

Review

Sustainable Wastewater Sludge Valorization: A Critical Review of Life Cycle Assessment and Techno-Economic Studies

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Abstract

Rapid population growth has led to increasing quantities of wastewater treatment sludge, creating environmental, economic, and public health challenges that require sustainable management strategies. This review critically examines recent advances in wastewater sludge management by evaluating sludge characterization, conventional and emerging valorization technologies, and the application of life cycle assessment (LCA) as a decision-support tool. The analysis shows that sludge can be successfully valorized through agricultural reuse, energy recovery, industrial applications, and resource recovery. However, the suitability of each pathway depends on sludge properties, environmental conditions, regulatory requirements, and economic feasibility. LCA highlights the environmental trade-offs associated with different management scenarios and provides a systematic framework for comparing their environmental and economic performance while supporting circular economy principles. Overall, integrating sludge valorization with comprehensive life cycle assessment enables more informed decision-making and promotes environmentally sustainable and economically viable wastewater sludge management. This review provides practical insights for researchers, policymakers, and industry stakeholders seeking to optimize sludge management strategies and advance sustainable wastewater treatment.

Keywords: wastewater treatment; sludge management; sludge valorization; life cycle assessment; techno-economic assessment



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1. Introduction

The treatment of wastewater has become an increasingly critical challenge due to rising global production levels. With approximately 380 billion m³ of wastewater generated annually, this figure is projected to increase significantly by 2030, driven by factors such as population growth, industrial expansion, and agricultural intensification [1,2]. Effective wastewater treatment is crucial for mitigating the environmental burden on natural ecosystems and enabling the reuse of treated water in various sectors, such as agriculture, industry, and health applications [3,4]. Countries like Germany exemplify advanced investment in wastewater infrastructure, employing technologies like activated sludge, anaerobic-anoxic-oxic (AAO) processes, and sequencing batch reactors [5]. Similarly, China has developed its wastewater treatment strategies in line with significant advancements in infrastructure. By 2019, the country had 5333 municipal wastewater treatment plants in operation, with

most meeting high discharge standards. Also, their facilities support various applications such as irrigation, industrial cooling, and groundwater recharge [6]. Spain and Latin America have adopted advanced technologies like ozonation and reverse osmosis to address contaminants, despite economic barriers. In southern Europe, particularly in Italy and Spain, they emphasize the potential of decentralized systems to bridge rural treatment gaps, ensuring environmental and public health protection [7]. Also, Morocco has made strides in wastewater treatment through programs [8], like the National Liquid Sanitation and Wastewater Treatment Program (PNA), which has spurred the modernization of treatment plants [9,10]. Advanced treatment processes in Agadir include anaerobic lagoon, sand bed infiltration-percolation, and ultraviolet disinfection to produce high-quality treated water [11]. But despite the innovative changes proposed by different countries to improve water quality, their financial and energy demands limit feasibility in less developed regions and rural areas, in addition to the solid sludge generated during the treatment process as a byproduct whose management presents significant challenges.

Sludge, known as a residual solid material produced during the wastewater treatment process, contains high levels of organic matter, nutrients, and potentially hazardous substances such as heavy metals and pathogens [12–14]. In this review, the term wastewater sludge primarily refers to municipal wastewater treatment sludge, with particular emphasis on mixed sludge generated from the combination of primary and secondary (biological) treatment processes. Since sludge composition and valorization potential vary depending on its origin and treatment process, these differences are considered throughout the discussion whenever they influence the environmental or techno-economic performance of sludge management strategies. The management of sludge involves complex processes to ensure its safe disposal or potential reuse [15]. Multiple strategies are employed in different countries to effectively manage sludge. These include addressing socio-economic challenges, improving regulatory frameworks, collecting and analyzing data, enhancing management practices, and developing solutions and recommendations [16,17]. However, these processes are often associated with high operational and maintenance costs and limited economic returns. This economic burden, coupled with the environmental risks of improper disposal, underscores the need for sustainable management solutions.

Furthermore, sludge valorization into value-added products (VAPs), such as agricultural fertilizers, renewable energy, biochar, construction materials, and recovered metals, offers a promising pathway to address these challenges while supporting the transition toward a circular economy [18,19]. Recent reviews indicate that most wastewater sludge valorization studies have focused on energy recovery, agricultural applications, and resource recovery technologies, reflecting the growing emphasis on circular economy strategies and sustainable sludge management [20–22]. Anaerobic digestion, incineration, gasification, and pyrolysis are widely investigated for energy production, generating biogas, syngas, bio-oil, and biochar as valuable products [23]. Agricultural applications include direct land application and composting, which improve soil fertility and nutrient content while mitigating environmental risks through rigorous monitoring [24,25]. Emerging approaches, including biochar production, bioflocculant synthesis, lipid extraction for biodiesel production, and metal recovery, further expand the range of valuable products that can be obtained from wastewater sludge [26,27]. Furthermore, co-processing in cement kilns highlights the dual benefits of waste reduction and material substitution [28]. While valorization can reduce industrial waste and generate economic benefits, the selection of technologies in line with this purpose is fraught with uncertainties. Techniques that appear efficient may not always align with environmental and economic sustainability, leading to suboptimal outcomes. This lack of strategic decision-making often results in the arbitrary adoption of technologies without adequate consideration of their long-term impacts.

Recently, life cycle assessment (LCA) has emerged as a vital tool to guide decision-makers in selecting appropriate techniques for different situations [29], including wastewater sludge valorization techniques. By systematically evaluating the environmental and economic impacts of different options, LCA provides a comprehensive framework to identify sustainable solutions [30]. This approach enables the evaluation of trade-offs between resource consumption, greenhouse gas emissions, and other environmental impacts that directly influence the environmental categories, ensuring that selected technologies align with sustainability goals [31]. Furthermore, LCA facilitates the comparison of alternatives, helping stakeholders prioritize options that not only minimize environmental footprints but also optimize economic feasibility [32]. Here, we will highlight the most innovative solutions that involve LCA in their selection and decision-making for the sustainable management of wastewater and wastewater sludge. The costs associated with different LCA scenarios in attempts to evaluate the economic benefits are also detailed to reveal the importance of considering the environmental impacts of greener and sustainable management solutions.

2. Wastewater Sludge

Due to its increasing volume and pollutant composition, the natural environment is increasingly struggling to self-purify these discharges, making wastewater treatment a crucial step in preserving ecosystem quality [33]. Addressing global water stress has made improving wastewater treatment techniques a priority for many nations [34]. Enhanced treatment can enable water reuse in various sectors, such as in agriculture for irrigation and in industry for machine cooling [35]. In some cases, treated wastewater can even meet potable water quality standards using advanced technologies [36]. However, the selection of treatment techniques is influenced by factors such as the wastewater's volume and composition, local environmental regulations, and the available budget [37]. Moreover, activated sludge treatment remains widely used for organic pollutant removal, while techniques like the sequencing batch reactor (SBR) or anaerobic-anoxic-oxic (AAO) processes face specific pollutant degradation needs [38]. However, these methods are often energy-intensive or resource-dependent, making their application challenging in resource-constrained regions.

In developing countries such as Morocco, rapid urbanization and inadequate infrastructure amplify the challenges of wastewater management [39]. The country has made significant strides through programs like the National Liquid Sanitation and Wastewater Treatment Program (PNA), which focuses on sanitation services and infrastructure modernization [10]. Although many investments in advanced treatment technologies in urban areas have been made in recent years, such as ultraviolet disinfection in Agadir, to highlight the potential for high-quality treated wastewater, it struggles with substantial treatment costs [11], in addition to the persistence of disparities, especially in rural areas, where basic wastewater treatment facilities are often unavailable. Furthermore, treated wastewater is increasingly valued in Morocco for agricultural irrigation, urban green space maintenance, and industrial reuse, contributing to water conservation and economic benefits [40]. However, challenges like soil salinization, uneven nutrient distribution, and public skepticism must be addressed to ensure sustainable reuse practices.

Wastewater treatment processes also produce sludge, an unstable byproduct that cannot be directly applied to land because of safety concerns [38,39]. Sludge is a semi-solid byproduct that comprises a mixture of water, organic and inorganic materials, and microorganisms extracted during various treatment stages. Proper management of this sludge is a pressing challenge, not only for mitigating environmental impacts but also for tapping into its resource recovery potential [41,42]. Although wastewater sludge is generally classified

into primary, secondary, and mixed sludge, considerable variations exist in its physicochemical properties depending on wastewater composition, industrial contributions, treatment technology, and climatic conditions. Consequently, sludge characteristics reported in different studies cannot be directly generalized. This variability significantly influences sludge management options, resource recovery potential, environmental impacts and economic feasibility. Therefore, sludge characterization should always be considered before selecting an appropriate valorization strategy.

3. Global Perspectives and Regional Frameworks

Managing sludge is a growing challenge in environmental engineering [43]. Advances in wastewater treatment have significantly improved effluent quality but have also resulted in an increasing volume of sludge [44]. Managing sludge from an innovative perspective is a vital part of sustainable wastewater treatment, driven by three main considerations. First, environmental preservation is essential to reduce impacts and ensure resources are protected for future generations. Second, economic viability plays a critical role as resource recovery and lower disposal costs make sludge management both cost-effective and aligned with circular economy principles. Finally, public health safety is critical, as proper treatment reduces pathogens and contaminants, minimizing risks associated with agricultural or industrial use [45]. These three pillars, including environmental sustainability, economic efficiency, and public health, highlight together the importance of sludge management in building a healthier, more balanced, and sustainable society.

3.1. Actions Across Regions

In Europe, sludge management relies on a systematic approach with six key components. It starts with collecting and reporting data on sludge quantities, treatment methods, and disposal routes. This information is processed and shared at the EU level through platforms like Eurostat, though challenges with data quality and consistency remain, calling for significant improvements. Treatment methods are chosen based on local regulations, available technology, and economic factors. Disposal routes for treated sludge often include agricultural reuse, landfilling, or incineration, guided by environmental and legislative requirements outlined in EU directives. A growing focus on understanding the entire sludge cycle aims to enhance management strategies, ensuring sustainability and improved efficiency in practices across Europe [46]. A French study highlights a comprehensive approach to sludge management, focusing primarily on the characterization of sludge in terms of organic matter, nutrients, and contaminants [44]. This detailed analysis aims to better identify the most suitable treatment processes before selecting final disposal or reuse options, with an emphasis on opportunities for resource recovery. The study also advocates for the integration of LCA as a valuable tool for evaluating the environmental impacts and guiding the decision-makers toward sustainable sludge management solutions [44].

In New Delhi, India, a study examined five critical aspects of sludge management, addressing challenges in sludge disposal, sustainable management strategies, and the physicochemical characteristics of sludge. The study also explored reuse options, including coagulant recovery, construction materials, and agricultural applications, highlighting their potential benefits [45]. Additionally, it emphasized the need for future research to improve environmental outcomes and enhance the cost-effectiveness of sludge management practices [45].

In Africa, the management of sludge is related to several aspects, with limitations and challenges that vary from one country to another. In Burundi's capital, sludge management focused on wastewater collection methods (pit latrines, septic tanks, and sewer systems), with treatment choices based on cost-effectiveness, retention time, and simplicity. How-

ever, challenges like low sewerage connection rates contribute to water eutrophication, highlighting the need for future improvements in sludge management [17]. In Yaoundé, Cameroon, sludge management practices were analyzed through a study focusing on five key aspects: diverse urban sampling, household surveys on sanitation facilities, assessment of latrine designs, health risks associated with inadequate sanitation, and recommendations for improvements. The findings highlighted widespread use of basic latrines, significant open defecation issues, and increased disease risks during the rainy season, underscoring the urgent need for enhanced sanitation infrastructure and management strategies [47]. In Cape Town, South Africa, a study evaluated four sludge management scenarios. The current operations involve a biosolids beneficiation facility. The first strategy proposes upgrading the anaerobic digestion process by adding three reactors to improve treatment efficiency. The second strategy incorporates thermal hydrolysis pretreatment (THP) into the process, while the third and fourth strategies combine reject water treatment with THP to optimize resource recovery. The study concludes that introducing THP offers significant benefits, including enhanced energy recovery, reduced sludge production, and improved overall treatment efficiency [48].

In China, a recent overview study highlighted five key aspects currently seen in sludge management [49]. These include the evaluation of sludge characteristics and their variability across different regions, sustainable treatment and disposal methods such as co-incineration in coal-fired plants, cement kilns, and thermal hydrolysis-anaerobic digestion. The study also emphasized the development of an integrated assessment framework that considers carbon emissions, economic costs, and environmental risks. Additionally, it identified research gaps and proposed technological recommendations to address these limitations [49]. The research also addressed policy mechanisms, including subsidies and standards to encourage the safe and efficient use of sludge-derived products like fertilizers; furthermore, it advocated for innovations such as phosphorus recovery from incineration ash and the creation of high-value bioproducts, ensuring these processes remain economically feasible and environmentally sound [49].

In Morocco, the management of wastewater sludge presents significant challenges due to the increasing production of sludge as wastewater treatment facilities expand across the country [50]. While the number of treatment plants has grown, the sludge infrastructure for effectively handling and disposing of it has not kept pace. Much of the sludge is still inadequately managed, often being disposed of in landfills without proper treatment, leading to potential environmental risks such as soil contamination and greenhouse gas emissions. This disconnect between wastewater treatment expansion and sludge management infrastructure underscores a critical gap in Morocco's environmental strategy, where the focus on wastewater treatment has surpassed the equally pressing issue of sustainable sludge handling. In some cases, sludge is used in agriculture without sufficient treatment, raising concerns about the spread of pathogens and heavy metals, as seen where sewage sludge was used as organic manure in sunflower culture [51]. Recent studies emphasize the urgent need for improved strategies in sludge treatment and valorization, particularly through energy recovery and safe agricultural reuse, because even though sludge reuse in agriculture offers potential benefits, such as nutrient recycling and reduced reliance on chemical fertilizers, the lack of stringent monitoring and adequate treatment poses serious risks to public health, soil quality, and long-term agricultural sustainability. These issues highlight the importance of developing comprehensive sludge management policies that align with Morocco's goals for sustainable development and environmental protection [50]. Achieving this requires significant investment in infrastructure, research on technical innovation with local socioeconomic practices and capacity building, alongside policy reforms to regulate sludge treatment and ensure compliance with safety standards. The wastewater

treatment plant in Rabat, Morocco, that serves the capital city follows these rules and preservation protocols. The plant produces a significant amount of sludge as a byproduct of its wastewater treatment processes [52]. To manage this sludge, the plant has explored various treatment and valorization options. One of the most notable initiatives is the use of anaerobic digestion to stabilize the sludge and recover biogas for energy production [24]. In many studies, the biogas generated is also used to power the plant, reducing its reliance on external energy sources and minimizing its carbon footprint and the economic treatment costs [53]. Additionally, the treated sludge is used as a soil conditioner in agriculture, following strict guidelines to ensure it is safe and beneficial for crop production [54]. These cases illustrate the potential for integrating energy recovery and agricultural reuse into sludge management practices, aligning with Morocco's broader environmental and sustainability goals. The widespread adoption of this type of management across the country could significantly mitigate most of the risks that sludge poses to human health.

Figure 1 illustrates the various factors affecting sludge management in different countries [55,56]. Public health and environmental concerns emerge as the most influential for sustainable management strategies [57]. Truly, preserving the environment and ensuring public health are primary for balanced development and acceptable living standards. India stands out for six distinct contributing factors that indicate the complex and interrelated nature of its sludge management challenges [58]. In contrast, countries such as China report fewer influencing factors, which may be attributed to specific national priorities or limited data availability [59]. Overall, the distribution of these factors emphasizes the need for specific management approaches that are responsive to growing environmental and regulatory pressures. The main characteristics of the studies included in this literature review are summarized in Table 1.

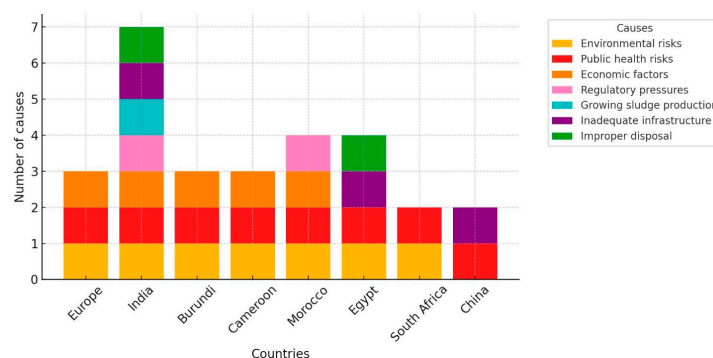


Figure 1. Distribution of sludge management causes by country.

Table 1. Main information of the studied references included in the literature about sludge management.

Local	The Cause of Sludge Management	The Routes of Managed Sludge			Stakeholder	References
		Reuse	Disposal	Treatment		
Europe	Lack of data quality and reliability environmental issues -Fragmentation of management systems;	Agricultural reuse (fertilizer)	Landfilling	Incineration Anaerobic digestion Composting	National governments Environmental agencies Waste treatment facilities	[46]
India	Environmental issues Regulatory pressures Public acceptance health risks Economic factors	Coagulant recovery Soil amendment Bio-based construction materials Adsorbent for contaminants	-	Co-conditioning Dewatering	Water treatment plant operators Environmental regulators	[45]

Table 1. Cont.

Local	The Cause of Sludge Management	The Routes of Managed Sludge			Stakeholder	References
		Reuse	Disposal	Treatment		
Bujumbura Burundi	Low public sewerage connection rate Informal and unregulated fecal sludge management Environmental and public health risks	Soil amendment Fertilizer	Untreated sludge disposal to the environment	Anaerobic-anoxic-oxic treatment Composting	Local authorities Community members Wastewater treatment operators Environmental organizations	[17]
Practices in various countries	Public health and environmental risks Legislative pressure Growing sludge production	Fertilizer	Landfill Dumping at sea	Incineration Composting Stabilization	Authorities Communities Wastewater industries Environmental assessors.	[44]
Yaoundé, Cameroon	Inadequate sanitation infrastructure and practices, exacerbated by overpopulation Public and environmental risks of contamination	Potential use as a fertilizer	Directly into the environment	-	Households Local government Private sector operators Health authorities	[47]
Morocco	Insufficient infrastructure for handling growing sludge production Technical, environmental, and economic constraints	Agricultural reuse Rehabilitation of degraded sites Ornamental plants	Landfill (combined landfill or mono-landfill)	co-incineration in cement plants	Municipalities Operators of sanitation services Environmental and health authorities Government agencies	[50]
Egypt	Improper disposal of 85% of unstabilized sludge Environmental issues Public health safety	Agricultural purposes (often improperly managed)	Selling it to local vendors Improper disposal methods	Anaerobic digestion Windrow composting Storage lagoons	Municipalities and WWTP managers Governmental organizations	[16]
South Africa	Processing capacity High operational costs Environmental regulations	Agricultural use	Landfill	Anaerobic digestion Thermal hydrolysis pretreatment Struvite precipitation and harvesting	Water utilities Regulatory authorities Local communities	[48]
China	Regional variability in sludge characteristics	Agricultural; Source of energy.	-	Anaerobic digestion Co-incineration Thermal hydrolysis	Government agencies; Wastewater treatment plants.	[49]
India	Rapid urbanization and population growth Inadequate infrastructure Health and environmental impact	Biogas generation Fertilizer	-Landfilling; -Dumping in water bodies.	Anaerobic digestion Composting Constructed wetlands	Local governments and municipal authorities Wastewater treatment facilities Environmental agencies Public health officials	[60]

Sludge management practices vary significantly across regions, driven by a mix of environmental, institutional, and socio-economic factors [61]. In Europe, challenges such as fragmented management systems, unreliable data, and financial constraints have steered practices toward agricultural reuse and more regulated treatment routes like incineration and composting, often under the oversight of national governments and environmental

agencies [62]. Meanwhile, in India, environmental and public health risks, combined with public resistance and economic considerations, have encouraged the development of diverse reuse pathways, including coagulant recovery and soil amendments [63]. In contrast, many African countries like Burundi, Cameroon, and Morocco face more structural issues, including inadequate sanitation infrastructure and growing sludge production, leading to less controlled disposal methods and variable reuse approaches [64]. These disparities highlight the importance of context-specific policies and stakeholder engagement in improving sludge management outcomes globally for greener countries.

Figure 2 shows the adoption rates for various sludge treatment technologies in different regions of the world, which serve to illustrate the global spread of technological activity in the field of wastewater sludge management [65,66]. Methods such as anaerobic digestion, incineration, and gasification are more advanced in some regions than in others due to infrastructural, economic, and ecological considerations. As an example, Europe displays a greater usage of advanced techniques such as anaerobic digestion and co-incineration because of its investment in green infrastructure and strong legal frameworks concerning environmental protection [44]. Also in the Asia region, developed countries like China, Japan, and South Korea adopted advanced technologies such as anaerobic digestion and incineration, resulting in an increase in the percentage of advanced sludge management techniques in recent years [47,62]. Conversely, several countries in Africa and South America continue to experience lower implementation of advanced sludge valorization technologies because of limited financial resources, infrastructure constraints, and regulatory and institutional challenges [67–69]. Although the geographical distribution of sludge management technologies appears highly heterogeneous, the observed differences are not solely explained by technological availability. Economic development, environmental legislation, energy prices, and public acceptance collectively determine the feasibility of sludge valorization pathways. Consequently, countries with similar technological capabilities may adopt entirely different management strategies depending on national policy priorities and market conditions. This finding highlights the importance of integrating technical innovation with regulatory and socioeconomic considerations when designing future sludge management policies.

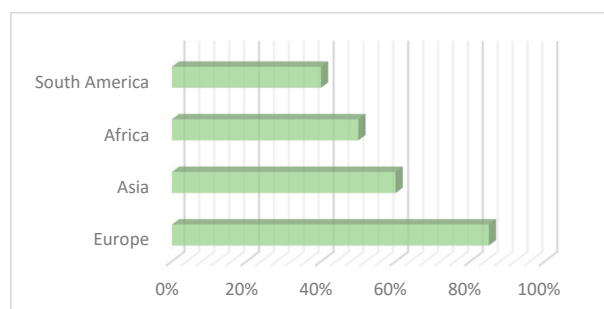


Figure 2. Advanced sludge treatment adoption in different regions.

The reviewed studies reveal that sludge management practices are largely driven by regional regulatory frameworks, economic development, infrastructure availability, and environmental priorities rather than by technological performance alone. European countries generally prioritize resource recovery and circular economy objectives, whereas many developing countries continue to rely on landfilling or uncontrolled disposal due to financial and technical constraints. Consequently, direct comparisons between regions should be interpreted cautiously, as different regulatory, economic, and environmental contexts strongly influence technology adoption. Beyond the regional differences described above, an important observation emerging from the literature is that no single

sludge management strategy can be considered universally optimal. Instead, successful implementation depends on the interaction between regulatory maturity, economic capacity, infrastructure availability, sludge characteristics, and local resource demands. European countries have demonstrated that stringent environmental regulations combined with financial incentives can accelerate the adoption of resource recovery technologies such as anaerobic digestion, phosphorus recovery, and thermal treatment. Conversely, many developing countries continue to prioritize safe disposal over resource recovery because limited investment capacity and insufficient institutional support restrict the deployment of advanced technologies. This suggests that technological innovation alone is insufficient to improve sludge management. Rather, effective governance, stable regulatory frameworks, and long-term investment strategies are equally critical for successful implementation. Future international strategies should therefore avoid promoting universal technological solutions and instead encourage adaptive management frameworks tailored to regional socioeconomic conditions, environmental priorities, and available infrastructure. Such an approach would improve technology transfer, increase the long-term sustainability of sludge valorization systems, and reduce the gap between developed and developing regions.

3.2. Challenges and Limitations

While sludge management provides essential solutions for the disposal of wastewater treatment byproducts, it remains a significant challenge due to its economic and environmental implications. Current practices often prioritize safe disposal, such as landfilling and incineration, but these methods offer limited economic returns and fail to fully capitalize on the resource potential of sludge [67]. This disconnect between disposal-focused strategies and opportunities for valorization is a recurring challenge across regions, as highlighted in several studies. In Morocco, for instance, sludge is often disposed of in landfills or used in agriculture without sufficient treatment, posing risks to public health and environmental sustainability [50]. Similarly, in New Delhi (India), the lack of comprehensive management strategies limits the reuse of sludge for coagulant recovery, construction materials, or agriculture, despite the potential benefits these applications could bring [45]. Even in regions with advanced infrastructure, challenges persist. European approaches emphasize compliance with regulations and systematic reporting, but issues with data consistency and quality impede effective decision-making [46]. In South Africa, strategies like thermal hydrolysis pretreatment show promise for energy recovery and reduced sludge production, but high implementation costs remain a barrier [48]. These case studies demonstrate that there is growing interest in sludge valorization for biogas, construction material production, and nutrient recycling, but economic and technical-related hurdles often restrict widespread adoption. For example, the wastewater treatment plant in Rabat, Morocco, exemplifies progress through anaerobic digestion and biogas recovery, yet this approach is not uniformly applied across the country [24]. To move beyond disposal-focused practices, it is essential to integrate sludge valorization into management systems. Transforming sludge into valuable products like bioenergy or fertilizers offers a dual benefit, permitting the resolution of disposal challenges while generating economic returns. Accordingly, by adopting the valorization strategy, the countries can align well with circular economy principles, reducing environmental and economic risks. The reviewed literature demonstrates that the principal obstacle to sustainable sludge management is no longer the lack of available treatment technologies but rather the limited integration of environmental, economic, technical, and regulatory considerations during decision-making. Most existing studies evaluate technologies independently, whereas real-world implementation requires balancing treatment efficiency with environmental performance, operational costs, infras-

structure availability, and regulatory compliance. Therefore, future sludge management strategies should increasingly rely on integrated decision-support frameworks combining life cycle assessment, techno-economic assessment, risk assessment, and multi-criteria decision analysis. Such integrated approaches would provide policymakers and wastewater utilities with more reliable tools for selecting context-specific sludge valorization pathways while minimizing environmental impacts and maximizing resource recovery.

Future research should prioritize integrated and standardized assessment frameworks that combine environmental, economic, technical, and social dimensions to improve technology evaluation. Policymakers should promote supportive regulations and financial incentives that facilitate the transition from sludge disposal to resource recovery, while industry should prioritize scalable, cost-effective, and environmentally sustainable valorization technologies adapted to regional conditions. Collaborative efforts among these stakeholders will be essential to accelerate the implementation of sustainable sludge management practices.

4. Sludge Valorization

Wastewater sludge valorization refers to the process of converting waste sludge generated from wastewater treatment into valuable products or resources [70]. This process encompasses various strategies aimed at enhancing the sustainability of sludge management [71]. These strategies include energy recovery, where sludge is utilized to produce energy through processes such as anaerobic digestion or incineration; material recycling, which involves recovering and repurposing materials like metals or organic matter; and nutrient recovery, where essential nutrients are extracted for use as fertilizers. By transforming waste sludge into beneficial products, valorization not only mitigates environmental impacts but also contributes to resource efficiency and sustainability in wastewater treatment practices.

Figure 3 presents an ensemble of different valorization pathways for wastewater sludge, cited in various studies [72,73]. It highlights several technologies for resource recovery and energy production. The processes include incineration, anaerobic digestion, ultrasonication, calcination, pyrolysis, gasification, and anoxic/aerobic fermentation, each yielding valuable outputs. Incineration produces ash for building materials, along with heat and electricity. Anaerobic digestion generates fuel gas and biogas. Ultrasonication recovers enzymes and proteins, produces biodiesel, extracts heavy metals, and may yield hydrogen gas. Calcination produces materials similar to pozzolans used in construction. Pyrolysis results in CO₂ and electricity. Gasification produces fuel gas and syngas, while anoxic/aerobic fermentation leads to bioplastics. These methods focus on converting wastewater sludge into valuable resources, supporting energy recovery and sustainable waste management practices [72].

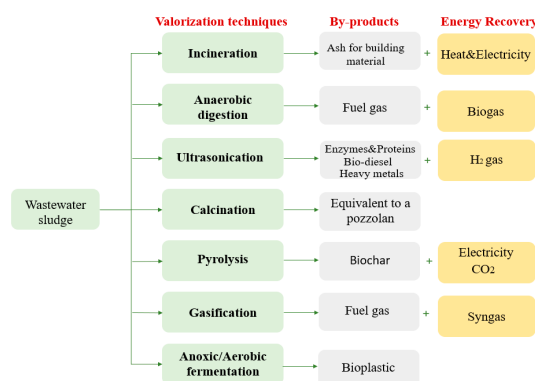


Figure 3. Valorization pathways of wastewater sludge and their recovered outputs.

4.1. Energy Valorization

There are several advanced techniques for wastewater sludge energy valorization, like anaerobic digestion, which utilizes microorganisms to decompose organic matter in sludge, producing biogas that can be used for electricity or heat generation. Incineration, where sludge is burned at high temperatures to generate heat and electricity while reducing its volume. Gasification is a process that converts sludge into syngas through partial oxidation, which can be utilized for energy production or as a chemical feedstock. Additionally, pyrolysis is explored in several studies, where sludge is thermally decomposed in the absence of oxygen to yield biochar, oils, and gases, all of which can serve as energy sources or soil amendments [23]. In contrast, a study focuses specifically on the Moroccan context and evaluates the practical application of these methods at local wastewater treatment plants. The research assesses the efficiency of anaerobic digestion for biogas production in Morocco, considering its feasibility and effectiveness in generating energy. It also examines incineration as a potential method for energy recovery, emphasizing the need to balance energy output with environmental impacts. The study further investigates co-digestion, where sludge is mixed with other organic waste streams to enhance biogas yield, and thermal hydrolysis, a pretreatment process that improves the efficiency of anaerobic digestion, thereby increasing the overall energy recovery potential of the sludge [74]. A summary of the studies on wastewater sludge energy valorization is presented in Table 2.

Table 2. Main information of the studied references included in the literature about sludge energy valorization.

Country	Technique Name	Method Classification	Technique's Type	Product	Waste	Environmental Benefits	Economic Benefits	References
Quebec, Canada	Microbial oil production	Non-conventional	Biological	Microbial oil	Biomass	Reduction of waste Reduction of greenhouse gas emissions Renewable energy source	Reduced treatment costs Byproducts that can be sold Cost-effective raw material Economic viability	[27]
	Biodiesel production	Conventional	Chemical (transesterification)	Biodiesel	Glycerol			
Spain	Incineration	Conventional	Thermal	Energy	Ash	Reduce waste volume and fossil fuels use	Reduced treatment costs	[74]
	Autothermal thermophilic aerobic digestion (ATAD)	Non-conventional	Biological	Biogas	Biosolids	Recycling nutrients back into the soil Reducing the fossil fuels use	Cost saving for sludge management Byproducts that can be sold	
	Anaerobic digestion	Conventional		Biogas	Digestate	-Renewable energy source; -Reducing the fossil fuels use.	Byproducts that can be sold Reduced treatment costs	
General methodologies on municipal sludge	Gasification	Non-conventional	Thermal	Energy Bio-oil	Slag	Reduce waste volume Production of renewable energy	Reduction sludge disposal costs Byproducts that can be sold	[20]
	Pyrolysis				Ash			
	Incineration	Conventional			Ash			
Coruña, Spain	Thermal pretreatment	Non-conventional	Thermal	VFAs	Solid content	Reduce waste volume Production of renewable energy Nutrient recovery	Cost saving for sludge management Renewable energy source Byproducts that can be sold	[75]
	Acidogenic fermentation		Biological	Energy VFAs				
	Anaerobic digestion	Conventional	Biological	Biogas	Digestate			
General methodologies	Aerobic fermentation	Conventional	Biological	Biogas	Biomass	-	Reduction sludge disposal costs Byproducts that can be sold	[28]
	Combustion and co-combustion		Thermal	Energy	Air emissions	Reduction of fossil fuels	Reduction sludge disposal costs Energy recover	
	Gasification	Non-conventional	Thermal		Slag		Reduction sludge disposal costs Byproducts that can be sold	
	Wet oxidation		Chemical/thermal	Oxidized sludge	Air emissions	-	Reduction sludge disposal costs Byproducts that can be sold	

Table 2. Cont.

Country	Technique Name	Method Classification	Technique's Type	Product	Waste	Environmental Benefits	Economic Benefits	References
European union	Anaerobic digestion	Conventional	Biological	Biogas	Digestate	Production of renewable energy to reduce fossil fuels use	Reduction sludge disposal costs Byproducts that can be sold	[72]
	Co-digestion							
	Ozone oxidation	Non-conventional	Chemical	Stabilized sludge	-	Stabilization of organic waste Reducing pathogens		
	Incineration	Conventional	Thermal	Energy	Ash	Reduce waste volume Production of renewable energy	Reduced treatment costs	
	Thermal hydrolysis			Biogas		Reduce waste volume Enhance biogas production	Reducing sludge treatment cost	
	Gasification	Non-conventional		Energy Biochar	-	Reduce waste volume Production of renewable energy	Reduction sludge disposal costs Energy recover	
	Pyrolysis			Energy Oil Biochar			Reduction sludge disposal costs Byproducts that can be sold	
Marrakech, Morocco	Anaerobic digestion	Conventional	Biological	Biogas	Biomass	Minimizing landfill use Energy production Reduction of greenhouse gas emissions	Cost-saving of energy and waste disposal	[76]
	Incineration		Thermal	Energy	Ash			
Norway	Gasification	Non-conventional	Thermal	Syngas	Gaseous emissions Ash	-Reduction of waste; -Renewable energy production; -Reduction of greenhouse gas emissions.	Cost-effective waste management Low-cost feedstocks Byproducts that can be sold	[26]
	Hydrothermal carbonization			Hydro-char	Gaseous emissions			
	Carbonization			Biochar	Gaseous emissions Ash			
Semi-arid and arid countries (Qatar)	Anaerobic digestion	Conventional	Biological	Biogas	Gaseous emissions Biomass	Renewable energy Digestate can be used as nutrient-rich fertilizer	Cost saving of energy and fertilizer production Cost saving in waste management	[77]
Skhirat, Morocco	Anaerobic digestion	Conventional	Biological	Biogas	Biomass	Waste management Energy production	Cost saving of energy production Cost saving in waste management	[24]
General methodologies	Pyrolysis	Non-conventional	Thermo-chemical	Biochar Bio-oil	Char	Reduction of greenhouse gas emissions Waste management Resource recovery Reduction of pollution	Cost saving in waste management Reduction in energy costs Byproducts that can be sold	[78]
	Gasification			Syngas	Ash			
	Fermentation	Conventional	Biochemical	Biodiesel Biogas Bioethanol	Biomass			

4.2. Agricultural Valorization

Agricultural valorization of wastewater sludge involves several techniques aimed at enhancing soil fertility and crop productivity while ensuring environmental safety. A study discusses the land application of treated sewage sludge as a soil amendment, where sludge is applied to agricultural fields to improve soil structure and provide essential nutrients like nitrogen and phosphorus [77]. This method is particularly effective in enhancing soil organic matter and nutrient content, which are crucial for sustainable crop production. Additionally, many studies explore composting, a process where sewage sludge is mixed with other organic materials to produce a stabilized compost [79]. Composting not only reduces pathogens and odors but also enhances the nutrient profile of the sludge, making it more suitable for agricultural use. A study in Germany highlights nutrient recovery techniques that ensure the efficient uptake of nutrients by plants, while minimizing potential environmental risks associated with sludge application [25]. In the Moroccan context, a similar concept is emphasized: the use of direct land application of treated sewage

sludge as a fertilizer [24]. The study evaluates the benefits of this technique in improving soil fertility and increasing crop yields, noting its potential as a sustainable solution for nutrient-poor soils in Morocco. Moreover, the research underscores the importance of composting to enhance the safety and effectiveness of sludge when used in agriculture, particularly in reducing the risk of pathogen transmission. To ensure that the benefits of sludge application are not compromised by environmental or health concerns, the study employs risk assessment techniques, focusing on monitoring heavy metal accumulation and other potential hazards in soils and crops. A summary of the studies on the agricultural valorization of wastewater sludge is presented in Table 3.

Table 3. Main information of the studied references included in the literature about sludge agricultural valorization.

Country	Technique Name	Method Classification	Technique's Type	Product	Waste	Environmental Benefits	Economic Benefits	References
South Brisbane, Australia	Vermifiltration	Non-conventional	Biological	Vermicompost (fertilizer)	-	Reduction of sludge volume and pathogen Nutrient recovery Low energy requirement	Cost-effectiveness Value addition	[80]
	Vermicomposting	Non-conventional	Biological	Vermicompost (fertilizer)	-	Utilization of waste	Byproducts that can be sold	
	Incineration	Conventional	Thermal	Ash (soil amendment)	-	-	Energy recovery Reduction of landfill costs	
Spain	Composting	Conventional	Biological	Fertilizer	Biosolids	Recycling nutrients back into the soil	Cost saving for sludge management Byproducts that can be sold	[74]
Bursa, Turkey	Composting	Conventional	Biological	Compost	-	Reduce waste volume Stabilization of organic waste Reducing pathogens	Cost saving for sludge management Byproducts that can be sold	[79]
General methodologies on municipal sludge	Resource recovery	Non-conventional	Biological/Chemical	Nutrients (VFAs, PHAs) Struvite (magnesium, ammonium and phosphate)	-	Reduce waste volume Reduction of artificial product Preservation of natural resources	Cost saving for sludge management Byproducts that can be sold	[20]
	Production of adsorbents		Chemical	Sludge-based adsorbents	-			
	Production of biofloculants		Biological	Biodegradable flocculants	-			
	Composting	Conventional	Biological	Fertilizer	-	Reduce waste volume Stabilization of organic waste Reducing pathogens	Reduction sludge disposal costs Byproducts that can be sold	
General methodologies	Composting	Conventional	Biological	Fertilizer	Biomass	Reduction of waste.	Reduction sludge disposal costs Byproducts that can be sold	[28]
	Aerobic fermentation							
	Pyrolysis	Non-conventional	Thermal	Biochar	Ash			
	Wet oxidation		Chemical/Thermal	Oxidized sludge	Air emissions			
European union	Anaerobic digestion	Conventional	Biological	Compost	-	Reducing the chemical compost use	Reduction of sludge disposal costs Byproducts that can be sold	[72]
	Co-Digestion							
	Composting							
	Ozone oxidation	Non-conventional	Chemical	Treated sludge with reduced organic content and pathogens	-	Stabilization of organic waste Reducing pathogens.	Byproducts that can be sold	
	Gasification							
	Pyrolysis							
	AirPrex	Non-conventional	Thermal	Biochar. Energy Oil Biochar	-	Reduce waste volume.	Reduction of sludge disposal costs Byproducts that can be sold	
	PhospaQ							
	Seaborne							
	AshDec							
Sieving	Conventional	Physical	Separation of solids and valuable materials	-	Reduce waste volume.	The valuable materials can be reused or sold.		
Marrakech, Morocco	Mechanical dewatering	Conventional	Physical	Dewatered sludge	Leachate	Minimizing landfill use fertilizer production Reduce greenhouse gas emissions	Cost-saving of fertilizer, and waste disposal	[76]
	Solar drying	Non-conventional	Physical	Dried sludge	-			

Table 3. Cont.

Country	Technique Name	Method Classification	Technique's Type	Product	Waste	Environmental Benefits	Economic Benefits	References
Germany	Wet chemical recovery	Conventional	Chemical	Struvite Calcium-phosphate compounds	Gaseous emissions	Reduce nutrient pollution	Cost-saving in fertilizer	[25]
	Metallurgical processes	Non-conventional	Thermal	Nutrient-rich ash		Minimizes landfill waste High nutrient recovery	-	
	Carbonization			Fertilizer		Improve soil quality Reduce greenhouse gas emissions	Byproduct that can be sold	
	Thermochemical treatment			Nutrient-rich ash		Reduce nutrient pollution	Cost-saving in waste disposal	
Norway	Pyrolysis	Non-conventional	Thermal	Biochar	Gaseous emissions	Reduction of waste Reduction of greenhouse gas emissions	Cost-effective waste management Low-cost feedstocks Byproducts that can be sold	[26]
	Carbonization							
	Composting	Conventional	Biological	Compost	Gaseous emissions Leachate			
Semi-arid and arid countries (Qatar)	Land application	Conventional	Biological	-	-	Enhances soil fertility Reduction of the chemical fertilizers Recycling of nutrients back into soil Reduce greenhouse gas emissions	Cost saving of energy and fertilizer production Cost saving in waste management	[77]
	Composting			Compost	Gaseous emissions			
	Anaerobic digestion			Digestate	Gaseous emissions Biomass	Digestate can be used as nutrient-rich fertilizer		
Skhirat, Morocco	Composting	Conventional	Biological	Compost	-	Waste management Reduction of the artificial compost production	Cost saving of fertilizer production Cost saving in waste management	[24]
General methodologies	Pyrolysis	Non-conventional	Thermochemical	Biochar	Char	Reduction of greenhouse gas emissions Waste management Resource recovery Reduction of pollution	Cost saving in waste management Byproducts that can be sold	[78]

4.3. Valorization in the Cement

The valorization of wastewater sludge in cement production involves several advanced techniques aimed at utilizing sludge as both a fuel and a raw material in the clinker production process (Figure 4). A study discusses the co-processing of wastewater sludge in cement kilns, where sludge is introduced into the kiln as an alternative fuel source. The organic content of the sludge is combusted, providing energy for the kiln, while its inorganic components contribute to the raw material mix, thus reducing the need for virgin materials. To enhance the suitability of sludge for co-processing, the study emphasized the importance of pretreatment methods such as dewatering, drying, or thermal treatment [28]. These processes reduce the moisture content of the sludge, increase its calorific value, and ensure more efficient combustion in the kiln [28]. In the Moroccan context, a study explores similar techniques, with a focus on the specific challenges and benefits of using wastewater sludge in the Moroccan cement industry [76]. The study also emphasizes co-processing in cement kilns, where sludge is used as a supplementary fuel and as part of the raw material feed. The research highlights the critical role of dewatering and drying in preparing the sludge for co-processing, noting that reducing the water content is essential for improving the sludge's energy content and combustion efficiency. Furthermore, the study examines the impact of sludge co-processing on clinker quality and composition, employing techniques for quality control and chemical adjustment to ensure that the addition of sludge does not compromise the final cement product [76].

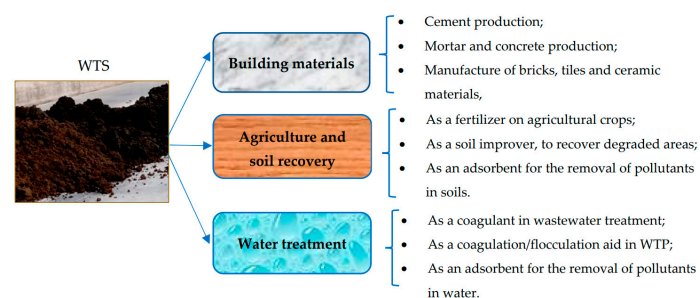


Figure 4. Emerging applications of wastewater sludge [81].

4.4. Advanced Valorization Techniques

There are several advanced techniques, known as non-conventional methods, for valorizing wastewater sludge. These approaches go beyond traditional disposal practices by maximizing resource recovery and supporting circular economy principles through the production of value-added products. Recent advances include biological, physicochemical, chemical, and electrochemical valorization pathways, each contributing to more sustainable sludge management. Among physicochemical approaches, carbonization and pyrolysis enable the conversion of sludge into biochar or activated carbon, which can subsequently be used as efficient adsorbents for pollutant removal from wastewater [82]. This sustainable and cost-effective strategy not only reduces sludge volume but also improves water quality while promoting circular resource management [26]. Biological valorization has also received increasing attention. Shi et al. demonstrated that wastewater sludge can be converted into biofloculants for colloid removal during wastewater treatment, thereby reducing sludge disposal while lowering operational costs [20]. Similarly, lipid extraction from sludge biomass using a chloroform–methanol mixture followed by centrifugation allows the recovered lipids to be utilized as microbial oil for biodiesel production [27]. Another promising biological route involves the production of volatile fatty acids (VFAs) through acidogenic fermentation. Thermal pretreatment combined with optimized substrate-to-inoculum ratios significantly enhances VFA production, providing valuable precursors for bioplastics and other bio-based chemicals while reducing methane emissions during sludge decomposition [75]. Furthermore, wastewater sludge can be converted into different biofuels through biochemical and thermochemical processes, contributing to renewable energy production and reducing greenhouse gas emissions through fossil fuel substitution [78]. Recent developments have also expanded chemical valorization pathways, particularly through nutrient and metal recovery. Chemical extraction and precipitation processes enable the recovery of phosphorus and valuable metals from wastewater sludge, reducing dependence on virgin raw materials while improving resource efficiency and supporting circular economy objectives [19,83]. In addition, electrochemical technologies have recently emerged as promising alternatives for sludge valorization. Processes such as electrooxidation, electrocoagulation, electro-Fenton oxidation, and microbial electrochemical systems improve sludge stabilization while facilitating contaminant removal and resource recovery [84,85]. Although these technologies are still largely at the laboratory or pilot scale, they require further technological development and large-scale validation before widespread industrial deployment. Nevertheless, they offer significant potential to enhance process efficiency while reducing chemical consumption and environmental impacts [84,86]. Overall, these advanced valorization techniques demonstrate that wastewater sludge should no longer be regarded solely as a waste stream but rather as a valuable resource capable of generating renewable energy, functional materials, valuable chemicals, and secondary raw materials. Nevertheless, further optimization, large-scale validation, and integrated environmental and techno-economic assessments remain necessary before their widespread industrial implementation.

4.5. Comparative Assessment of Sludge Valorization Technologies

The comparative assessment of wastewater sludge valorization technologies demonstrates that no single pathway can be considered universally optimal, as their environmental, economic, and technical performances are highly dependent on sludge characteristics, treatment capacity, local energy mix, regulatory frameworks, available infrastructure, and the intended use of the recovered products. Consequently, technology selection should be based on site-specific conditions rather than generalized conclusions reported in individual studies. Biological treatments, particularly anaerobic digestion and composting,

are widely recognized for their ability to recover energy and nutrients while operating under relatively moderate conditions, and they are considered the most technologically mature and commercially implemented, whereas electrochemical processes, advanced nutrient recovery systems, and several bio-based valorization routes remain largely at the laboratory or pilot scale and therefore require further technological development before widespread industrial deployment. However, their sustainability remains strongly influenced by factors such as methane recovery efficiency, digestate management, sludge quality, greenhouse gas emissions, odor generation, and regulatory restrictions governing agricultural applications. Similarly, thermal technologies, including incineration, pyrolysis, gasification, and co-processing in cement kilns, provide efficient sludge volume reduction, pathogen destruction, and opportunities for energy and material recovery. Nevertheless, these technologies generally require high capital investment and energy input, while their environmental performance depends on operating conditions, emission control systems, transport requirements, product quality, and the availability of stable markets for recovered products. Likewise, nutrient recovery and sludge-derived products represent promising strategies within the circular economy by reducing dependence on virgin resources. However, their large-scale implementation remains constrained by technological complexity, additional chemical requirements, uncertain market acceptance, and the absence of harmonized quality standards. Furthermore, direct comparisons among valorization pathways remain challenging because published studies employ different functional units, system boundaries, allocation procedures, databases, and assumptions regarding avoided products and energy substitution, often leading to inconsistent conclusions. Overall, sludge valorization should not be viewed solely from the perspective of resource recovery or immediate economic benefits. Each technology involves environmental, economic, technical, and social trade-offs that may limit its practical implementation. For example, although thermal processes can maximize energy recovery, they may increase greenhouse gas emissions and operational costs, whereas agricultural applications provide nutrient recycling but may face public concerns regarding heavy metals, pathogens, and emerging contaminants. Consequently, selecting an appropriate valorization strategy requires a comprehensive evaluation that simultaneously considers environmental impacts, economic feasibility, technical performance, regulatory compliance, and social acceptance. This explains why technologies with superior environmental performance in LCA are not always implemented in practice, as investment costs, technological maturity, regulatory constraints, existing infrastructure, market demand, and operational reliability frequently outweigh environmental considerations during technology selection. Therefore, LCA, combined with techno-economic assessment (TEA), should be adopted as an integrated decision-support framework to identify the most sustainable sludge management strategy under specific local conditions. Such an approach enables decision-makers to balance environmental protection, resource recovery, economic viability, and long-term sustainability while supporting the transition toward a circular economy. These findings also provide strategic guidance for different stakeholder groups. Researchers should prioritize integrated environmental and techno-economic evaluations supported by pilot- and full-scale validation to improve technology comparability and practical applicability. Policymakers should establish harmonized quality standards and incentive mechanisms that encourage resource recovery while ensuring environmental protection. Industrial stakeholders should focus on scalable valorization technologies that are economically viable, environmentally sustainable, and adaptable to local sludge characteristics and market conditions.

5. Environmental and Economic Analysis of Sludge Management

5.1. Impact of Wastewater Sludge

The impact of wastewater sludge on the environment, human health, and the economy has been the subject of extensive research, with studies highlighting both the potential benefits and risks associated with sludge management practices [87]. A detailed review highlights that the most significantly impacted categories by sewage sludge management are environmental and human health [88]. Moreover, sewage sludge management practices, such as incineration and landfilling, can lead to substantial greenhouse gas emissions, contributing to climate change. Additionally, improper disposal or application of sludge can result in soil and water contamination, particularly through the leaching of heavy metals and excess nutrients, which pose risks to ecosystems. From a human health perspective, the presence of heavy metals like cadmium, lead, and mercury in sewage sludge is a major concern, especially when the sludge is used as a soil amendment or contaminates the water sources [88]. Moreover, sewage sludge often contains harmful pathogens, including bacteria, viruses, and parasites, which can present serious health risks if the sludge is not properly treated before use or disposal [15]. These environmental concerns are revisited in a new study [89], which assesses various sludge treatment processes using an LCA approach, emphasizing the need to balance environmental sustainability with economic feasibility. Environmentally, this study also highlights that different treatment methods, such as anaerobic digestion and incineration, result in varying levels of greenhouse gas emissions, which contribute to climate change. Additionally, the use of energy and materials in these processes, particularly incineration, leads to resource depletion, affecting sustainability. Economically, the study emphasizes the importance of cost-effectiveness, noting that anaerobic digestion is more favorable due to its potential for energy recovery, making it a more cost-effective option compared to incineration, which typically incurs higher operational costs. The study also examines the trade-offs between the operational costs of different treatment processes and their environmental benefits, considering factors such as initial investment, maintenance, and potential revenue from byproducts [89]. On the human health front, a study focuses on the health risks associated with the agricultural use of wastewater sludge, particularly the potential for heavy metals to accumulate in the soil and enter the food chain, which underscores the importance of monitoring and managing heavy metal concentrations in sludge to minimize dietary exposure risks [90]. Similarly, another study analyzed the dual impact of sludge application on soil quality and crop production, highlighting both the benefits of improved soil fertility and the risks posed by heavy metal contamination [91]. This study highlights that the application of wastewater sludge significantly impacts both soil quality and crop production. In terms of soil quality, sludge application can enhance soil fertility by increasing nutrient levels, with studies showing a rise of 20–30% in soil nitrogen and phosphorus content. However, the research also raises concerns about heavy metal contamination; sludge application can lead to soil concentrations of heavy metals such as cadmium and lead exceeding regulatory limits, potentially reaching levels of 0.5 to 1.0 mg/kg for cadmium and 50 to 100 mg/kg for lead. Regarding crop production, the application of sludge can boost crop yields by up to 25% due to improved soil conditions [91]. Nonetheless, the study also addresses health implications associated with heavy metal accumulation in crops, which can pose risks to human health, particularly if concentrations of metals like cadmium exceed 0.1 mg/kg in edible parts [91]. Therefore, while sludge can enhance soil fertility and crop productivity, careful management is crucial to mitigate associated risks. The final study provides a multi-disciplinary perspective on the social, environmental, and economic impacts of wastewater sludge reuse, advocating for an integrated approach to sludge management that considers the broader implications for sustainability and public health [92]. Collectively, these studies

demonstrate that the environmental, human health, and economic impacts of wastewater sludge are highly interconnected and should not be evaluated independently. Technologies that maximize economic benefits may simultaneously increase environmental burdens, whereas environmentally favorable options may require higher investment costs or stricter operational control. Consequently, sustainable sludge management requires balancing environmental protection, economic feasibility, resource recovery, and public health rather than optimizing a single performance criterion. This reinforces the need for integrated assessment tools capable of evaluating multiple sustainability dimensions simultaneously.

Figure 5 illustrates the various wastewater sludge treatment techniques and links them to their environmental impacts. These practices contribute to greenhouse gas emissions such as methane and carbon dioxide produced during incineration, soil and water contamination, depletion of natural resources like fossil fuels and clean water due to high energy use, disruption of local ecosystems through habitat degradation and biodiversity loss, and air pollution such as particulate matter and volatile organic compounds resulting from incomplete combustion or chemical treatments. The diagram highlights the detrimental effects of these methods on the environment, emphasizing the need for more sustainable and environmentally friendly alternatives in wastewater sludge management.

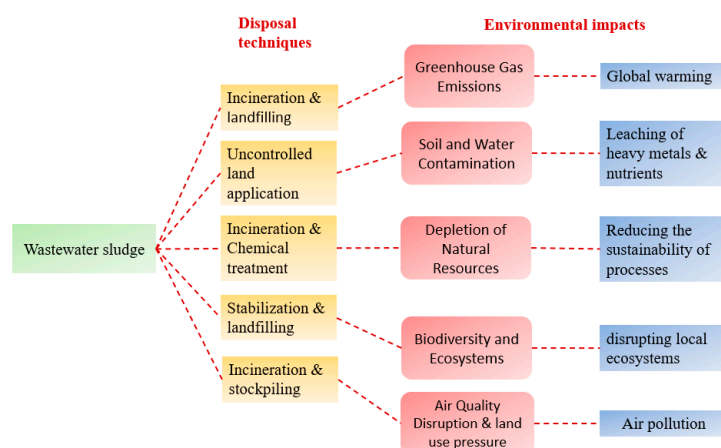


Figure 5. Techniques for the treatment of wastewater sludge and their environmental impacts.

5.2. Life Cycle Assessment

LCA serves as a valuable framework for understanding the environmental and economic impacts of wastewater treatment plants and sludge management, since it provides a clear picture of these effects and helps guide better decision-making and action in this field.

Figure 6 illustrates the stages and framework of LCA research, along with the key processes involved in sludge and wastewater treatment, and disposal as discussed in the reviewed literature [93,94]. This section of the review synthesizes findings from several LCA studies on sludge and wastewater treatment, each presenting its case study (Table 4). These studies are compiled here to provide a comprehensive overview of LCA applications in various regions worldwide [95].

Table 4. Main information of the studied references included in the literature about LCA.

Location	Study Target	FU	Software	LCIA Methodology	Database	Reference
Europe	Wastewater urban sludge	1 ton of dry matter disposed	SimaPro	ReCiPe midpoint	-	[96]
Egypt	Sludge	1 ton of sludge	Umberto	CML	-	[97]

Table 4. Cont.

Location	Study Target	FU	Software	LCIA Methodology	Database	Reference
China	Wastewater	105 m ³ of wastewater	SimaPro	CML Baseline 2000	-	[98]
Sub-Saharan Africa	Sludge	1 ton of biodegradable waste	-	-	-	[99]
Germany	Sludge	MJ per T of dry matter	-	CML	Gemis database v4.9	[100]
Italy	Sludge	Total annual amount of entering sludge	-	CML-IA	Ecoinvent 3.0	[101]
India	Municipal sludge	1 m ³ of biogas produced or utilized	SimaPro 8.1	ReCiPe midpoint	-	[102]
-	Municipal sludge	1000 kg of wet mixed sludge	Aspen Plus	-	Ecoinvent v3.6	[103]
Germany	Sludge	1 ton of raw sludge	OpenLCA	ReCiPe midpoint (H)	Ecoinvent 3.5	[104]
Italy	Municipal and industrial sludge	1 kg of fresh matter of sludge	GaBi software	ReCiPe midpoint	Ecoinvent	[105]
-	Sludge	1000 kg of dried sludge	-	-	-	[106]
-	Sludge	1 ton of sludge	-	Environmental footprint (EF) 3.0	Ecoinvent 3.6	[107]
Norway	Aquaculture sludge	1 ton of fish mortalities	SimaPro 9.0.0.49	ReCiPe midpoint	Ecoinvent 3.1	[108]
-	Wastewater urban sludge	1000 m ³ of secondary effluent	SimaPro	ReCiPe midpoint	Ecoinvent	[109]
Greece	Wastewater	1 m ³ of wastewater	OpenLCA	-	Ecoinvent	[110]
Spain	Metal-rich sludge	1 ton of sludge produced during the treatment of acid, mine drainage	OpenLCA	ReCiPe endpoint	Ecoinvent 3.5	[111]
China	Sludge	1 ton of dry matter disposed	OpenLCA	CML-IA	Ecoinvent 3.8	[112]

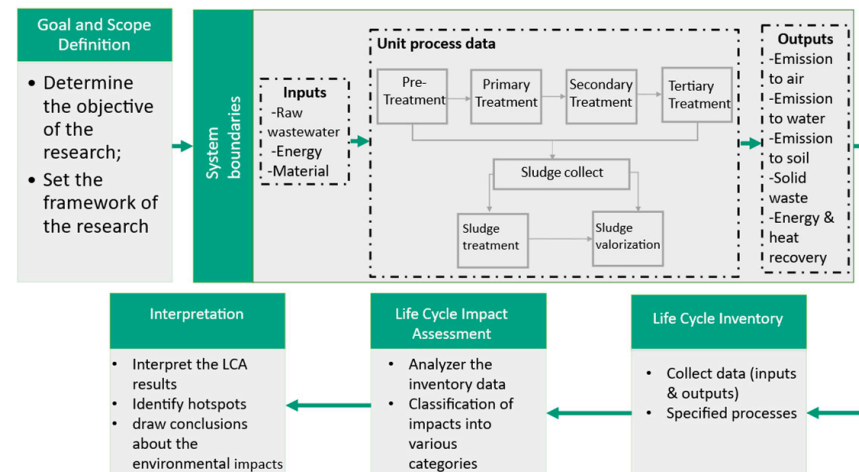


Figure 6. Representative schema of life cycle assessment framework.

5.2.1. Definition of Goals and Scope

A rigorous definition of system boundaries has a profound impact on LCA outcomes [113]. In the literature reviewed, the system boundaries encompass all processes involved in the wastewater treatment and sludge management, and treatment or valorization strategy. In this context, the LCA is divided into two phases: the construction phase and the exploitation phase [114]. The impact of the construction phase is distributed over the entire lifespan of the treatment plant and the number of functional units (FU) during this period. As a result, the environmental impacts associated with the construction phase are often minimal when averaged over the plant's lifetime [115]. Consequently, most studies tend to overlook this phase; in fact, most studies reviewed here did not consider

the construction phase at all. Instead, they focus solely on the exploitation phase, which includes the operation of vehicles, machinery, auxiliary equipment, and the transportation processes for both wastewater and sludge [95]. For these studies, the system boundaries are defined to include only the exploitation phase, extending from the plant's intake to the final discharge.

The FU is a critical metric in LCA, representing the output function of the product system [116,117]. Its primary purpose is to provide a consistent reference point for comparing the associated inputs and outputs across different scenarios. By standardizing the performance measure of the system under study, the FU serves as the essential foundation that enables the simultaneous comparison and analysis of alternative scenarios, ensuring that the results are meaningful and comparable [95]. In the LCA of wastewater, all studies reviewed selected volume as their FU, with the specific quantities ranging from 1 m³ to 105 m³, similar to Tsangas's work [101], where they use the standard of 1 m³ of wastewater, depending on the capacity of the treatment plant or the system being studied. However, for the sludge's LCA, the majority of studies opted for mass as the FU, though some studies used more specific FUs tailored to the characteristics of the waste being assessed, such as the biodegradable waste fraction or mixed sludge [99]. Similar to wastewater, the quantity used as the FU for sludge depends on the treatment plant's capacity and the sludge productivity, which in turn is influenced by the type of wastewater and sludge [118]. The choice of FU can significantly influence the outcomes and comparability of LCA studies. In addition to conventional metrics like volume and mass, some studies have proposed alternative FUs that capture the beneficial outputs of sludge treatment processes. For instance, in [109], 1 TJ of steam generated from sludge incineration was utilized as the FU, highlighting the energy recovery potential of sludge treatment. This approach emphasizes the multifunctionality of sludge treatment systems, where the FU is not just a measure of input but also reflects the valuable outputs generated by the process, such as energy or materials recovery [95]. Such alternative FUs can offer a more comprehensive assessment of the environmental and economic benefits of sludge treatment technologies, providing deeper insights into their sustainability and efficiency [119]. In many cases, the choice of FU depends on the specific pathway for sludge management, treatment or valorization, ensuring the results are meaningful and relevant to each scenario. For instance, a study exploring the energetic use of sewage sludge used megajoules per ton of dry matter (MJ/t DM) as the FU [100]. Similarly, research on recovering the organic fraction from sewage sludge relied on the total annual amount of incoming sludge as the FU [101]. Another study focused on biogas production used 1 cubic meter of biogas produced or utilized [102]. This tailored approach helps provide insights that align closely with the goals of each study.

Although many LCA studies exclude the construction phase on the assumption that its contribution is negligible compared with the operational stage, this assumption should not be universally accepted. Its validity depends largely on the technology being assessed, plant lifetime, infrastructure complexity, and material requirements. For conventional wastewater treatment plants, operational energy consumption often dominates the overall environmental impacts. However, for infrastructure-intensive technologies, such as thermal treatment systems, anaerobic digestion facilities, or advanced resource recovery units, the environmental burdens associated with construction materials, equipment manufacturing, and infrastructure development may become significant. Therefore, excluding the construction phase without proper justification may underestimate the total environmental impacts and reduce the comparability of LCA studies. Future assessments should explicitly justify system boundary selection and evaluate the influence of infrastructure whenever relevant.

5.2.2. Life Cycle Inventory

Life Cycle Inventory (LCI) is the phase of LCA where all inputs (energy, water, chemicals) and outputs (emissions to air, water, soil) associated with a product system are quantified [120]. In sludge treatment, LCI involves gathering detailed data on resource consumption and environmental releases across all stages of the treatment process [95]. This data serves as the basis for assessing and comparing the environmental impacts of different treatment strategies [121]. Given the challenges in collecting foreground data, this information is often stored in LCI databases, such as Ecoinvent [122]. As presented in Table 4, six studies did not specify the database they used, while 10 studies relied on the Ecoinvent database, utilizing various versions. In the literature, data collection methods vary by study but are generally constrained to sources like field data collection, references, databases, statistical yearbooks, government or business reports, experimental data, and expert interviews [95]. Due to potential gaps in available information, researchers frequently have to rely on calculations and estimations to fill in missing data [123], and it should be noted that all reviewed studies adopted the concept of estimation, whether in small datasets or extensive ones. This reliance on estimation underscores the importance of using comprehensive and reliable databases to ensure accurate and consistent LCI data for LCA [95].

5.2.3. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the stage in LCA where the results from the LCI are processed and interpreted to assess environmental impacts. The primary objective of LCIA is to evaluate and compare the relative environmental effects of various products, processes, or activities rather than quantifying absolute damage. By analyzing the inventory data through impact categories such as global warming potential, acidification, and eutrophication, LCIA aims to highlight which options have greater or lesser environmental burdens. This comparative approach helps identify more sustainable choices and understand the relative contributions of different stages of the life cycle to overall environmental impact [95,124].

Figure 7 presents the reviewed studies, highlighting a broad range of environmental impact categories within the context of the 17 reviewed studies (Table 4). Climate change emerges as the most frequently addressed category, appearing in all studies. This emphasis reflects the increasing awareness of the carbon footprint associated with sludge management, particularly in processes like energy-intensive treatments and emissions from sludge disposal or valorization pathways [125]. Similarly, freshwater eutrophication, freshwater ecotoxicity, and human toxicity are extensively studied and covered in several reports [126]. This focus highlights the critical importance of water quality, as pollutants from sludge can significantly impact aquatic ecosystems and pose direct and indirect risk to human health through contamination of water resources [126]. Ozone depletion underscores its global relevance, as sludge management processes, particularly incineration or chemical treatments, can release ozone-depleting substances [127,128]. Furthermore, marine eutrophication and photochemical oxidation are of moderate significance, particularly in scenarios where untreated or partially treated sludge is disposed of in marine environments, contributing to nutrient loading, or where thermal or chemical treatments release pollutants that affect air quality [129,130]. In contrast, agricultural land occupation, natural land transformation, and urban land occupation are the least addressed categories, with only two studies each. This may indicate that these categories are either less relevant to current sludge management practices or lack sufficient data to support analyses.

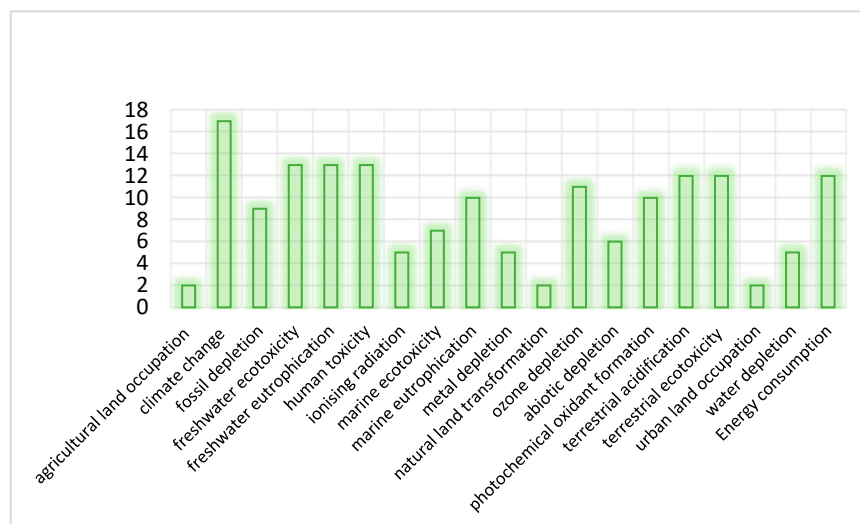


Figure 7. Category coverage for the 17 reviewed studies.

In LCIA, two specialized approaches are commonly used: midpoint and endpoint methods. The midpoint method focuses on measuring environmental impacts at an intermediate stage and typically involves less data integration and weighting, generally resulting in higher reliability and precision [131]. In contrast, the endpoint method involves more extensive data integration and weighting to assess the final environmental impacts more comprehensively. Although the endpoint method may have lower reliability due to its complexity and value choices, it is often preferred for its ability to provide a clearer understanding of the ultimate environmental consequences [124,132]. This makes it particularly useful for decision-makers and stakeholders who need to evaluate and compare the long-term impacts of various scenarios.

5.2.4. Results and Discussion

This part of the LCA study is a section where the findings from the LCA are presented and interpreted [133]. This part details the quantitative outcomes of the assessment, including the environmental impacts, resource use, and emissions identified throughout the product's or system's life cycle [134]. The Discussion part provides an in-depth interpretation of these results, comparing them to existing literature and contextualizing their significance. This review encompasses various approaches and methodologies employed across different research efforts, highlighting both commonalities and discrepancies in the results. Each study interprets the results based on the specific objectives and design of its research. The methodologies and analytical frameworks used can lead to different emphases on particular environmental impacts, reflecting the unique focus and context of each study. These differences explain why contradictory conclusions are frequently reported in the literature and highlight the importance of harmonizing methodological assumptions when comparing sludge management scenarios across different studies and geographical regions.

5.3. Economic Assessment

Several studies have highlighted the importance of conducting economic assessment for sludge management and valorization systems (Table 5), focusing on their performance, applicability and environmental sustainability [87]. Evaluating economic feasibility is a critical step that aids decision-makers in choosing between different sludge treatment options for different cases. Depending on the type and purpose of the study, such assessments involve various methodologies, including analyzing capital and operating costs, evaluating

economic risks and feasibility, performing comparative analyses, and identifying financial support requirements [135]. These assessments also support sustainable practices by predicting mass and energy flow rates, calculating minimum selling prices to stay up in the worst-case scenario policy, identifying influential parameters, and guiding future plant design and optimization [136].

In China, multiple studies addressed these economic and sustainable crises. Y. Huang et al., in their study, evaluate the economic viability of four sludge treatment methods: co-incineration in coal power plants, mono-incineration, anaerobic digestion, and pyrolysis [126]. The findings reveal that co-incineration stands out as the most economically advantageous option, followed closely by pyrolysis. In the same path, another Chinese study evaluates the feasibility and benefits of using municipal sludge in co-combustion power generation [137]. Its report revealed co-combustion not only provides significant economic gains, but also highlights the importance of managing raw material costs to enhance the overall success of sludge valorization efforts [137]. In India, a study performed a techno-economic assessment to evaluate the feasibility of producing renewable fuels from sludge using hydrothermal liquefaction. It concludes that this process is both feasible and economically viable with a competitive minimum selling price [136]. Moreover, a Nigerian study [129] focused on anaerobic digestion treatment and incineration treatment by comparing the techno-economics of these methods. The study showed that anaerobic digestion gives greater potential for long-term economic benefits, particularly in generating higher revenue from electricity sales, making it a promising solution for sustainable energy production in the 36 states of Nigeria. However, in some cases, none of the available options for a particular study may be suitable for a valorization action. In such situations, decision-makers need to consider alternative pathways. For example, a techno-economic study was conducted in the USA to evaluate anaerobic digestion, biorefineries, and co-digestion [138]. Their findings revealed that none of these techniques were economically viable for their specific scenarios without subsidies.

The choice of the evaluated sludge treatment techniques often varies based on factors such as the region, the quantity of sludge generated and specific environmental and budgetary conditions. However, some studies in the literature present generalized evaluations without considering specific case scenarios [139]. For instance, another techno-economic analysis was conducted to assess the feasibility of valorizing municipal sludge in energy and phosphorus production using various combustion techniques, including mono- and co-combustion in fluidized bed and grate boilers. Their findings underscore the economic potential of these recovery methods, indicating that with appropriate technological adaptation the valorization will be both viable and beneficial for promoting sustainable waste management. Another biologically oriented study compares the financial viability of anaerobic digestion alone with anaerobic digestion combined with thermal hydrolysis and wet oxidation [140]. The findings show that combining anaerobic digestion with 100% wet oxidation is the most economically feasible option, despite its higher initial investment [140]. However, the absence of specific case conditions and limitations in these literature studies often results in a more theoretical approach that may not fully reflect the complexity of real-world scenarios. Therefore, without accounting for the variability in factors such as regional characteristics, sludge composition, and economic constraints, these generalized studies risk being disconnected from practical applications. Future techno-economic assessments, therefore, should increasingly incorporate regional market conditions, policy incentives, energy prices, resource demand, and uncertainty analyses to improve their practical relevance and support evidence-based investment decisions. Integrating TEA with life cycle assessment would further enable more balanced evaluations of both environmental and economic sustainability.

Table 5. Main information of the studied references included in the literature about techno-economic assessment.

Local	Type of Sludge	Purpose	Technology	FU	Software Tool	Economic Benefit	References
South Korea	Sewage sludge	Valorization through bioethanol production	Hydrothermal liquefaction	100 t of sludge	-	120 \$ per ton	[141]
USA	Paper mill sludge	Valorization through biofuels production	De-ashing	Production of bioethanol from the respective feedstocks	Aspen Plus	20% reduction in producing bioethanol compared to corn stover 13.32 MJ/h reduce in energy demand	[142]
			Enzymatic hydrolysis				
Scandinavia	Wastewater sludge	Valorization through product recovery	Anaerobic digestion	1 t of sludge	SuperPro designer	None of the scenarios were profitable without subsidies	[138]
			Biorefinery				
			Co-digestion				
General study	Municipal sludge	Valorization through energy recovery and phosphorus fertilizer production	Mono-combustion	Energy and fertilizer produced per ton of sludge	-	Greater economic benefits due to lower recovery costs	[143]
			Co-combustion			Higher recovery costs	
China	Municipal sludge	Valorization through energy recovery	Co-incineration	-	-	The best, with the highest comprehensive index (0.758)	[135]
			Mono-incineration			Comprehensive index 0.186	
		Valorization through biogas	Anaerobic digestion			Comprehensive index 0.57	
		Valorization through gaseous products and biochar	Pyrolysis			Comprehensive index 0.691	
China	Municipal sludge	Valorization through energy recovery	Co-combustion	1 t of wet sludge	-	Benefit of 947 ¥ per ton of sludge	[137]
Nigeria	Sewage sludge	Valorization through energy recovery	Anaerobic digestion	Electricity generated per ton of sewage sludge	-	Higher than the incineration benefit	[144]
			Incineration			Range between 0.31 and 1.6 million USD	
India	Wastewater sludge	Valorization through renewable fuels production	Hydrothermal liquefaction	Production of renewable fuels per ton	Aspen Plus	4.04 \$ per gasoline gallon equivalent	[136]
General application	Activated municipal sludge	Management and valorization	Anaerobic digestion	86.4 t	Aspen Plus	30.14 \$ per ton	[140]
			Thermal hydrolysis with anaerobic digestion			2.27 \$ per ton	
			Wet oxidation with anaerobic digestion			25.82 \$ per ton	

5.4. Sources of Uncertainty in Life Cycle Assessment of Wastewater Sludge Management

LCA has become one of the most widely used tools for evaluating the environmental performance of wastewater sludge management systems. However, despite its standardized framework (ISO 14040 and ISO 14044) [145,146], significant uncertainties remain throughout the assessment process, often leading to considerable variations in reported environmental impacts. These uncertainties originate from differences in data quality, methodological choices, system boundaries, and regional assumptions, making direct comparisons among published studies particularly challenging. One of the primary sources of uncertainty is the quality and representativeness of life cycle inventory (LCI) data. Many studies rely on secondary databases such as Ecoinvent, GaBi, or ELCD, which may not

accurately represent local sludge characteristics, electricity generation mixes, transportation distances, or operational practices. Moreover, primary data collected from wastewater treatment plants are often limited or incomplete, forcing researchers to adopt assumptions that introduce additional uncertainty into the assessment. Methodological choices also play a critical role in influencing LCA results. Significant differences arise from the selection of the functional unit, system boundaries, allocation methods, and impact assessment models. For example, studies may express results per cubic meter of treated wastewater, per ton of wet sludge, per ton of dry solids, or per unit of recovered energy, making quantitative comparisons difficult. Similarly, some assessments include only the operational phase, whereas others consider construction, transportation, chemical production, and end-of-life management, leading to substantially different environmental profiles. Recent research has further demonstrated that methodological choices extend beyond conventional inventory modelling and system definition. In particular, the accounting of non-CO₂ greenhouse gas emissions, together with the selection of system boundaries, can substantially influence the attribution of climate impacts and environmental responsibilities across supply chains, potentially leading to different policy conclusions. These findings reinforce the importance of transparent methodological assumptions and harmonized accounting approaches to improve the robustness, comparability, and policy relevance of LCA-based assessments of wastewater sludge management [69]. Another important source of uncertainty concerns the estimation of avoided environmental burdens associated with resource recovery. Environmental credits assigned to electricity generation, fertilizer substitution, biochar application, or material recovery are highly dependent on local market conditions and assumptions regarding displaced products. Consequently, identical sludge valorization technologies may exhibit substantially different environmental performances depending on the assumptions adopted during system expansion or allocation. Regional variability further contributes to uncertainty in sludge LCA studies. Factors such as climate conditions, sludge composition, energy sources, regulatory frameworks, and agricultural practices differ considerably among countries and directly influence the environmental performance of sludge management technologies. Therefore, conclusions drawn from one geographical context cannot always be generalized to other regions without careful consideration of local conditions. Despite these challenges, only a limited number of studies perform comprehensive uncertainty and sensitivity analyses, reducing the robustness and transparency of their conclusions. Sensitivity analyses are particularly important for identifying influential parameters, whereas uncertainty analyses, including Monte Carlo simulation and scenario analysis, provide valuable information regarding the reliability of environmental impact estimates. Overall, uncertainty should not be considered a limitation of LCA itself but rather an inherent characteristic of complex environmental systems. Future studies should prioritize the use of high-quality primary data, harmonized methodological approaches, transparent reporting of assumptions, and systematic uncertainty analyses to improve the reliability, reproducibility, and comparability of wastewater sludge management assessments. Integrating these practices will strengthen the role of LCA as a robust decision-support tool for selecting sustainable sludge valorization strategies. Based on the reviewed literature, the robustness of LCA studies should be assessed according to several key criteria, including the quality and representativeness of inventory data, transparency in system boundary definition, justification of the selected functional unit, application of sensitivity and uncertainty analyses, and clear reporting of methodological assumptions. Considering these aspects together enables more reliable interpretation and comparison of sludge management scenarios while improving confidence in decision-making.

5.5. Emerging Digital Tools for Sludge Valorization

Recent advances in artificial intelligence (AI), machine learning (ML), and digital technologies are opening new opportunities for wastewater sludge valorization [147]. AI-based models have been increasingly applied to optimize anaerobic digestion, predict biogas production, estimate sludge characteristics, optimize operating conditions, and support LCA and techno-economic analysis (TEA). In addition, digital twins, process simulation, and real-time monitoring systems can improve process efficiency, reduce operational costs, and facilitate predictive maintenance. Although these technologies have shown promising results at laboratory and pilot scales, their large-scale implementation remains limited due to data availability, model transferability, and integration challenges. Future research should focus on combining AI-driven optimization with environmental and economic assessment tools to support more efficient and sustainable sludge management strategies. Beyond process optimization, future digital platforms could support real-time environmental monitoring, predictive maintenance, dynamic life cycle assessment, and intelligent decision-support systems capable of assisting wastewater utilities in selecting the most sustainable sludge management strategy under changing operational conditions.

6. Conclusions

Wastewater treatment inevitably generates sludge, presenting both a significant management challenge and an opportunity for resource recovery. This review demonstrates that no single sludge valorization technology can be considered universally optimal, as environmental, economic, technical, and regulatory performances are strongly influenced by sludge characteristics, local infrastructure, energy systems, market conditions, and regional policy frameworks. Consequently, technology selection should not rely on generalized conclusions but instead be based on site-specific sustainability priorities and local implementation conditions.

The reviewed literature shows that different valorization pathways offer distinct advantages and limitations. Biological processes remain among the most mature technologies for simultaneously recovering energy and nutrients, while thermal processes provide effective sludge volume reduction and energy recovery but generally require greater capital investment and operational control. Likewise, agricultural reuse and nutrient recovery contribute to circular resource management when supported by appropriate quality standards and regulatory oversight. Rather than identifying a universally superior technology, this review highlights that the most sustainable strategy is the one that best balances environmental protection, resource recovery, economic feasibility, technological maturity, and regulatory compliance within a given context. From a decision-making perspective, technology selection should be guided by the primary sustainability objective. When climate change mitigation is prioritized, technologies maximizing greenhouse gas reduction and renewable energy recovery should be favored. Where resource recovery and circular economy objectives dominate, nutrient recovery and agricultural valorization become attractive options, provided that environmental safety and product quality are ensured. Conversely, where economic feasibility and existing infrastructure are the main constraints, commercially mature technologies may represent the most practical solutions. Such a context-specific approach provides a more robust basis for sustainable sludge management than the pursuit of a single universal solution.

Life cycle assessment remains one of the most effective tools for evaluating the environmental performance of sludge management systems. However, this review also demonstrates that LCA alone cannot fully capture all dimensions of circular economy performance, including resource security, market development for recovered products, technological maturity, and broader socio-economic benefits. Therefore, integrat-

ing LCA with techno-economic assessment and complementary decision-support approaches provides a more comprehensive framework for identifying sustainable sludge management strategies.

Future progress in wastewater sludge management will depend less on developing entirely new technologies than on improving the integration, optimization, and large-scale implementation of existing valorization pathways. Future research should prioritize harmonized LCA methodologies, high-quality inventory data, and integrated environmental and techno-economic evaluations, while policymakers and industry should promote supportive regulatory frameworks and scalable valorization technologies adapted to regional conditions. Such multidisciplinary efforts will be essential to accelerate the transition toward resilient, circular, and resource-efficient wastewater sludge management systems.

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