recovery under real operating conditions, and governance research on financing, institutional coordination and social acceptance. Such focuses will enhance the utility of future studies for decision-making processes and contribute to a strengthening of the overall contribution of research concerning sewage sludge management.

9. Conclusion

Municipal sewage sludge management constitutes a critical public health and sustainability challenge within urban water systems. The literature reviewed confirms that sludge should not be treated solely as a disposal burden, and nor should it be viewed uncritically as a resource. Safe and sustainable management requires the matching of treatment and resource recovery options to local sludge characteristics, infrastructure, monitoring capacity, regulatory frameworks and community context. No single option is universally optimal. Agricultural reuse, energy recovery, incorporation into construction materials, land reclamation and biofuel production each offer potential benefits, but each entails distinct technical and risk-management requirements. In many systems, landfilling and incineration remain important, but their role should be limited increasingly to well-controlled residual management within broader resource recovery strategies. An integrated approach that combines IWRM principles, sustainability assessments -including life-cycle assessment and multi-criteria decision-making tools- and strong governance is essential for the protection of public health while supporting circular economy goals. In Latin America and other regions with limited infrastructure or monitoring capacity, staged and context-appropriate improvements may offer the most realistic pathway toward safer sludge management. Future work should prioritize contaminant monitoring, phosphorus recovery, long-term performance studies and the analysis of social acceptance and environmental justice, in order to support more robust policy decisions.

Authors’ contributions

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ChatGPT (GPT-5) was used for language editing, specifically to improve the grammar, clarity and readability of the manuscript. The authors subsequently revised, edited and verified the entire content, and assume full responsibility for the final version of the manuscript.

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