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Review

Emerging Technologies for Resource Recovery from Industrial Wastewater Sludge: Advances in Circular Economy Applications

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Abstract

Industrial activities produce substantial amounts of heterogeneous wastewater sludge. Traditionally, these are handled by unsustainable "cradle-to-grave" linear solutions like landfilling and incineration. This review aims to bridge the identified knowledge gaps with regard to the absence of standardized protocols and comparative evaluations of these emerging solutions by critically evaluating 54 specific studies out of 105,000 sources. Though solutions like Thermal Hydrolysis are well developed and operational, advanced solutions like Microbial Electrolysis Cells are hindered by severe scaling barriers, hurdles like high capital and operational costs, and technical instabilities. The novelty of the current review lies in its specific attention to the complex and toxic nature of industrial sludge as opposed to municipal sewage sludge and its integration of Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA). This review provides a strategic roadmap for "technological leapfrogging," which will be of immense value to stakeholders for transforming sludge into a sustainable economic opportunity aligned with the UN SDGs 6, 11, 12, and 13.

Keywords

Circular economy, Wastewater treatment, Industrial Wastewater sludge, Life cycle assessment

1. INTRODUCTION

Industrial operations generate vast amounts of wastewater, which needs complete treatment before disposal because untreated waste will harm the environment. Conventional wastewater treatment methods, which include physical, chemical, and biological treatment processes, successfully remove water pollutants but generate substantial amounts of industrial wastewater sludge, which exists as concentrated semi-solid waste (Kumar et al. 2025). Industrial wastewater sludge exhibits extreme physicochemical diversity because its characteristics depend on both the specific manufacturing methods used and the quality of raw water applied during production. (Trpčevská et al. 2025). Sludge from this type of waste material contains hazardous contaminants that exist in complex and concentrated forms, which include persistent organic materials, artificial chemical substances, coagulant waste, and poisonous heavy metals, including cadmium and mercury (Alemneh et al. 2025). The vast volume of hazardous sludge generated during wastewater treatment presents a major difficulty for its safe and correct disposal.

The conventional method of handling industrial sludge involved the use of linear disposal techniques, which included landfill, incineration, and land application. Environmental, economic, and regulatory restrictions have begun to limit traditional "treat-and-dispose" methods, which exist as standard waste management techniques (Neri et al. 2024). The practice of landfilling has become unsustainable because of land depletion and the potential environmental catastrophe that results from toxic leachate that contaminates groundwater (Kumar et al. 2025). The process of incineration achieves effective volume reduction results, but requires significant energy consumption, which leads to greenhouse gas emissions and hazardous secondary pollutants that include toxic fly ash. The direct land application of industrial sludge faces strict prohibitions and tight regulations because heavy metals and persistent organic pollutants bioaccumulate in soil, creating severe dangers to both human health and environmental safety.

The world currently undergoes a complete transformation because conventional waste disposal methods face major limitations, while the need for environmentally friendly resource management becomes increasingly urgent. Industrial sludge treatment now focuses on transforming waste into valuable resources according to Circular Economy (CE) principles (Neri et al. 2024). The CE imperative requires all waste materials to be permanently returned to economic circulation. Industrial sludge holds both energetic content and material resources, which businesses can extract to create products with market value. Certain technological developments now enable the production of sludge-derived biochar, which can be used for environmental cleanup (Wang et al. 2025). The process involves converting stabilised sludge into energy while using it as a building material for low-cost projects. The resource recovery methods that we implement will decrease the environmental impact from sludge disposal while decreasing our need for new raw materials, thus supporting our business operations to achieve worldwide sustainability targets.

The academic and industrial sectors have shown increasing interest in wastewater resource recovery, yet existing research studies show important shortcomings according to recent literature. The comprehensive reviews predominantly examine municipal sewage sludge because its characteristics show more predictable behaviour and lower hazardous potential than industrial sludge (Trpčevská et al. 2025). Industrial sludge reviews encounter a fundamental problem because they restrict their analysis to a single pretreatment technique, while they study only one recovery method without examining its role in complete circular economy systems (Wang et al. 2025). Currently existing research studies do not provide a synthetic analysis that evaluates multiple new recovery technologies that have been developed to treat industrial sludge that contains diverse hazardous substances. This review provides a complete assessment of industrial sludge valorisation processes throughout the entire value chain. The main goals include systematic evaluation and comparison of new industrial sludge pretreatment methods and advanced biological conversion technologies, which aim to extract energy and nutrients and functional materials from industrial sludge. The review discusses how effectively these recovered materials function within circular economy applications while maintaining their safety standards. The paper evaluates how well emerging technologies handle waste compared with traditional disposal methods, identifies technical challenges that hinder progress, and outlines regulatory obstacles, while also creating a plan for future research and implementation. Consistent with its title, the scope of this review is restricted to sludge generated by industrial process wastewater treatment, including textile, tannery, electroplating, metallurgical, chemical, pulp and paper, and food-processing effluents, and municipal sewage sludge, biogas, or agricultural-waste literature is discussed only where it directly informs a technology, standard, or comparison applicable to industrial sludge.

2. METHODOLOGY

Considering the abundance of publications concerning the latest technologies for recovering resources from industrial sludge, this review started with a comprehensive search resulting in around 105,000 sources. The literature search process employed Scopus, Web of Science Core Collection, and ScienceDirect data-bases, complemented by additional literature search in Google Scholar and citation databases, with lit-erature sources from January 2015 to March 2026. The search string included controlled vocab-ulary keywords together with free text keywords such as: (‘industrial sludge’ OR ‘industrial waste-water sludge’ OR ‘tannery sludge’ OR ‘textile sludge’ OR ‘electroplating sludge’ OR ‘pulp and paper sludge’ OR ‘metallurgical sludge’) AND (‘resource recovery’ OR ‘valorization’ OR ‘circular economy’ OR ‘life cycle assessment’ OR ‘techno-economic analysis’). To maintain the review’s transparency and allow for replicating it, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to narrow down the number of references to use in the study. The screening process was done by following the conventional four-step screening process as per the PRISMA guidelines: (a) Identification of relevant articles via database and additional searches, (b) Elimination of duplicated and non-peer-reviewed papers (resulting in 8,200 references), (c) Title and abstract screening with respect to the following eligibility criteria (resulted in 612 articles), and (d) Full text screening with respect to the eligibility criteria of which 54 articles satisfied all the inclusion criteria. The flowchart of the PRISMA is shown in Fig. 1. Articles were screened according to the following criteria for exclusions: (i) focusing on the municipal sludge alone (except the articles which compared municipal sludge with industrial sludge), (ii) covering only one pretreatment technique, (iii) did not include Techno-Economic Analysis (TEA) and/or Life Cycle Assessment (LCA), (iv) not available in English, (v) conference abstracts and non-peer-reviewed articles and (vi) before 2015, leading to selection of 54 studies, considered most appropriate and representing recent developments in circular economy solutions for industrial sludge management.

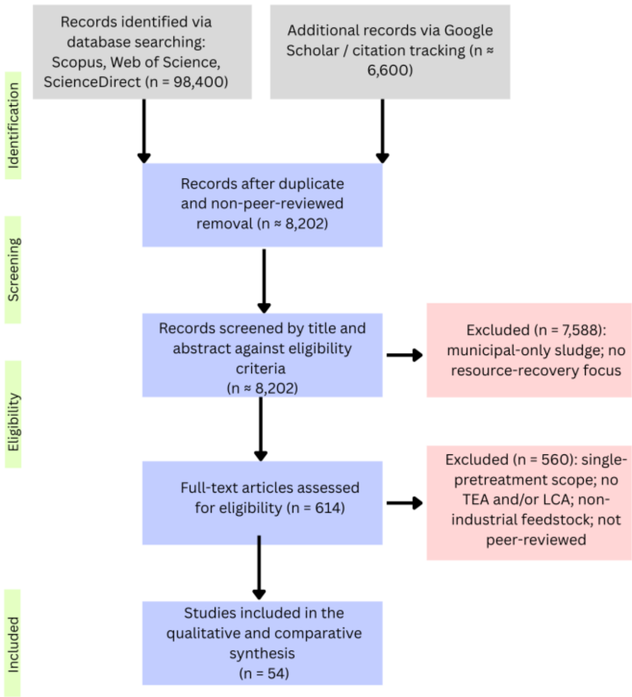

Fig.1: PRISMA-style flow diagram of the systematic literature search and study-selection process

3. INDUSTRIAL SLUDGE AS A SECONDARY RESOURCE IN THE CIRCULAR ECONOMY

The transition towards sludge valorisation fundamentally depends on a precise understanding of its complex composition. Industrial wastewater sludge contains multiple distinct biological profiles that scientists use to identify its industrial sources, as demonstrated in Fig 2, which includes textile, metallurgical, chemical, food processing, and pulp and paper production industries (Smol et al. 2020). The industrial sludge presents a physicochemical challenge because it consists of three different components, which include water that exists at levels above 80-90% before dewatering, and both organic and inorganic solids and extracellular polymeric substances (EPS) that bind moisture and pollutants (Zhen et al. 2017). The specific characteristics vary drastically; for instance, food and beverage industry sludges are typically rich in biodegradable organic carbon, nitrogen, and phosphorus, making them highly putrescible. Conversely, sludge from electroplating or tannery sectors is characterised by high concentrations of recalcitrant organics, synthetic dyes, and heavy metals (e.g., chromium, zinc, copper), but possesses low inherent biodegradability (Raheem et al. 2018). Understanding these specific physicochemical profiles is the critical first step in determining the most viable technological pathway for resource recovery.

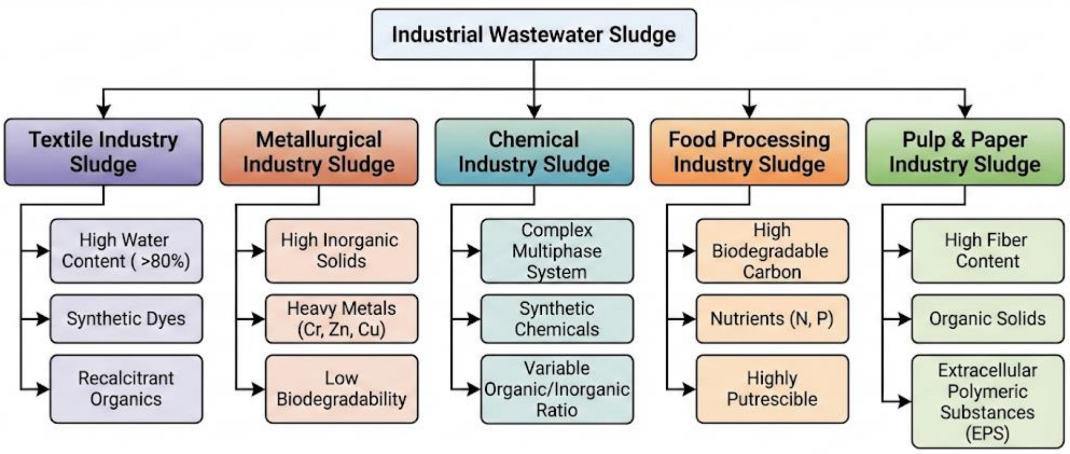

Fig. 2: Classification of industrial sludge based on origin and physicochemical characteristics

The industrial sludge, which retains its hazardous classification from its past, holds hidden secondary resources that remain unexploited. The hidden worth of this complex system can be extracted through four primary pathways, which include energy extraction, nutrient extraction, metal extraction, and material extraction (Hao et al. 2019). Industries generate specific sludges that contain high organic materials, which can provide renewable energy resources through biological systems like anaerobic digestion and through thermochemical systems that use pyrolysis and gasification to produce biogas, biohydrogen, and bio-oil (Raheem et al. 2018). Agri-food sludges and biological treatment sludges from wastewater treatment facilities hold crucial nutrient components in high concentrations. In this case, “agri-food sludge” refers specifically to sludge generated on-site by dairy, brewery, sugar, and other food-processing industries, rather than municipal sewage sludge. The struvite process (magnesium ammonium phosphate) is a physicochemical process for the removal of ammonium from wastewater. In this process, magnesium ammonium phosphate, or struvite, crystals are formed. The process takes place when the magnesium, ammonium, and phosphate ions react in an equimolar ratio of 1:1:1, which means there is a requirement of 1 mole of magnesium, 1 mole of ammonium, and 1 mole of phosphate. In this process, the pH needs to be maintained between 8.5 and 9.5. In the case of wastewater, there might be excess amounts of ammonium. In this case, the process needs to be carried out by adding external sources of magnesium and phosphate, which can be in the form of MgO and H3PO4, or MgCl2·6H2O and Na2HPO4·7H2O, and the pH needs to be maintained by adding NaOH. After this, the mixture needs to be stirred well, and the formed struvite needs to be separated from the mixture. In this process, the removal of ammonia can be as high as 75-80%. This process can remove ammonia from wastewater much better than the process of biological nitrification. In this process, the struvite formed can be used as a fertilizer (Zisman et al. 2024). This struvite process functions as a solution for nitrogen and phosphorus recovery, which creates slow-release fertilisers while addressing the global problem of decreasing minable phosphorus reserves (Smol et al. 2020). Sludge generated from metallurgical and electronic production processes contains recoverable base metals and precious metals, which exist at economically feasible concentrations, resulting in critical raw material supplies for the area through new hydrometallurgical and bioleaching recovery methods (Hao et al. 2019). The thermochemical conversion process transforms sludge into carbon-rich functional materials, with biochar serving as the primary product. Sludge-derived biochar functions as a strong carbon sink when used for soil improvement, while also serving as a fertiliser, which enhances soil properties that support better agricultural production. Crucially, the high-temperature pyrolysis process simultaneously immobilises heavy metals and eradicates pathogens, ensuring the final biochar is stabilised for safe environmental application or as an adsorbent in advanced wastewater treatment processes (Tomczyk et al. 2020). Implementing CE principles allows organisations to use their resources because these principles create fundamental changes to the existing linear system, which operates through resource extraction and production processes until waste disposal. The application of CE principles to industrial sludge management requires wastewater treatment plants to operate as integrated biorefineries or water resource recovery facilities (WRRFs) rather than existing solely as pollution control centres (Kakwani & Kalbar 2020). The framework shown in Fig 3 treats sludge as the main material that will enter industrial production processes instead of treating it as a result of the treatment process. Organisations must extract all possible value from the sludge matrix according to CE principles while they implement measures to reduce environmental impact. The organisation achieves this operational goal through the implementation of cascading use strategies. A biorefinery model begins by extracting high-value biochemicals and precursors from its system and then converts all remaining biodegradable organic matter into bioenergy before it uses residual digestate and thermal ash as construction materials and agricultural applications (Smol et al. 2020). The organisation achieves its sustainability goals by closing all loops for water, energy, and materials through CE integration, which results in a significant reduction of industrial dependence on fresh raw materials and an extensive decrease of production-related carbon emissions.

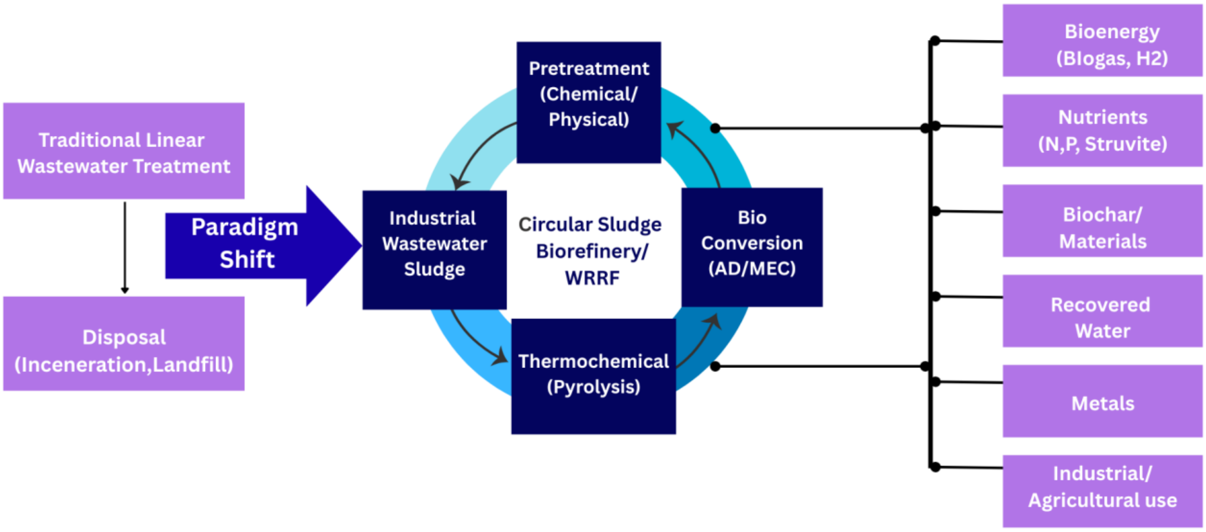

Fig 3: Conceptual framework of an industrial sludge biorefinery.

Ultimately, the transition from conventional disposal to circular valorisation represents a significant shift in both environmental engineering and industrial policy. Historically, the primary drivers for sludge management were hazard mitigation and the minimisation of disposal costs, such as landfill tipping fees (Kakwani & Kalbar 2020). The contemporary paradigm, however, shifts the economic driver squarely toward value creation. Advanced valorisation technologies possess the capability to transform a costly and hazardous waste stream into a portfolio of marketable secondary products. While the initial capital expenditure (CAPEX) for emerging recovery technologies, such as hydrothermal liquefaction units or advanced pyrolysis reactors, currently exceeds the costs associated with conventional mechanical dewatering and landfilling, the comprehensive life-cycle economics are rapidly shifting in favour of recovery. The revenue generated from the commercialisation of recovered resources, coupled with the financial avoidance of escalating disposal taxes and the carbon credits associated with reduced greenhouse gas emissions, makes valorisation an increasingly competitive economic strategy. This ongoing shift is not exclusively technological; it is inherently regulatory, necessitating the development of new, progressive policy frameworks that recognise, standardise, and certify sludge-derived products to stimulate market demand and ensure their safe, continuous integration back into the global economy.

4. EMERGING PRETREATMENT TECHNOLOGIES FOR ENHANCED RESOURCE RECOVERY

The structural recalcitrance of industrial sludge is primarily governed by its EPS matrix, intracellular biopolymers, and embedded inorganic fractions, which collectively limit hydrolysis, the rate-limiting step in most biological conversion pathways. Recent literature increasingly frames pretreatment not merely as a disruption step but as a hydrolysis acceleration strategy that shifts the bottleneck of resource recovery systems. (Ćwiertniewicz-Wojciechowska et al. 2023; Siddiqui et al. 2023). Most studies show that solubilization and methane yield increase, but only a small number of studies examine energy balance and operational scalability, and downstream process compatibility, which creates a gap between laboratory efficiency and industrial viability.

4.1. Physical Pretreatment Methods

The most advanced pretreatment technology currently available uses thermal hydrolysis (THP) as its method. The current research shows that THP increases organic material solubility and enhances dewatering efficiency while boosting biomethane production through faster sludge decomposition (Siddiqui et al. 2023). The full-scale implementation of the technology shows that it has achieved a high level of technological readiness. The recent evaluations demonstrate that energy gains from the facility depend on the specific plant because they rely on two factors: the composition of sludge and the efficiency of heat recovery. The operational strength of THP depends on its heat integration system because that system determines its sustainability, while hydrolysis efficiency functions as a secondary factor. Scientists have developed microwave pretreatment as an alternative method that uses less energy for producing volumetric heating. Li et al. (2024) state that microwave irradiation shortens treatment duration while creating non-thermal effects that selectively destabilise EPS structures compared to standard heating. The studies about energy efficiency present conflicting results because they show varying results, which depend on the specific scale of dielectric heating experiments. The pilot scale of microwave systems demonstrates their technological benefits because they function effectively only in particular situations (Li et al. 2024). Ultrasonication uses mechanical disintegration through shear forces, which result from cavitation and the creation of radicals. The research shows that soluble Chemical Oxygen Demand (SCOD) and digestibility have increased through multiple studies, but Zhen et al. (2023) identify one ongoing issue, which causes high electrical energy consumption for processing each unit of sludge. The efficiency of cavitation decreases when sludge solids content exceeds a specific limit, which creates problems for using this method on industrial sludges that contain high concentrations of solids without any dilution. Therefore, although ultrasonication is mechanistically effective, its economic feasibility remains constrained (Ćwiertniewicz-Wojciechowska et al. 2023).

4.2. Chemical Electrochemical Pretreatment

The process of alkaline pretreatment increases the solubility of substances because it changes the surface charge, which enables the saponification of lipids and the hydrolysis of proteins along with polysaccharides. The research shows that alkaline dosing improves biodegradability, but excessive chemical use creates higher salinity and residual sodium levels, which can disrupt biological processes that follow(Ćwiertniewicz-Wojciechowska et al. 2023). The effectiveness of chemical pretreatment needs to be evaluated together with its effects on the microbiological processes of the processing system. The Advanced Oxidation Processes (AOPs), which include Fenton and ozonation systems, show high efficiency in breaking down persistent organic matter and newly developed pollutants. The main benefit of these products comes from their ability to create radicals, which conduct non-selective oxidation. The non-selective behaviour of the process creates two different outcomes because incomplete oxidation produces intermediate substances that need additional treatment. The full-scale application of the system faces two main challenges, which involve its operational expenses and the needed chemical substances (Yang et al. 2024). The application of AOPs shows better results when used to treat toxic industrial sludges compared to typical municipal sludge treatment processes. Electrochemical disintegration has gained attention in recent years because of the development of reliable electrode materials and more efficient energy management systems. The 2025 study showed better solubilization results, together with enhanced anaerobic digestion results from using dimensionally stable anodes. The electrochemical system provides a benefit over chemical oxidation because it enables on-site production of radicals, which decreases the need for chemical storage. The system still faces operational challenges because it does not have long-lasting electrode stability protection against fouling, and it requires high initial investment costs. The research lacks extensive operational data because only small-scale data have been collected (González-Ledesma et al. 2025).

4.3. Biological and Enzymatic Approaches

Biological pretreatments present a lower-energy alternative, and their process operates according to circular economy principles. Enzyme-assisted hydrolysis and microbial augmentation enable the targeted breakdown of EPS and complex polymers through their operation at low-temperature conditions. The two methods exhibit slower reaction kinetics in comparison to physicochemical methods, while their operational efficiency depends on specific environmental conditions, which include pH and temperature (Ćwiertniewicz-Wojciechowska et al. 2023). Biological pretreatment only achieves environmental benefits because it fails to deliver the fast solubilization needed for quick industrial production processes.

4.4 Hybrid Systems

The research direction now focuses on hybrid systems because all pretreatment methods show thermal systems consume high energy, chemical methods create operational challenges, and biological systems operate at slow speeds. The combined use of thermo-chemical and sono-chemical systems produces better results in solubilization efficiency than either system operating alone (Yang et al. 2024). The analytical insight emerging from recent reviews is that no single pretreatment technology optimises all performance indicators simultaneously; instead, integration allows compensation for individual weaknesses.

4.5 Comparative Performance and Scalability Considerations

The industrial sludge matrix can be disrupted by various pretreatment technologies, which show effective results, yet their actual application requires testing that compares their performance and their ability to expand. The evaluation process uses sludge solubilization as the primary metric because it corresponds to measured SCOD increases, which lead to better resource recovery results in biomethane production and dewatering efficiency (Zhou et al. 2024). THP and microwave irradiation physical treatments achieve higher solubilization results, which increase biogas production from treated sludge by 30% to 50% compared to untreated sludge. The relationship between performance and time shows a pattern in which performance increases at a declining rate until it reaches its highest capacity. The recent study discovered that when operators excessively increase thermochemical pretreatments beyond their normal boundaries, they experience performance losses that return to normal after the treatment. Extreme conditions create chemical recombination, which produces bio-crudes and long-chain fatty acids and phenolic compounds that inhibit subsequent biological conversion processes (Nahar et al. 2026). The biological and enzymatic pretreatments prevent the production of harmful byproducts through their mild operational conditions, yet their performance remains limited because of their slow reaction rates and their lower maximum solubilization efficiencies when compared to physical treatment methods.

The assessment of performance metrics needs the evaluation of the Technology Readiness Level (TRL) together with a techno-economic assessment, which establishes the capability of technology to grow from laboratory testing to industrial production. The THP technology (TRL 8-9) currently represents the most advanced technology in its field, which operates multiple commercial facilities around the world that can process continuous industrial operations (Salva et al. 2025). The advanced electrochemical and advanced hybrid oxidation processes show high solubilization efficiency, but they remain mostly restricted to pilot and bench testing stages, which fall within Technology Readiness Levels 3 and 5. The process of scale-up faces difficulties because costs associated with durable electrode materials, together with electricity requirements for operation, create financial obstacles. The sustainable biological pathways show operational costs that become economically unfeasible because commercial enzyme dosing expenses reach up to ten times the expenses of standard physical treatments, which include microwave irradiation. The process of selecting sludge pretreatment methods leads to the conclusion that no single solution exists. The selection process requires a customized TEA, which needs to evaluate the expensive capital costs and energy requirements of physical/chemical techniques against the high operational expenses and low output of biological methods to determine the economic and environmental boundaries that the industrial biorefinery must follow.

5. ADVANCED BIOLOGICAL CONVERSION TECHNOLOGIES

While advanced physicochemical pretreatments are highly effective at dismantling the complex extracellular matrices of industrial sludge, the actual recovery of embedded energy and biochemicals fundamentally relies on the efficacy of subsequent biological conversion platforms

5.1 Enhanced Anaerobic Digestion and Co-digestion Strategies

Anaerobic digestion (AD) remains the most historically established biological technology. However, the mono-digestion of industrial sludge frequently underperforms due to unfavourable carbon-to-nitrogen (C/N) ratios, recalcitrant organics, and the presence of inhibitory compounds. To circumvent these biological bottlenecks, enhanced co-digestion strategies have transitioned into an operational necessity. For example, recent studies on pulp and paper mill sludge (PPMS), which is notoriously difficult to degrade due to high lignocellulosic content and resin acids, demonstrate that co-digestion with food waste drastically improves system stability. The microbial community dynamics reach their optimal state through this synergy, which leads to a 36% methane yield increase when compared with mono-digestion methods, and it also helps to decrease overall treatment expenses (Uddin et al. 2025). The co-digestion process for raw industrial sludge and agri-food waste materials leads to improved hydrolysis kinetics, which protects the system from acidification while it maximises energy recovery capabilities at industrial estates (Jellali et al. 2021). In addition to this, operational issues such as ammonia buildup and fats, oils, and grease (FOG) are also major inhibitors of methanogenic activity, which are mainly attributed to instability in sludge processes. Excessive ammonia buildup can cause a proton balance problem, which can inhibit methanogenic activity, while FOG can cause instability in the sludge process, leading to a buildup of long-chain fatty acids, which in turn can cause biomass washout. All these factors contribute to the inhibitory effects on the methane generation process, thus requiring the incorporation of pre-treatment processes in the co-digestion system (Atchala et al. 2025). The process achieves improvements, yet it faces a major restriction because non-biodegradable heavy metals in primary industrial sludge will result in co-digestion, which creates concentrated contaminants that remain in the final digestate product, making it impossible to use as an agricultural biofertilizer through circular application methods.

5.2 Biohydrogen and Biomethane Production

The specialised method for creating biohydrogen through dark fermentation exceeds traditional methanogenesis because it produces more valuable energy. Dark fermentation operates between pH 4.5 and 6.0 by using specific microbial groups to transform dissolved organic materials into hydrogen without needing a methanogenic stage (Suyasa et al. 2025). The thermodynamic analysis shows that metabolic pathways restrict chemical oxygen demand (COD) conversion to hydrogen because only a small part of the initial COD can be turned into hydrogen, while the remaining energy stays in the acidic liquid waste as volatile fatty acids (VFAs). A two-stage biomethane system was researched to solve the energy deficit. The systems shown in Fig 4 combine a primary dark fermentation reactor for hydrogen with a secondary methanogenic reactor to consume the residual VFAs for methane. The process requires different pH levels, which need to be optimised across multiple stages because hydrogen production requires a pH of 5.5, and methane production needs a pH of 7.5 to achieve maximum energy recovery from sludge. (Sufyan et al. 2023) The need to control two entirely different microbial systems creates substantial difficulties for operations and requires substantial capital investment, which prevents immediate scale-up to industrial production.

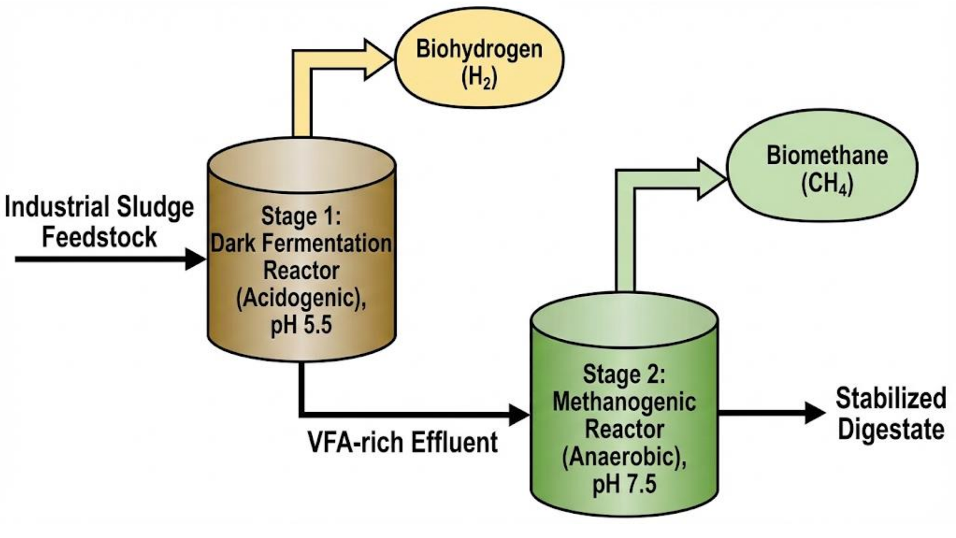

Fig. 4: Two-Stage Biomethane Production Process

5.3 Microbial Electrochemical Systems (MFCs and MECs)

Microbial electrochemical systems use exoelectrogenic bacteria to create a new method of bioconversion because these bacteria oxidise organic matter while transferring electrons to solid anodes. The Microbial Fuel Cells (MFCs) directly capture this bioelectricity, but the Microbial Electrolysis Cells (MECs) need an external voltage because they must break thermodynamic constraints to produce hydrogen gas with high purity (Koul et al. 2022). These systems provide a theoretical solution to treat toxic industrial sludges, which would otherwise disrupt conventional AD systems. The recent research shows that the combination of MECs with oxidative pretreatments such as ozonation leads to sludge matrix disintegration, which results in an eightfold increase in biogas production rate when compared to untreated controls (Hu et al. 2025). The examination of their commercialisation path reveals critical technical obstacles that prevent their progress. The transition from bench-scale to full-scale industrial reality is severely crippled by escalating internal ohmic resistances, pH gradients across membranes, and the prohibitive cost of requisite noble metal catalysts. The current situation produces a Levelized Cost of Energy (LCOE), which renders industrial sludge generation uncompetitive because of its extensive volumetric throughput.

5.4 Algal, Bacterial, and Fungal-based Valorisation Systems

The process of biological valorisation uses algal-bacterial consortia combined with specialised fungal systems to recover resources through their metabolically active partnerships. The white-rot fungal system operates through its production of extracellular enzymes, which can break down complex xenobiotic substances and organic waste materials that regular bacterial groups find impossible to decompose (Chaurasia et al. 2025). Specialised anaerobic microbiomes enable the fermentation of highly toxic tannery sludge waste into valuable short-chain fatty acids, which serve as bioplastics and biofuels production precursors while they dissolve chromium heavy metals (Tonanzi et al. 2025). The algal-bacterial systems (ABSS) use solar energy to stabilise organic materials while transforming nutrients into biomass, which can be harvested through their process of oxygen and carbon dioxide exchange (Qu et al. 2025). The industrial implementation of metabolic advantages faces major operational difficulties because they exist at two separate points. Fungal strains require extended time periods to develop, while their growth is obstructed by native bacteria in environments that lack sterilisation. The effectiveness of algal systems becomes fundamentally mismatched with the extreme turbidity present in concentrated industrial sludge because the reduction in light penetration stops photosynthesis, which needs to dilute the system with large water volumes that create impractical spatial demands for all normal industrial operations. Table 1 provides a detailed overview of the performance comparison, together with the technology readiness assessment and the main obstacles that emerging technologies face.

Table 1: Comparative analysis of emerging technologies for industrial sludge valorisation

Technology Pathway	Representative Industrial Sludge Source(s)	Typical Pretreatment / Operating Condition	Recovery Product	TRL	Key Limitation	Reference
Thermal Hydrolysis (THP)	Municipal-adjacent industrial WAS; food-processing sludge	160–180 °C, 6–30 bar, batch/continuous	Solubilised organics; enhanced biogas	TRL 8–9	High energy demand for heating; high CAPEX	Siddiqui et al. 2023
Enhanced Anaerobic Co-digestion	Pulp and paper mill sludge (PPMS) + food waste; agri-food sludge	Mesophilic 35–37 °C, co-substrate ratio optimised	Biomethane; stabilised digestate	TRL 7–9	Heavy-metal accumulation in digestate; sensitivity to toxic shock	Uddin et al. 2025
Dark Fermentation	Food and beverage processing sludge	Mesophilic/thermophilic, pH 5–6 controlled	Biohydrogen; volatile fatty acids (VFAs)	TRL 4–5	Severe thermodynamic limits; rapid pH drops requiring buffering	Jiang et al. 2023

Microbial Electrolysis Cells (MECs)	Electroplating and chemical-industry sludge (bench-scale)	Applied voltage 0.2–1.0 V, ion-exchange membrane	High-purity biohydrogen; bioelectricity	TRL 3–4	Prohibitive electrode/membrane costs; internal ohmic resistance	Hu et al. 2025
Pyrolysis (>500 °C)	Tannery, textile, and metallurgical sludge	Dried feedstock, inert atmosphere, 500–700 °C	Biochar; syngas; bio-oil	TRL 5–7	Extensive pre-drying requirement; high thermal energy input	Wang et al. 2025

6. ENVIRONMENTAL, ECONOMIC, AND SOCIAL SUSTAINABILITY ASSESSMENT

While the biochemical and physical mechanisms of emerging sludge valorisation technologies demonstrate immense laboratory potential, their true viability can only be determined through rigorous, multi-dimensional sustainability assessments.

6.1 Life Cycle Assessment (LCA) of Emerging Technologies

Life Cycle Assessment (LCA) has established itself as the standard method for measuring the environmental impact of sludge management practices. The latest LCA research shows that the sustainability assessment of new technologies depends on which methods researchers use to establish system boundaries and the distribution of environmental benefits. Recent LCAs of sewage and industrial sludge pyrolysis operations demonstrate that these processes produce extensive environmental benefits through their ability to achieve negative Global Warming Potentials (GWP), which exceed 400 kg CO2-equivalent per dry ton when compared to traditional techniques (Hosseinian et al. 2024). This Fig 5 reflects optimistic system-boundary assumptions, including full substitution of mineral fertiliser and fossil diesel by recovered products, reported for a single Swedish case study; it should not be generalised across feedstocks, climates, or scales without site-specific verification. The optimistic data presented in Fig 5 depends on the belief that biochar and bio-oil products will completely replace mineral fertilisers and fossil diesel in the marketplace, which will provide the system with substantial carbon offset credits. The process becomes an environmental liability because the system requires substantial power to operate both the sludge drying and the endothermic pyrolysis processes. The LCA results show that biological production of VFAs from sludge reduces eutrophication potential, yet the assessment overlooks the significant amount of chemicals, which include pH buffers and extraction solvents, that are needed for purification during subsequent treatment steps (Gracia et al. 2024). The LCA results should be understood as context-specific models that do not provide absolute proof of their findings.

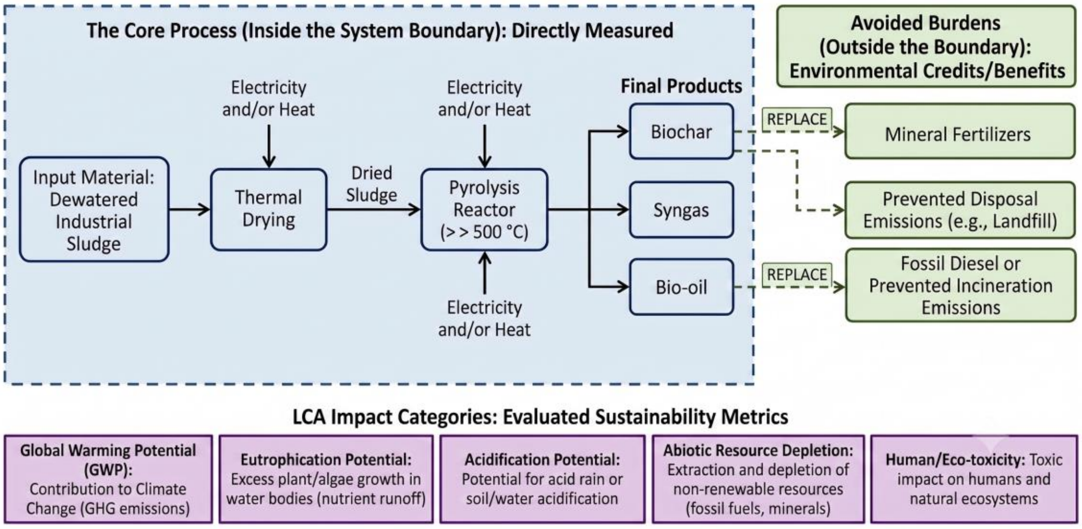

Fig 5: Conceptual cradle-to-gate system boundary for pyrolysis-based sludge valorisation, showing process inputs, avoided-burden credits, and the LCA impact categories reported across the reviewed studies

6.2 Techno-Economic Analysis (TEA) and Cost–Benefit Considerations

The economic system serves as the fundamental factor that determines the shift from a linear disposal model toward a circular biorefinery implementation. As detailed in Table 2, Techno-Economic Analysis demonstrates that organizations that attempt to achieve maximum resource recovery will not succeed in attaining sustainable financial outcomes. The advanced biological systems of two-stage biohythane production and MECs face substantial financial barriers because of their high CAPEX requirements. The system requires two reactors together with advanced gas treatment systems and expensive materials, which include proton exchange membranes, to operate at energy production costs that exceed those of traditional natural gas systems and standard anaerobic digestion systems (Jiang et al. 2023). The Operational Expenditures (OPEX) of new valorisation routes experience substantial fluctuations (Smol & Koneczna 2021). The sludge biorefinery economic model depends on revenue from secondary product sales, while a traditional landfilling system provides stable yet rising tipping fees. The market value of these products remains unstable because struvite biochar and biohydrogen face competition from heavily subsidized virgin raw materials. The complete TEAs demonstrate that private sector investment in advanced sludge valorisation requires both government funding and carbon tax implementation, together with mandatory secondary resource purchasing by industries (Uddin et al. 2025).

Table 2: Structured comparison of system boundaries, energy balance, GWP, CAPEX/OPEX indicators, and scale of application across the technologies.

Technology	System Boundary (LCA)	Net Energy Balance	GWP Indicator	CAPEX Indicator	OPEX Indicator	Typical Scale	Reference
Anaerobic Co-digestion + CHP	Cradle-to-gate; digestate end-use excluded	Positive (net energy source)	Negative to neutral, dependent on fossil-energy offset	Medium (existing WWTP infrastructure)	Low–Medium; subsidy-dependent biogas revenue	Commercial	Uddin et al. 2025; Smol & Koneczna 2021

Pyrolysis (Biochar/Bio-oil)	Cradle-to-gate + avoided-burden credit for fertiliser/fuel substitution	Neutral to positive, sensitive to drying energy	Reported as highly negative only under full product-substitution assumptions	High (reactor, drying, gas handling)	Medium–High; revenue depends on volatile biochar market	Pilot/Demonstration	Hosseinian et al. 2024
Dark Fermentation / Two-stage Biohythane	Cradle-to-gate; downstream VFA purification excluded from most LCAs	Negative to neutral (purification chemical demand)	Not consistently reported; likely underestimated (solvents/buffers excluded)	High (dual-reactor, gas-treatment systems)	High; membrane and enzyme costs	Pilot	Gracia et al. 2024; Jiang et al. 2023
Microbial Electrolysis Cells (MECs)	Gate-to-gate (bench scale); full system boundary not yet reported	Data-limited; electrode energy demand offsets gains	Not yet quantified at pilot/commercial scale	Very high (catalysts, membranes)	High; limited operational data	Bench/Early Pilot	Hu et al. 2025

6.3 Social Acceptance and Regulatory Compliance

The success or failure of a technology depends on non-technical barriers, which determine its outcome even when the technology reaches positive LCA and TEA assessment results. The circular sludge economy transition faces its most significant challenge from regulatory compliance requirements. The European Union and North America currently implement legislative frameworks that treat industrial sludge and its direct derivatives as "waste" materials that require strict handling regulations. The classification requires organisations to obtain specialised waste handling licenses, which involve significant financial expenses. For a sludge-derived product (such as biochar or recovered phosphorus) to be commercially traded, it must achieve "End-of-Waste" (EoW) status (Neri et al. 2024). The criteria for EoW regarding industrial sludge are currently ambiguous, fragmented across different jurisdictions, and exceptionally difficult to meet due to the persistent fear of heavy metal and perfluoroalkyl substance (PFAS) contamination. Compounding this regulatory paralysis is the issue of social acceptance. While industrial stakeholders prioritise economic efficiency, civil society and agricultural end-users often exhibit a profound "yuck factor" or risk aversion toward applying waste-derived products to soils or entering them into the supply chain. (Farfán Chilicaus et al. 2025). Overcoming this requires not just technological optimisation, but robust, transparent institutional pressure and standardised certification schemes to build market trust. (Smol & Koneczna 2021). Overcoming this resistance is likely to require independently verified certification schemes and transparent third-party testing data, rather than indirect comparisons, so that end-users and regulators can evaluate the safety of sludge-derived products against clearly defined thresholds for contaminants such as heavy metals, PFAS, and pathogens.

6.4 Comparison with Conventional Sludge Management Pathways

The emerging valorisation technologies, which scientists developed, now face fundamental environmental idealism versus operational reliability conflicts when scientists compare them to existing waste management methods, which include landfilling and incineration. Contemporary research literature contains widespread condemnation of conventional incineration because it produces high greenhouse gas emissions while destroying latent nutrients and creating hazardous fly ash (Hosseinian et al. 2024). Industrial facilities consider incineration to be an established technology which delivers high operational reliability because it instantly reduces waste volume while killing all pathogens in any type of incoming sludge. Advanced biological systems, which include enhanced co-digestion and fungal bioremediation processes, show extreme vulnerability to sudden increases in load and toxic chemical exposure and fluctuations in environmental conditions, which lead to their complete operational breakdown (Johansson 2023; Kadam et al. 2022). The actual waste-to-energy process offers industries better operational reliability than incineration, which provides theoretical environmental advantages through circular biorefinery systems. Emerging technologies require future research to prove their industrial-scale operational strength through continuous-flow testing instead of testing their resource yield capacity in laboratory conditions. The two competing systems present their primary environmental impacts together with their economic incentives in Table 3.

Table 3: Synthesised environmental and economic profiles of sludge management pathways

Management Pathway	Representative Industrial Sludge Source(s)	Typical Scale of Application	Key Limitation / Certification Need	Reference
Landfilling	Mixed industrial sludge (all sectors)	Full commercial scale	Land availability; long-term leachate liability	Kumar et al. 2025
Incineration	Tannery, chemical, and metallurgical sludge (high inorganic content)	Full commercial scale	Fly-ash disposal; emission-control compliance	Neri et al. 2024
Anaerobic Digestion + CHP	Food-processing, pulp and paper sludge	Commercial (single WWTP scale)	Requires stable co-substrate supply; digestate certification (EU 2019/1009) needed for land application	Uddin et al. 2025
Thermochemical (Pyrolysis)	Tannery, textile, metallurgical sludge	Pilot to early commercial	Biochar requires EBC/IBI certification before market sale; PFAS testing gap	Wang et al. 2025

7. BARRIERS, CHALLENGES, AND RISKS IN CIRCULAR SLUDGE VALORISATION

While the paradigm of the CE offers a theoretically elegant solution to industrial sludge management, the transition from linear disposal to closed-loop biorefineries is severely obstructed by a complex matrix of technical, economic, and regulatory barriers. A critical analysis of the current state of the art reveals that these challenges are not merely incremental engineering hurdles, but fundamental systemic bottlenecks.

7.1 Technical and Operational Limitations

The primary technical challenge that prevents successful sludge valorisation occurs because the feedstock contains diverse components that require complex processing. Industrial sludge shows greater variability in its moisture content, organic materials, and contaminant levels compared to the consistent feedstocks which chemical manufacturing processes. Continuous-flow systems face major disruptions because of these changes in operation. The industrial sludge contains more than 80 per cent water content, which remains after mechanical dewatering, because thermochemical conversion technologies, which include gasification and pyrolysis, need specific moisture levels to function properly. The process of thermally drying sludge to obtain latent heat energy for reactor entry results in negative net energy outcomes because it consumes more energy than the syngas or bio-oil production generates (Makowska et al. 2025). The presence of high inorganic ash content and heavy metals in industrial sludge creates issues for advanced thermochemical conversions because they function as catalyst poisons. Anaerobic digesters and bio-electrochemical systems experience biological system failures because recalcitrant organics, extreme pH changes, and heavy metal or synthetic dye discharges create toxic conditions that stop metabolic processes (Botte et al. 2024).

7.2 Scale-up and Implementation Challenges

The technological landscape of sludge valorisation is heavily skewed toward low Technology Readiness Levels (TRL 3–5). The technology transition gap in scaling from precisely controlled bench-top reactors to robust, continuous-flow industrial pilot plants exposes severe implementation challenges. Scale-up non-linearities, such as mass and heat transfer limitations in large-scale pyrolysis reactors or chronic mixing inefficiencies and dead zones in large-scale anaerobic digesters, drastically reduce the theoretical resource yields observed in laboratories. The establishment of advanced valorisation trains through two-stage biohythane production and hydrothermal liquefaction processes demands excessive initial CAPEX requirements. The system faces financial challenges because its high CAPEX needs to be managed together with uncertain OPEX and unstable revenue streams, which arise from the fluctuating market for sludge-derived products like biochar and recovered phosphorus that face competition from heavily subsidised virgin raw materials (Taron et al. 2023). The spatial logistics of implementation present a substantial hurdle because industrial wastewater treatment plants that operate at high centralisation cannot acquire enough space to install extensive biological valorisation systems, while decentralised facilities need to reach certain production levels before they can afford the expensive thermochemical equipment.

7.3 Regulatory and Policy Constraints

The most rigid constraint that stops circular sludge management from functioning properly stems from the existing legislative frameworks, which create an unbreakable barrier for this process. Globally, regulatory bodies operate under a strict precautionary principle regarding industrial effluents (Pivato et al. 2022). Most industrial sludge, together with its direct byproducts, gets classified as "hazardous waste" according to strict regulatory requirements instead of being recognised as "secondary raw materials." The recovered resource of biochar needs to reach End-of-Waste EoW status before it can be traded and used in the economy. The legal standards that countries require to establish EoW status remain divided among multiple jurisdictions, while those standards create persistent confusion and present extreme challenges to compliance. Policymakers often require complete protection from danger, which leads them to establish contaminant limits that no technology or business can achieve. The regulatory system creates a circular impasse because industries need a legally protected market for their products before they spend money on costly valorisation methods, while regulatory authorities demand that industries provide extensive safety evidence for decades before they will recognise these markets as legal.

7.4 Health, Safety, and Environmental Risks

The paradox behind circular sludge valorisation centres on its tendency to introduce dangerous pollutants back into nature. The treatment methods that utilize thermal and biological processes succeed in destroying most organic contaminants. Recent studies show that per- and polyfluoroalkyl substances (PFAS), which scientists call "forever chemicals", and microplastics continue to exist within the sludge matrix. The high-temperature pyrolysis process, which operates above 600 °C, can eliminate some chemical compounds through either volatilisation or degradation, but all lower-temperature processes, together with biological methods, fail to achieve this goal (Wang et al. 2025). The application of sludge-derived digestate or low-temperature biochar on agricultural soils results in emerging contaminants that start to leach into groundwater aquifers while they accumulate throughout the food web. Heavy metals, which include cadmium, lead, and chromium, undergo partitioning instead of destruction. The process of pyrolysis enables heavy metals to become encapsulated within biochar, which decreases their immediate bioavailability. The process of soil acidification, together with weathering, may result in the uncontrolled emission of high concentrations of metals into the surrounding environment (Makowska et al. 2025). The process of industrial sludge resource extraction needs extensive chemical and energy consumption, which produces dangerous waste products. This situation leads to environmental sustainability problems that affect all aspects of the "circular" process. To certify the safety of recovered materials for recycling, not only is it necessary to show the effectiveness of removing the contaminants in one study but also to establish compliance with established standards and independent verification of testing methods. About biochar, the European Biochar Certificate (EBC) and International Biochar Initiative (IBI) standards have set permissible levels (EBC, 2024) of heavy metals, polycyclic aromatic hydrocarbons, and PFAS contamination, as well as traceability of the feedstock and pyrolysis conditions. As regards struvite and digestate, the criteria set by the EU Fertilising Products Regulation (Regulation 2019/1009, 2019), determine the contaminant threshold and quality requirements that a recovered nutrient product needs to comply with before it could be sold as fertiliser rather than waste. About sludge-based construction materials like compressed stabilised earth blocks (Alemneh et al. 2025), certification will additionally necessitate conducting standard leaching tests such as EN 12457 (CEN, 2002) and performance tests before their approval for construction uses. Compliance with the above standards will help to compare recovered products across different studies and jurisdictions.

8. FUTURE PERSPECTIVES AND RESEARCH GAP

The transition of industrial sludge from a hazardous liability to a cornerstone of the CE represents one of the most critical environmental engineering challenges of the 21st century. However, the current literature needs a critical synthesis because the transition requires different academic research paths and international regulatory systems to change.

8.1 Technology Readiness and Innovation Gaps

Current research on sludge valorisation faces a major research issue because scientists prefer to study complicated new laboratory methods instead of developing practical solutions for industrial use. The literature is currently saturated with studies optimising highly specific, functionalized nanomaterials such as heteroatom-doped, sludge-derived biochars (SDB) or genetically engineered exoelectrogens for microbial electrolysis, that rarely progress beyond a Technology Readiness Level (TRL) of 3 or 4 (Wang et al. 2025). The essential development gap requires engineers to create continuous-flow pilot systems (TRL 6–8), which operate under the extreme toxicity and variable moisture content and shock loads that raw industrial sludge presents. Research must urgently change its focus to study how systems operate over extended periods. There is an urgent need for longitudinal studies that quantify the life-cycle degradation of catalytic electrodes in bioelectrochemical systems, the energy-mass balances of large-scale hydrothermal liquefaction reactors operating on highly heterogeneous feedstocks, and the integration of artificial intelligence (AI) and machine learning (ML) for real-time predictive control of biological crashes in anaerobic co-digestion systems. (Hernandez-Mora et al. 2024). Industrial valorisation technologies will remain useless to the market until researchers find ways to bridge the technology transition gap between laboratory potential and industrial reliability.

8.2 Policy and Governance Needs

The process of technological advancement needs to progress through both technological development and policy development. The existing system of governance functions as a major obstacle that prevents the circular economy from functioning. Environmental laws throughout the world maintain a strong connection to a linear system, which focuses on danger reduction because they treat industrial sludge and its byproducts as strict "hazardous waste" materials (Johansson 2023). Industries need to make substantial capital investments in advanced biorefineries, but they hesitate to proceed because they lack market security, which "End-of-Waste" (EoW) legal status would provide for their recycled materials. Regulatory agencies demand extensive safety data about the bioaccumulation of emerging contaminants, including per- and polyfluoroalkyl substances (PFAS) and microplastics, before they will grant EoW status, which industries need to create (UNEP 2025). Future policy research must focus on developing dynamic, risk-based legislative frameworks that standardise CE indicators across jurisdictions (Smol 2024). The government needs to shift from its current role of enforcing regulations to actively building markets through methods that require Green Public Procurement (GPP) quotas to use safe secondary materials from sludge in public buildings and farming projects that receive government funding (Neri et al. 2024).

8.3 Opportunities in Developing and Industrialising Economies

The recent literature review shows that advanced wastewater resource recovery research and technological development work mainly exists in the Global North, which includes both Europe and East Asia (Wada et al. 2026). The best chances to implement CE systems exist in developing countries and industrialising nations that make up the Global South. The region's experience of rapid industrialisation exceeds all previous historical records. The centralised activated sludge systems of developed countries create an extensive infrastructure that restricts all innovation activities (Sesay & Fang 2025). This situation creates a unique historical chance to achieve technological "leapfrogging."

The concept of leapfrogging may be defined as a possibility for emerging or developing nations to bypass already-outdated technologies that developed nations were once compelled to use and employ novel technologies instead (Lee et al. 2021). Leapfrogging initially appeared in the domain of telecommunication since mobile technologies could help completely bypass the need to build wired communications infrastructure (CSIS 2022). The concept could easily be applied to the environmental domain regarding technologies related to power generation, waste disposal, and sanitation (Sesay & Fang 2025; Wada et al. 2026). Of course, it is especially true for the management of industrial sludge. At present, countries of the Global South experience rapid development in their industry but have not yet been constrained to establish activated sludge treatment plants like those in Europe and East Asia (Wada et al. 2026).

Studies have revealed that there is an overwhelming bias towards research and implementation of circular economy and innovative technologies for resource recovery from sewage in the Global North, where about 39% of synthesized studies were found to be conducted in Europe specifically, whereas other developing nations, such as Sub-Saharan Africa and certain areas of Southeast Asia, still suffer from lack of adequate facilities, funding, and other institutional barriers (Wada et al. 2026). Instead of adopting the same old linear system of wastewater treatment and disposal, which developed countries introduced during the last century, emerging nations can develop decentralised modular biorefinery systems through the principles of the circular economy (Sesay & Fang 2025; Kakwani & Kalbar 2020). The "lock-in" problem facing the developed nations due to high sunk costs associated with established centralized technology, which makes changeover to new technology difficult, does not exist in the industrializing regions, thus offering what economic theory calls "the advantage of backwardness" (Lee et al. 2021). This is proven by studies that have shown that the approach taken is realistic; for instance, decentralized biogas production technology utilizing local waste in a process called anaerobic digestion is feasible in sub-Saharan Africa when it comes to handling industrial waste and agricultural soil rejuvenation (Robin & Ehiaze Ehimen 2024). Moreover, there is an emerging trend of mobile companies that provide small-scale pyrolysis, such as Takachar, MASH Makes, and Biocare Biochar, deploying low-temperature pyrolysis technology in India, Kenya, Sri Lanka, and Ghana to manufacture sludge biochar, which solves the problem of industrial waste as well as degraded soils (International Biochar Initiative 2026). These examples remain small-scale deployments, and their outcomes should be interpreted as indicative rather than as confirmation that leapfrogging or market readiness has been achieved at an industrial scale; systematic monitoring data over longer time frames are still lacking.

This is clear from the actual use of such technologies in practice since the theoretical advantages resulting from the theory of leapfrogging are also applicable in practice. From the viewpoint of governance and finance, the process of leapfrogging will not be a spontaneous one. Instead, any study conducted on the shift to circular economy in Low- and Middle-Income Countries (LMICs) tends to cite financial challenges, lack of governance processes, and failure to gain support from institutions as the main constraints (Sesay & Fang 2025). It means that to make leapfrogging possible, there is a need to establish certain policies involving technology transfer at international levels, local green bonds, and blended finance, a combination of public and private sources of development finance to cover any potential risks (Wada et al. 2026). Otherwise, LMICs might end up embracing the same linear disposition of resources as the Global North countries do.

8.4 Roadmap for Circular Economy–Driven Sludge Management.

Future academic and industrial efforts need to develop a comprehensive multi-disciplinary approach that will establish a complete solution for all existing knowledge gaps. The framework needs to establish advanced characterisation and detoxification as its main goals because it currently lacks these essential elements. The research needs to develop standardised rapid detection methods that can detect emerging persistent contaminants, including PFAS, microplastics, and new pharmaceuticals, which exist within the sludge matrix. Technological innovation needs to develop low-energy pretreatment methods that will permanently eliminate toxins or safely store them before the final products undergo downstream valorisation to guarantee complete safety and product viability.

The industrial eco-parks must receive sludge treatment operations because safe recovery parameters need to be established for new sludge processing methods. Future studies need to create interconnected supply chains that will treat waste heat and recovered bio-syngas and heavy metals from a sludge Water Resource Recovery Facility (WRRF) as essential operations instead of endpoint processes. The facilities need to establish direct connections between their operations and adjacent metallurgical, chemical, and agricultural facilities because this connection improves both thermodynamic efficiency and economic efficiency (Geetha 2025).

The academic community requires its researchers to stop studying separate small research topics because they need to study complete systems through which they can evaluate the success of integrated systems. The actual operational capacity of advanced sludge valorisation pathways needs to undergo complete testing through combined dynamic Life Cycle Assessments, stochastic Techno-Economic Analyses, and Social Impact Assessments (Soo et al. 2025). Stakeholders need this complete evaluation framework, which uses standardised methods to identify, manage, and develop the technologies that will achieve industrial wastewater sludge treatment systems.

9. CONCLUSIONS

The urgent environmental need to manage industrial wastewater sludge through waste disposal has become essential because it creates a sustainable recycling system, which forms the foundation of contemporary circular economic systems. The critical review has combined two technological progressions, which show that valorisation technologies have developed quickly, while their complete biochemical potential remains restricted because of their difficulties in achieving full production capacity. Advanced physicochemical pretreatments, which include thermal hydrolysis and ultrasonication, and advanced oxidation processes, serve as effective methods to break down the resistant sludge structure, which hides both organic and inorganic resources. Emerging biological conversion platforms, which include enhanced co-digestion and two-stage biohythane production and microbial electrochemical systems, show a theoretical potential for producing high-purity bioenergy and biochemicals. The actual synthesis of these technological advancements shows that researchers waste their efforts on developing bench-scale innovations. The actual realisation of these technologies needs to solve three major challenges, which include overcoming extreme thermodynamic restrictions, fixing biological systems that operate unpredictably, and spending excessively on building up their capabilities. The successful operation of these technologies despite major engineering challenges brings significant benefits to the worldwide development of circular economy systems. The industrial sludge treatment process transforms wastewater treatment plants into WRRFs, which create new operational value by treating industrial sludge as an important multiple-use secondary input instead of a final waste material. The process of restoring bioenergy sources, critical base metals, precious metals, and biochar acts as an energy source that offsets the energy requirements needed for extracting newly mined resources. The circular system approach to waste disposal, which replaces traditional methods through which waste material is processed, because it leads to lower greenhouse gas emissions and prevents the release of dangerous waste material. The new paradigm, which uses industrial metabolism, creates solid evidence proving that organisations can successfully manage their water and energy resources while processing highly toxic industrial wastewater materials. The circular system vision requires immediate operational shifts, which need to be executed across three areas: industrial operations, public policy development, and research planning. Enterprises should abandon existing methods that treat waste through single treatment systems because they need to implement industrial symbiosis, which should connect their water resource recovery facilities to their complete eco-parks for achieving optimal energy and economic benefits throughout their entire supply operations. The existing regulations, which treat all industrial sludge materials as hazardous waste, need to be immediately terminated because they create critical obstacles for policymakers. The establishment of scientifically validated "End-of-Waste" criteria needs to occur because private business investment requires this, which needs to be achieved through green public procurement requirements. The academic research community needs to change its complete research direction. Future research should focus on conducting extended testing using continuous-flow pilot studies, which evaluate the destruction or containment of new persistent contaminants like PFAS and microplastics, and implement standardised procedures for dynamic Life Cycle Assessments and Techno-Economic Analyses. The global industrial sector needs to create sustainable economic assets through effective wastewater sludge treatment, which requires a unified effort across various fields of study.

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11. REFERENCES

1. Alemneh, L. Y., Yimer, G. G., Ayele, Z. B., Adgo, T., Mulatu, C. A., Anteneh, Z. L., Aklog, D., & Asress, S. (2025). Recycling industrial sludge in low-cost construction: a sustainable approach using compressed stabilised earth blocks. Water Practice & Technology, 20(12), 2508–2519. https://doi.org/10.2166/wpt.2025.159

2. Atchala, M. S. R., Rao, P. V., Pilli, S., Pawar, A., Ganiga, R., & Tyagi, R. D. (2025). Pre-treatment and post-treatment strategies for enhancing anaerobic digestion in poultry slaughterhouse wastewater management. Sustainable Chemistry for the Environment, 9(June 2024), 100199. https://doi.org/10.1016/j.scenv.2024.100199

3. Botte, G. G., Donneys-Victoria, D., Alvarez-Pugliese, C. E., Adjei, J., Sahin, S., Wilson, N. W., Millerick, K., Hardberger, A., Furst, A. L., Hu, N., & Medford, A. J. (2024). Innovative Approach to Sustainable Fertiliser Production: Leveraging Electrically Assisted Conversion of Sewage Sludge for Nutrient Recovery. ACS Omega, 9(50), 49692–49706. https://doi.org/10.1021/acsomega.4c07926

4. CEN (2002) EN 12457-22002 Characterisation of Waste-Leaching-Compliance Test for Leaching of Granular Waste Materials and Sludges-Part 2 One Stage Batch Test at a Liquid to Solid Ratio of 10 L/kg for Materials with Particle Size below 4 mm (without or with Size Reduction). European Committee for Standardization. - References - Scientific Research Publishing. (n.d.). https://www.scirp.org/reference/referencespapers?referenceid=4177997

5. Chaurasia, P. K., Bharati, S. L., Singh, S., Sivalingam, A. M., Shankar, S., & Mani, A. (2025). Fungal pretreatment methods for organic wastes: advances and challenges in biomass valorization. RSC Sustainability, 3(3), 1234–1266. https://doi.org/10.1039/D4SU00582A

6. Ćwiertniewicz-Wojciechowska, M., Cema, G., & Ziembińska-Buczyńska, A. (2023). Sewage sludge pretreatment: current status and future prospects. Environmental Science and Pollution Research, 30(38), 88313–88330. https://doi.org/10.1007/s11356-023-28613-7

7. CSIS. (2022). The need for a leapfrog strategy. Center for Strategic and International Studies. https://www.csis.org/analysis/need-leapfrog-strategy

8. EBC (2024) 'European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.' Carbon Standards International (CSI), Frick, Switzerland. (http://european-biochar.org). Version 10.4 from 20th Dec 2024

9. Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products, Official Journal of the European Union, L 170, 1–114. europa.eu.

10. Farfán Chilicaus, G. C., Cruz Salinas, L. E., Silva León, P. M., Lizarzaburu Aguinaga, D. A., Vera Zelada, P., Vera Zelada, L. A., Luque Luque, E. O., Licapa Redolfo, R., & Ramos Farroñán, E. V. (2025). Circular Economy and Water Sustainability: Systematic Review of Water Management Technologies and Strategies (2018–2024). Sustainability, 17(14), 6544. https://doi.org/10.3390/su17146544

11. Geetha, R. (2025). Circular economy through integrated industrial ecology: Innovations in resource recovery and process re-design. Biotechnology Notes, 6, 245–259. https://doi.org/10.1016/j.biotno.2025.10.005

12. González-Ledesma, S., Romero-Serrano, M. C., Sánchez-Vázquez, V., González, I., & Durán-Hinojosa, U. (2025). Electrochemical pretreatment to improve the biodegradability and valorization of waste activated sludge from aerobic wastewater treatment plants. Biotechnology for Biofuels and Bioproducts, 18(1), 97. https://doi.org/10.1186/s13068-025-02693-8

13. Gracia, J., Cabeza, I., & Acevedo, P. (2024). Life cycle analysis for the production of volatile fatty acids from wastewater treatment plant sludge. Cogent Engineering, 11(1). https://doi.org/10.1080/23311916.2024.2335846

14. Hao, X., Wang, X., Liu, R., Li, S., van Loosdrecht, M. C. M., & Jiang, H. (2019). Environmental impacts of resource recovery from wastewater treatment plants. Water Research, 160, 268–277. https://doi.org/10.1016/j.watres.2019.05.068

15. Hernandez-Mora, A., Duboc, O., Lombi, E., Bünemann, E. K., Ylivainio, K., Symanczik, S., Delgado, A., Abu Zahra, N., Nikama, J., Zuin, L., Doolette, C. L., Eigner, H., & Santner, J. (2024). Fertilization efficiency of thirty marketed and

experimental recycled phosphorus fertilizers. Journal of Cleaner Production, 467, 142957. https://doi.org/10.1016/j.jclepro.2024.142957

16. Hosseinian, A., Brancoli, P., Vali, N., Ylä-Mella, J., Pettersson, A., & Pongrácz, E. (2024). Life cycle assessment of sewage sludge treatment: Comparison of pyrolysis with traditional methods in two Swedish municipalities. Journal of Cleaner Production, 455(November 2023). https://doi.org/10.1016/j.jclepro.2024.142375

17. Hu, K., Zhang, X., Sun, X., Xu, H., Chen, W., & Wang, W. (2025). Integrated approach to enhance excess sludge degradation in microbial electrolysis cell: Role of ozone pretreatment. Bioelectrochemistry, 166, 109028. https://doi.org/10.1016/j.bioelechem.2025.109028

18. International Biochar Initiative. (2026). Biochar as a diversified carbon dioxide removal pathway: Research and technology integration update 2023–2025. https://biochar-international.org/news/biochar-as-a-diversified-carbon-dioxide-removal-pathway-research-and-technology-integration-update-2023-2025/

19. Jellali, S., Charabi, Y., Usman, M., Al-Badi, A., & Jeguirim, M. (2021). Investigations on Biogas Recovery from Anaerobic Digestion of Raw Sludge and Its Mixture with Agri-Food Wastes: Application to the Largest Industrial Estate in Oman. Sustainability, 13(7), 3698. https://doi.org/10.3390/su13073698

20. Jiang, J., Lopez-Ruiz, J. A., Bian, Y., Sun, D., Yan, Y., Chen, X., Zhu, J., May, H. D., & Ren, Z. J. (2023). Scale-up and techno-economic analysis of microbial electrolysis cells for hydrogen production from wastewater. Water Research, 241, 120139. https://doi.org/10.1016/j.watres.2023.120139

21. Johansson, O. (2023). The End-of-Waste for the Transition to Circular Economy: A Legal Review of the European Union Waste Framework Directive. Environmental Policy and Law, 53(2–3), 167–179. https://doi.org/10.3233/EPL-220064

22. Kadam, R., Khanthong, K., Jang, H., Lee, J., & Park, J. (2022). Occurrence, Fate, and Implications of Heavy Metals during Anaerobic Digestion: A Review. Energies, 15(22), 8618. https://doi.org/10.3390/en15228618

23. Kakwani, N. S., & Kalbar, P. P. (2020). Review of Circular Economy in urban water sector: Challenges and opportunities in India. Journal of Environmental Management, 271, 111010. https://doi.org/10.1016/j.jenvman.2020.111010

24. Koul, Y., Devda, V., Varjani, S., Guo, W., Ngo, H. H., Taherzadeh, M. J., Chang, J.-S., Wong, J. W. C., Bilal, M., Kim, S.-H., Bui, X.-T., & Parra-Saldívar, R. (2022). Microbial electrolysis: a promising approach for treatment and resource recovery from industrial wastewater. Bioengineered, 13(4), 8115–8134. https://doi.org/10.1080/21655979.2022.2051842

25. Kumar, K., Sharma, R., & Goyal, S. K. (2025). Current practices for the management of sludge generated from common effluent treatment plants-A review. Indian Journal of Chemical Technology, 32(2), 149–160. https://doi.org/10.56042/ijct.v32i2.7937

26. Lee, J.-D. C. of T. and E. C. in E. E., Lee, K., Meissner, D., Radosevic, S., & Vonortas, N. (2021). The Challenges of Technology and Economic Catch-up in Emerging Economies (J.-D. Lee, K. Lee, D. Meissner, S. Radosevic, & N. Vonortas (eds.)). Oxford University PressOxford. https://doi.org/10.1093/oso/9780192896049.001.0001

27. Li, Y., Campos, L. C., & Hu, Y. (2024). Microwave pretreatment of wastewater sludge technology—a scientometric-based review. Environmental Science and Pollution Research, 31(18), 26432–26451. https://doi.org/10.1007/s11356-024-32931-9

28. Makowska, D., Pandiyan, M., Kapusta, K., Kolarz, K., Stypka, Z., Boehman, A. L., & Wooldridge, M. S. (2025). Effects of pyrolysis parameters on biochar derived from sewage sludge including environmental risk assessment of heavy metals. Journal of Environmental Management, 395, 127888. https://doi.org/10.1016/j.jenvman.2025.127888

29. Nahar, K., Krohn, C., Hakeem, I. G., Ngo, T., Chiang, K., Surapaneni, A., Ball, A. S., & Shah, K. (2026). Advancing wastewater sludge valorisation: Evaluating hydrothermal treatment and anaerobic digestion integration pathways. Bioresource Technology, 442, 133713. https://doi.org/10.1016/j.biortech.2025.133713

30. Neri, A., Rizzuni, A., Garrone, P., & Cagno, E. (2024). Influence of policymakers and civil society stakeholders on sewage sludge management strategies: Empirical results from European utilities. Journal of Environmental Management, 364, 121396. https://doi.org/10.1016/j.jenvman.2024.121396

31. Pivato, A., Beggio, G., Bonato, T., Butti, L., Cavani, L., Ciavatta, C., Di Maria, F., Ferrara, R., Grenni, P., Johansson, O., Maggi, L., Mazzi, A., Peng, W., Peres, F., Pettersson, M., Schievano, A., & Varghese, G. (2022). the Role of the Precautionary Principle in the Agricultural Reuse of Sewage Sludge From Urban Wastewater Treatment Plants. Detritus, 19(2000), V–XII. https://doi.org/10.31025/2611-4135/2022.15202

32. Qu, J., Ren, R., Wu, Z., Huang, J., & Zhang, Q. (2025). From Waste to Resource: Algal–Bacterial Systems and Immobilization Techniques in Aquaculture Effluent Treatment. Clean Technologies, 7(4), 97. https://doi.org/10.3390/cleantechnol7040097

33. Raheem, A., Sikarwar, V. S., He, J., Dastyar, W., Dionysiou, D. D., Wang, W., & Zhao, M. (2018). Opportunities and challenges in sustainable treatment and resource reuse of sewage sludge: A review. Chemical Engineering Journal, 337, 616–641. https://doi.org/10.1016/j.cej.2017.12.149

34. Robin, T., & Ehiaze Ehimen. (2024). Exploring the potential role of decentralised biogas plants in meeting energy needs in sub-Saharan African countries: a techno-economic systems analysis. Sustainable Energy Research, 11(1). https://doi.org/10.1186/s40807-024-00101-7

35. Salva, J., Sečkár, M., Schwarz, M., Samešová, D., Mordáčová, M., Poništ, J., & Veverková, D. (2025). Analysis of the current state of sewage sludge treatment from the perspective of current European directives. Environmental Sciences Europe, 37(1), 59. https://doi.org/10.1186/s12302-025-01097-7

36. Sesay, R. E. V., & Fang, P. (2025). Circular Economy in Municipal Solid Waste Management: Innovations and Challenges for Urban Sustainability. Journal of Environmental Protection, 16(02), 35–65. https://doi.org/10.4236/jep.2025.162003

37. Siddiqui, M. I., Rameez, H., Farooqi, I. H., & Basheer, F. (2023). Recent Advancement in Commercial and Other Sustainable Techniques for Energy and Material Recovery from Sewage Sludge. Water, 15(5), 948. https://doi.org/10.3390/w15050948

38. Smol, M., Adam, C., & Preisner, M. (2020). Circular economy model framework in the European water and wastewater sector. Journal of Material Cycles and Waste Management, 22(3), 682–697. https://doi.org/10.1007/s10163-019-00960-z

39. Smol, M., & Koneczna, R. (2021). Economic Indicators in Water and Wastewater Sector Contributing to a Circular Economy (CE). Resources, 10(12), 129. https://doi.org/10.3390/resources10120129

40. Soo, A., Gao, L., & Shon, H. K. (2025). Roadmap for Australian wastewater nutrient recovery – Towards a sustainable circular economy. Desalination and Water Treatment, 323, 101273. https://doi.org/10.1016/j.dwt.2025.101273

41. Sufyan, F., Ali, M., Khan, S., & Hossain, N. (2023). Biohythane Production from Domestic Wastewater Sludge and Cow Dung Mixture Using Two-Step Anaerobic Fermentation Process. Sustainability, 15(19), 14417. https://doi.org/10.3390/su151914417

42. Suyasa, W. B., Simpen, I. N., Dewi, I. G. A. K. S. P., & Suastuti, N. G. A. M. D. A. (2025). Biohydrogen Production Potential from Organic Waste in Balinese Markets and Utilization of Residual Byproducts for Polluted Water Treatment. Nature Environment and Pollution Technology, 24(4), D1755. https://doi.org/10.46488/NEPT.2025.v24i04.D1755

43. Taron, A., Singh, S., Drechsel, P., Ravishankar, C., & Ulrich, A. (2023). Sewage sludge: a review of business models for resource recovery and reuse. https://doi.org/10.5337/2023.211

44. Tomczyk, A., Sokołowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Biotechnology, 19(1), 191–215. https://doi.org/10.1007/s11157-020-09523-3

45. Tonanzi, B., Massimi, A., Valentino, F., Tuci, G. A., Gottardo, M., Rossetti, S., & Crognale, S. (2025). Microbial-driven valorization of tannery sludge for fatty acids production: unraveling microbiome activity and functional redundancy. Frontiers in Microbiology, 16. https://doi.org/10.3389/fmicb.2025.1675618

46. Trpčevská, J., Maruškinová, G., Laubertová, M., Kundráková, K., & Oráč, D. (2025). Industrial Sludge Valorization in Soil Application. Metals, 15(1), 55. https://doi.org/10.3390/met15010055

47. Uddin, M. N., Hartog, C., Murray, E., Loveless, J. B., Roberson, L., Aslan, A., Cubas, F., & Rowles, L. S. (2025). Advancing Circular Bioeconomy through a Systems-Level Assessment of Food Waste and Industrial Sludge Codigestion. ACS Environmental Au, 5(5), 479–489. https://doi.org/10.1021/acsenvironau.5c00049

48. UNEP. (2025). The Climate Technology Progress Report 2025. https://www.unep.org/resources/report/climate-technology-progress-report-2025

49. Wada, O. Z., Ige, A. O., Egbewole, B. I., & Olawade, D. B. (2026). Circular economy from wastewater resource recovery: A review of recent advances and global disparities. Sustainable Chemistry One World, 9, 100187. https://doi.org/10.1016/j.scowo.2026.100187

50. Wang, L., Liang, L., Li, N., Chen, G., Guo, H., & Hou, L. (2025). A Mini-Review of Sludge-Derived Biochar (SDB) for Wastewater Treatment: Recent Advances in 2020–2025. Applied Sciences, 15(11), 6173. https://doi.org/10.3390/app15116173

51. Yang, M., Vander Elst, M., Smets, I., Zhang, H., Li, S., Baeyens, J., & Deng, Y. (2024). Reviewing Improved Anaerobic Digestion by Combined Pre-Treatment of Waste-Activated Sludge (WAS). Sustainability, 16(15), 6419. https://doi.org/10.3390/su16156419

52. Zhen, G., Lu, X., Kato, H., Zhao, Y., & Li, Y.-Y. (2017). Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: Current advances, full-scale application and future perspectives. Renewable and Sustainable Energy Reviews, 69, 559–577. https://doi.org/10.1016/j.rser.2016.11.187

53. Zhou, P., Li, D., Zhang, C., Ping, Q., Wang, L., & Li, Y. (2024). Comparison of different sewage sludge pretreatment technologies for improving sludge solubilization and anaerobic digestion efficiency: A comprehensive review. Science of The Total Environment, 921, 171175. https://doi.org/10.1016/j.scitotenv.2024.171175

54. Zisman, O., Kushmaro, A., & Brenner, A. (2024). Bio-chemical treatment of landfill leachates with high load of organic and nitrogen compounds. Sustainable Chemistry for the Environment, 5(January), 100061. https://doi.org/10.1016/j.scenv.2024.100061

12. LIST OF ABBREVIATIONS

- Advanced Oxidation Processes (AOPs),
- Algal-bacterial systems (ABSS)
- Anaerobic digestion (AD)
- Artificial intelligence (AI)
- Capital expenditure (CAPEX)
- Capital Expenditures (CAPEX)
- Chemical oxygen demand (COD)
- Circular Economy (CE)
- End-of-Waste" (EoW)
- Extracellular polymeric substances (EPS)
- European Biochar Certificate (EBC)
- Fats, oils, and grease (FOG)
- Global Warming Potentials (GWP)
- Green Public Procurement (GPP)
- International Biochar Initiative (IBI)
- Levelized Cost of Energy (LCOE)
- Life Cycle Assessment (LCA)
- Low- and Middle-Income Countries (LMIC)
- Machine learning (ML)
- Microbial Electrolysis Cells (MECs)
- Microbial Fuel Cells (MFCs)
- Operational Expenditures (OPEX)
- Perfluoroalkyl substance (PFAS)
- Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)
- Pulp and paper mill sludge (PPMS),
- Sludge-derived biochars (SDB)
- Soluble Chemical Oxygen Demand (SCOD)
- Techno-Economic Analysis (TEA)
- Technology Readiness Level (TRL)

- Thermal hydrolysis Process (THP)
- Thermal Hydrolysis Processes (THP)
- Volatile fatty acids (VFAs).
- Water Resource Recovery Facility (WRRF)

13. BACKGROUND INFORMATION FOR RECORD

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