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TRENDS IN SLUDGE RESEARCH: INNOVATIONS, CHALLENGES AND FUTURE PERSPECTIVES

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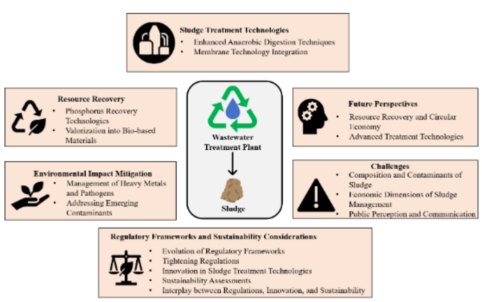
Graphical abstract



Abstract

The management and valorization of sludge from wastewater treatment plants represent critical challenges due to environmental concerns, regulatory pressures, and sustainable development policies. In wastewater treatment, sludge is generated as primary solids during sedimentation and as secondary biomass from biological processes, and is typically thickened, stabilized, and dewatered before treatment or reuse. This review aims to synthesize recent developments in sludge treatment technologies, focusing on resource recovery-based technological advancements and progress toward minimizing the environmental impacts of sludge disposal as well exploring for sustainable options and solutions. Specifically, the review synthesizes developments across biological (anaerobic digestion), thermal (pyrolysis, hydrothermal processing), and chemical (precipitation, membrane) methods that underpin resource recovery and environmental protection and summarize how sludge is subsequently managed through treatment and valorization pathways. This paper provides an overview of recent advancements in this field, highlights common problems and presents the committee with a plan on how to alter studies that could lead to innovative research for sludge management by reviewing relevant past research.

Keywords: Sludge management, Wastewater treatment, Resource recovery, Environmental impacts, Sustainable disposal

Abstrak

Pengurusan dan pemanfaatan enap cemar dari loji rawatan air kumbahan merupakan cabaran kritikal disebabkan oleh kebimbangan alam sekitar, tekanan peraturan, dan dasar pembangunan mampan. Dalam rawatan air kumbahan, enap cemar dihasilkan sebagai pepejal primer semasa pemendakan dan sebagai biojisim sekunder daripada proses biologi, dan lazimnya dipadatkan, distabilkan serta dinyahairkan sebelum dirawat lanjut atau diguna semula. Kajian ini dilakukan bertujuan untuk mensintesis perkembangan terkini dalam teknologi rawatan enap cemar, dengan memberi tumpuan kepada kemajuan teknologi berasaskan pemulihan sumber dan kemajuan ke arah meminimumkan kesan alam sekitar daripada pelupusan enap cemar serta meneroka pilihan dan penyelesaian mampan. Secara khusus, kajian ini mensintesis perkembangan merentas kaedah biologi (pencernaan anaerobik), termal (pirolisis, pemprosesan hidrotermal) dan kimia (pemendakan, teknologi membran) yang menyokong pemulihan sumber dan perlindungan alam sekitar, serta merumuskan bagaimana enap cemar seterusnya diurus melalui laluan rawatan dan pemanfaatan. Kajian ini juga memberikan gambaran keseluruhan tentang kemajuan terkini dalam bidang ini, menekankan masalah umum, dan mengemukakan rancangan kepada jawatankuasa tentang cara mengubah kajian yang boleh membawa kepada penyelidikan inovatif untuk pengurusan enap cemar dengan mengkaji kajian-kajian terdahulu yang berkaitan.

Kata kunci: Pengurusan enap cemar, Rawatan sisa air, Pemulihan sumber, Kesan alam sekitar, Pelupusan mampan

1.0 INTRODUCTION

As urbanization continues to accelerate across the globe, the challenges associated with managing the byproducts of human and industrial activity have become more pronounced. The production of sludge and its disposal are some of the most problematic byproducts. Sludge, a by-product of the wastewater treatment processes is complex in nature and comprises organic matter (OM), pathogens, heavy metals and emerging contaminants such as pharmaceuticals and microplastics[1], [2]. Proper treatment and handling of sludge are essential for preventing environmental squalor, as well as protection against human illness. However, with ever-stricter environmental regulations and an emphasis on the sustainability of biosolids management practices the traditional means of sludge disposal such as landfilling or incineration are being reassessed for their environmental footprints and potential risks to human health.

In a typical wastewater treatment plant, sludge is produced as a by-product of physical, chemical, and biological processes [3, 4]. Primary sludge forms during sedimentation (settling of suspended solids), whereas secondary (biological) sludge arises from microbial biomass grown during biological treatment (e.g., activated sludge) [4]. Tertiary polishing and nutrient removal may generate additional sludge (e.g., chemical precipitates) [5]. The combined sludge stream is then thickened, stabilised (e.g., anaerobic digestion or chemical conditioning), and dewatered before disposal or valorisation (e.g., energy and nutrient recovery) [3-5].

This review synthesises recent research on sludge to focus on the most up-to-date advancements in treatment technologies for this waste product. Specifically, the paper highlights how current methods of biological treatment, thermal processing and chemical extraction help to inherently reduce the amount of sludge generated [3], neutralise its pathogenic components [6], and recover useful resources contained within [5].

Recovering resources from sludge has become an especially promising area of research. Efficient technologies now capable of extracting nutrients [7] for agricultural use (fertilizer, such as compost), generating energy from anaerobic digestion, and recovering water for non-potable uses [4, 8–13]. In addition to enhancing the sustainability of wastewater treatment processes, these strategies offer potential economic profit by converting valuable goods from waste.

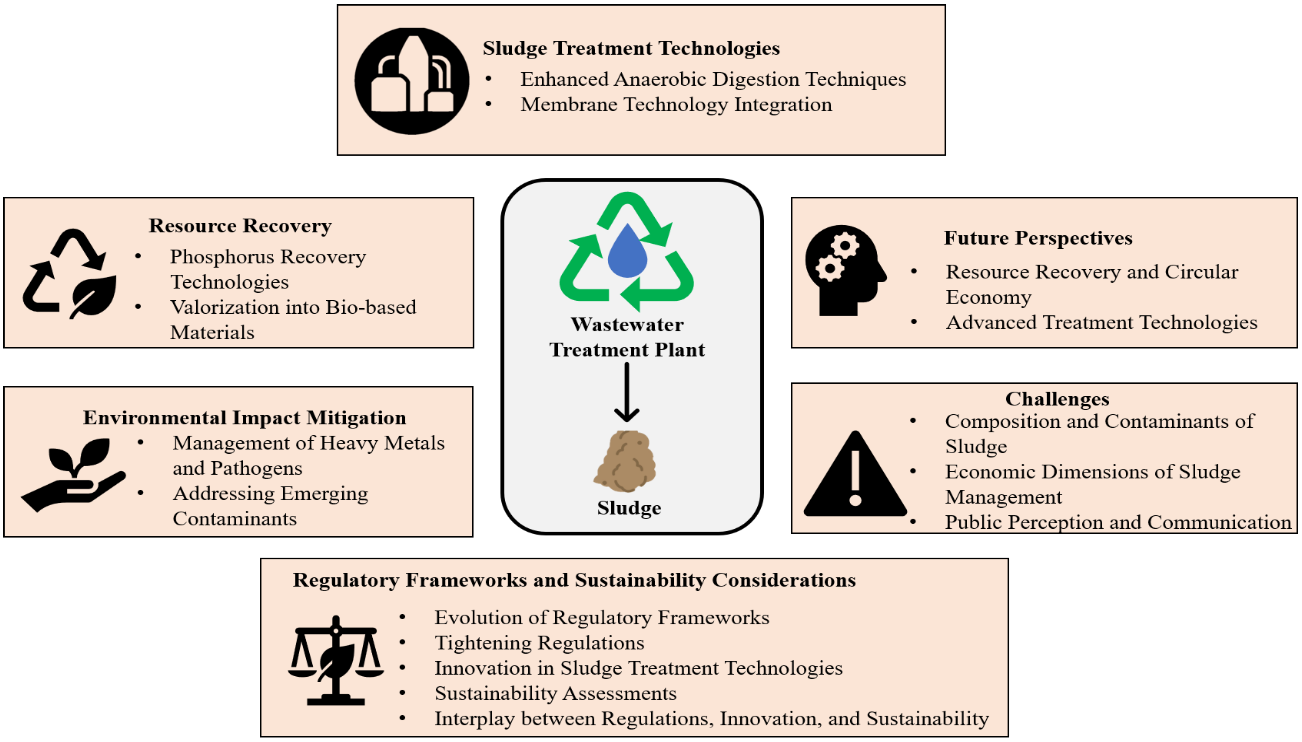


Figure 1 Graphical abstract of the review for Trends In Sludge Research: Innovations, Challenges and Future Perspectives

Additionally, the review assesses mitigation approaches to the sludge residue's environmental impacts, including optimisation of technological processes to reduce the release of pollutants, minimisation of the energy and carbon footprint of the sludge management cycle, and the implementation of legislative and policy frameworks designed to protect the environment and public health.

The review also outlines possible future directions for sludge research and technological development. These must be interdisciplinary efforts, coalescing knowledge from fields such as engineering, microbiology, and policy. As the field progresses, it is expected that innovative technologies and methodologies will emerge leading to more effective, sustainable, and cost-efficient sludge treatment. By providing a thorough overview of current trends and prospective developments in sludge research, this review aims to serve as a guide for researchers, policy makers, and industry practitioners aiming to manage sludge in an environmentally responsible manner. The graphical abstract in Figure 1 illustrated the key point of the findings discussed in the paper.

2.0 ADVANCES IN SLUDGE TREATMENT TECHNOLOGIES

2.1 Enhanced Anaerobic Digestion Techniques

Anaerobic digestion (AD) is extensively applied in wastewater treatment plants to stabilise sludge and enable renewable-energy recovery [3, 5, 12]. In practice, AD reduces sludge volumes and supports resource-efficient wastewater operations, making it an important element of sustainable sludge management [3, 12]. AD can simply be described as the breakdown of materials such crop residues, animal feeds or sewage using microorganisms but in the absence of oxygen. This is done anaerobically in a closed chamber and results in biogas made of methane and carbon dioxide and the digestate which is a nutrient-rich output useful as a fertilizer. In the waste management field and production of energy, anaerobic digestion is employed because biogas can be used in production of electricity, heat and fuel; hence anaerobic digestion is renewable energy.

AD is widely recognised as one of the most sustainable and efficient waste management and energy generation technologies, with the industry constantly seeking to improve the process for maximum effectiveness. Two main objectives of these developments are; (1) to reduce the amount of sludge generated during wastewater treatment procedures, and (2) to produce methane more efficiently, a sustainable energy source [14]. These innovations are important in response to both the energy sustainability and waste reduction issues that make the AD technologies and systems more attractive for adoption. Figure 2 shows the four stages of AD process.

In AD process, the first step involves hydrolysis where insoluble molecules are transformed into soluble molecules. These soluble materials are then broken down by bacteria into volatile fatty acids through a process called acidogenesis. After that, the volatile fatty acids go through acetogenesis process that converts them to acetic acid. Finally, the acetic acid gets further degradation to yield methane at the methanogenesis process [15].

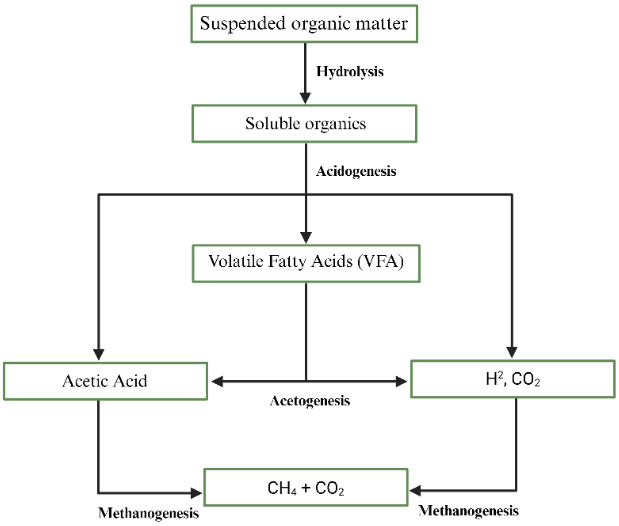


Figure 2 Principles of anaerobic digestion (AD) process [15]

Currently, one of the most discussed and promising fields of development in AD is the application of thermochemical pretreatment technologies. These processes are intended to improve solubility of various organic compounds within sludge, which is essential for increasing the yields of biogas. Methods like hydrothermal pre-treatment, steam explosion and thermal hydrolysis reduce the extent of the organic structure of the materials so that the anaerobic microorganisms can easily digest [16]. Hydrothermal pretreatment can improve the degradation of organic matter and thus increase methane production [17].

The application of steam explosion as thermal hydrolysis pretreatment for sludge, according to Balasundaram *et al*, in the year 2023 [18], indicated enhanced methane yield, increased extent of organic matter and solids removal and effective pathogen elimination during AD. This method also benefited in achieving high standard biosolids to be used as fertilizer. In addition, Zarei (2020) [7] has captured the potential of these methods in the context of the study through a quantitative exploration and has provided evidence that they can increase both energy recovery rates and efficiency of AD processes. Pretreatment that takes place is also important in enhancing the process of converting waste to methane besides reducing the volume of sludge.

Concurrently with the technological advancements, a particular focus has been given to the engineering of new microbial consortia that could enhance the AD process [19, 20]. Such consortia comprise of specially chosen or genetically created microorganisms which are endowed with efficiency in methane synthesis and wastes degradation processes. For instance, methanogenic archaea is a unique class of microbes that produced methane contributing to 55% yield of the variability in biogas output and significantly enhances the rates of biogas production in waste treatment through anaerobic digestion processes [21].

The other recognized potential microbial groups for the synthesis of biogas are the recurrent phylotypes including *Methanoculleus, Methanothermobacter, and Syntrophomonas* [22]. Hassa *et al.*, (2018) [23], explained the disadvantages associated with cultivation dependent methods in studying microbial communities; however they highlighted on the advantages of the metagenomics strategies.

Compared with culture-based microbial counts, these strategies offer a much deeper understanding of the complexity, roles and fluctuations of microbial communities in biogas generation. As described by Krohn *et al*. (2022) [24], research efforts now focus on optimising AD kinetics and improving robustness across operating conditions. When tuned to sludge characteristics, engineered consortia can enhance AD performance, maintain stability under environmental perturbations and increase biogas yields.

In practical applications, engineered microbial consortia are used at full scale to stabilise digesters, raise methane yields and shorten retention time. Bioaugmentation with methanogenic archaea and syntrophic partners helps recover underperforming units and improves acetate turnover and long-chain fatty-acid (LCFA) degradation, leading to higher methane production [15, 19, 21, 24]. Utilities also apply targeted inocula when shifting to co-digestion or operating at higher organic loadings to limit volatile-fatty-acid (VFA) build-up and foaming [19, 24]. Meta-omics resources and plant-scale monitoring enable community-guided adjustments that increase resilience to pH, ammonia and temperature stress [20–25].

The integration of thermochemical pretreatments with tailored microbial consortia has further advanced AD technology. According to Hagen *et al.*, (2017) [25] pretreatment can enhance biomass deconstruction and foster synergistic relationships (e.g., with the proteolytic bacterium Coprothermobacter proteolyticus), supporting stability and metabolic activity in thermophilic biogas reactors. This aligns with Ho *et al.*, (2013) [26], who reported that Methanosarcinaceae and acetate-oxidising pathways can dominate in high-rate thermophilic AD of waste-activated sludge, improving methane generation.

These developments open up new avenues for research in addition to promising to increase the effectiveness of methane production and reduce sludge volume [27], [28]. Subsequent research endeavours are anticipated to delve into the intersections of diverse pretreatment methodologies, the enhancement of microbial consortiums for certain waste categories, and the expandability of these resolutions for industrial use. The continued advancement of AD technology highlights its promise as a pillar of renewable energy generation and sustainable waste management, providing a viable path forward for tackling some of the most urgent environmental issues of our day.

2.2 Membrane Technology Integration

Membrane technology in sludge treatment refers to the use of selective filtration processes to separate contaminants from wastewater. It involves a thin, porous material that allows water to pass through while retaining solids, microorganisms, and other pollutants. This method is highly effective in reducing sludge volume and improving the quality of treated water. Membrane technology is known for its efficiency, compact design, and ability to treat wastewater with minimal energy and chemical use, making it a sustainable option in modern wastewater management.

Currently, the membrane bioreactor or MBR is the perfect example of advanced oxidation technology that employs both suspended growth processes and membrane filtration in order to improve not only the sludge reduction but also the quality of the effluent [29–31]. This new method makes it easier to discharge numerous types of pollutants and ensures that the process of disposal of the wastewater is more effective and environmentally friendly as well. MBRs are especially remarkable in that they provide high-quality effluent that can be easily discharged to ambient environment or reused, making impressive contribution to non-rejection of water conservation. This is due to the ability of MBRs in producing high quality effluent that is suitable for reuse or disposal thus expanding the conservation of water significantly. MBRs are more efficient and compact than the conventional activated sludge methods of advanced wastewater treatment as they offer better permeate quality, operational ease, and reduce the space requirements [32].

Additionally, research concluded on laboratory scale MBRs show that regardless of the increased concentration and viscosity of sludge resulting from extended sludge retention durations (SRTs) and chemical oxygen demand (COD) removal efficiency also remains above 96% which indicates the scope of MBR as a green and sustainable wastewater treatment [33]. Past research, as highlighted by Lei *et al.,* (2018) [34] have pointed out that treating MBRs in parallel with conventional AD processes is efficient. This combined approach leverages the strengths of both systems: AD processes are quite useful in managing sludge by decomposing organic matter thus minimizing on volume and generating biogas as an energy source likewise, MBR enhances the effluent refining through eradication of residual pollutants. This synergy is not only useful in increasing the level of contaminant removal but also in the capability for water regain making it one of the most effective ways of wastewater treatment and water preservation.

Membrane technology has been expanded greatly in the said years especially with the concern on the innovations done on nanofiltration as well as reverse osmosis membranes. Wang *et al.,* (2024) [35] shows how these membranes can be used in MBR systems to produce even higher level of water quality in the treated water. Nanofiltration membranes are designed to filter out organic formulations, pesticide, and metals and reverse osmosis membranes operate at a pinnacle level of filtering where almost all of the contaminants are filtered out. The studies by Mahmoodi and Saffar-Dastgerdi (2019)[36] proved that highest contaminant removal was observed in sodalite zeolite nanoparticles (SZN) which enhanced the efficiency of pollutant removals in MBR system. Furthermore, issues related to non-functionalized membranes are solved through functionalization of these membranes with nanoparticles: for example, with Ag nanoparticles that increase the effectiveness of pathogen elimination, particularly regarding Gram-negative bacteria [37].

The use of these enhanced membranes for MBR systems signifies the future possibility of attaining the extreme form of wastewater recycling which is the ZLD in the sludge treatment strategies. Getting to this new production level for the sludge treatment processes is a significant step in reducing total discharge of liquids and increasing water recycling significantly. The implementation of the most developed MBR systems with exciting nanofiltration and reverse osmosis technologies presents a realistic way of attaining this end. Through proper addressing of the wastewater treatment, these systems do minimize the volume of waste as well as ensure the water that is released to the environment or recycled is of high quality. Therefore, the continuous deployment and adoption of these technologies show a positive outlook for wastewater management, which achieves both resource utilisation and environmental sustainability. Such problems include high costs and potential toxicity due to leaching of nanomaterials in which further research and development to tailor it for usage in everyday applications is needed [31].

In practice, membrane technologies are implemented at full scale in municipal and industrial wastewater treatment. In Singapore, large membrane bioreactor (MBR) facilities support high-quality effluent and water-reuse under the national NEWater programme [33, 35]. In Europe (e.g., Germany and the Netherlands), utilities have integrated (An)MBR with anaerobic digestion to improve effluent quality while supporting energy recovery [34, 35]. In China (e.g., Beijing and Shanghai), nanofiltration (NF) and reverse osmosis (RO) trains are operated to produce very high-quality permeate and, in some cases, to approach near-zero liquid discharge in metropolitan settings [30, 35]. Functionalised membranes with nanomaterial-enabled surfaces have also progressed to pilot and demonstration plants in South Korea and Japan, showing improved pathogen control and fouling resistance under operational conditions [29, 31, 37]. Collectively, these deployments indicate that membrane processes are no longer confined to laboratory studies and are increasingly adopted in real-world sludge and wastewater management [33–35]. Table 1 summarises the recent advancement and findings of sludge treatment technologies.

Table 1 Summary of recent advancement and findings of sludge treatment technologies

Technology	Key Advancements	Findings/Impact	References
Enhanced Anaerobic Digestion (AD)	Thermochemical pretreatment (hydrothermal, steam explosion, thermal hydrolysis)	Improves solubility of organic compounds, enhances biogas yield, and reduces sludge volume.	[16], [17], [18], [19]
	New microbial consortia (genetically engineered microbes)	Increases methane yield, improves reactor stability and robustness under varying environmental conditions, and boosts efficiency in biogas production.	[20], [21], [22], [23], [24], [25]
Thermochemical Pretreatment	Hydrothermal, steam explosion, and thermal hydrolysis methods	Increases methane production and enhances organic matter degradation, pathogen removal, and biosolid quality for fertilizer.	[16], [17], [18]
Microbial Engineering	Development of microbial consortia, including methanogenic archaea, *Methanoculleus*, *Methanothermobacter*, and *Syntrophomonas*	Enhanced biogas production and increased process robustness with improved understanding of microbial communities using metagenomics strategies.	[19], [21], [22], [23], [24]
Membrane Bioreactor (MBR) Systems	Combination of conventional AD with MBR technology	Higher quality effluent for safe disposal or reuse, improved water recovery, and resource conservation.	[29], [30], [31], [32]
	Nanofiltration and reverse osmosis membranes	Achieved near-zero liquid discharge (ZLD), removing contaminants like organic compounds, pesticides, and heavy metals.	[35], [36], [37]
	Functionalized membranes with nanoparticles (Ag, sodalite zeolite)	Enhanced pathogen removal, particularly Gram-negative bacteria, and improved pollutant removal efficiency.	[36], [37]
Challenges & Future Prospects	High operational costs and potential leaching of nanomaterials	Requires further research on cost reduction, scalability, and safety of nanomaterials.	[31], [37]
Overall Impact	Integration of AD and MBR technologies, enhanced microbial consortia, and advanced membranes are pivotal in improving sludge treatment efficiency and sustainability.	Substantial reduction in sludge volume, improved energy recovery, and higher quality effluent, advancing toward sustainable and environmentally friendly wastewater management practices.	[27], [28], [31], [35]

3.0 RESOURCES RECOVERY FROM SLUDGE

3.1 Phosphorus Recovery Technologies

Phosphorus is an essential nutrient for plant growth, making it a critical component of agricultural fertilizers [38]. However, the primary source of phosphorus, phosphate rock, is a non-renewable resource that is depleting at an alarming rate due to high demand and limited supplies. This situation has led to increased interest in sustainable methods of phosphorus recovery, particularly from wastewater sludge, which is rich in this nutrient. Recovering phosphorus from sludge not only addresses the issue of resource scarcity but also transforms waste into a valuable product, thereby contributing to a more sustainable and circular economy.

As seen in Figure 3, phosphorus recovery is typically carried out in four sequential steps: pre-treatment, enrichment, recovery, and post-treatment where the recovery process is a crucial part of phosphorus recovery technology [39].

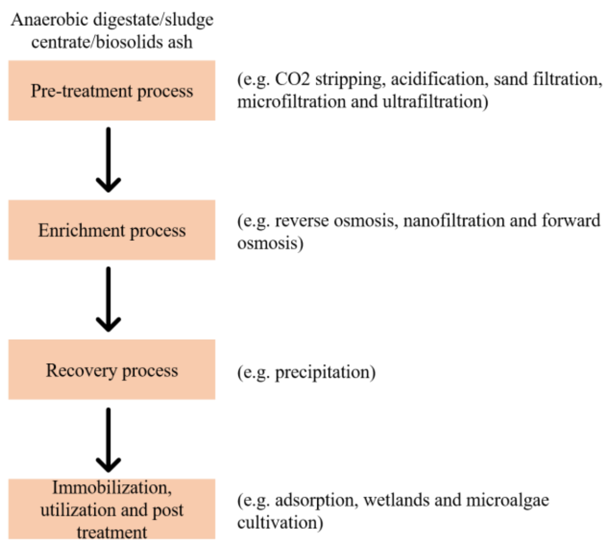


Figure 3 Schematic diagram showing major steps in phosphorus recovery [39]

Among the various methods explored for phosphorus recovery, advanced precipitation technique has shown considerable promise. This technique involves the chemical treatment of sludge to precipitate phosphorus in a form that can be easily recovered and used as a fertilizer. For instance, the addition of salts such as magnesium chloride ($MgCl_2$) can precipitate phosphorus in the form of struvite (magnesium ammonium phosphate), a highly effective and slow-releasing fertilizer. In fact, the majority of commercially available methods for recovering phosphorus from the liquid phase, which in this example, the anaerobic digestate, use chemical precipitation [40]. Di Capua et al., (2022) [41] points out that precipitation techniques are effective not only in the recovery of phosphorus but also in minimizing the negative effects of sludge disposal. This technique assists in minimization of the effects of eutrophication, decrease in dependence on the mined phosphate rock and decrease in environmental implications of applying sludge on the agricultural lands because of contaminants such as heavy metals and pathogens [42].

Another emerging technique of removing phosphorus is through ion exchange. This process employs use of either ion exchange resins or membranes for selective removal of phosphorus ions from the matrix sludge in a way that enables their concentration and recovery [43]. Ion exchange methods are so much desirable since they exhibit high selectivity, efficiency and flexibility for direct incorporation into existing wastewater treatment procedures. Despite these methods providing a method of recovering phosphorus in a more compact and pure manner than the previous methods, they provide a way of extracting phosphorus that is good for direct use in agriculture or even as a base for commercial fertilizer production. The ion exchange resins method described by Ding *et al.*, (2022) [44] can release the EPS-bound P, intracellular polyphosphate (Poly-P), and P-precipitate. Ding *et al*., (2022) also established the acidic cation exchange resin (ACER) extraction method in which efficiency of phosphorus release was increased by 13-23% along with the amount of metal in the liquid phase reduced a lot. This was made possible by ion exchange and acidification to capture the metal hence making the process effective. The mechanism of ACER extraction method to extract phosphorous in waste activated sludge (WAS) is depicted in Figure 4.

The process of recovering phosphorus from sludge and its conversion into a resource for agricultural applications benefits agricultural production and environmental sustainability. This strategy helps reduce the environmental problems related to sludge disposal and increases the security of phosphorus supplies for agriculture by converting waste into a useful ingredient for crop production. Furthermore, the use of recovered phosphorus as a fertilizer supports sustainable farming practices by providing a renewable source of this essential nutrient, thus reducing dependency on finite natural resources.

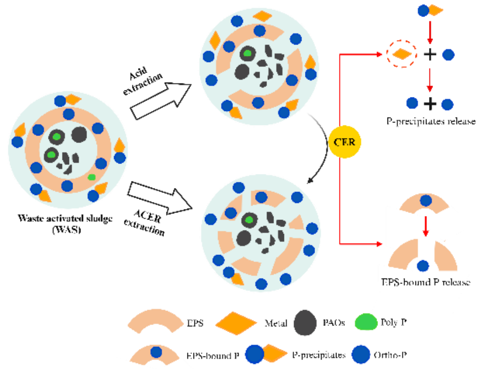


Figure 4 Mechanism diagram of the phosphorus release by ACER extraction [44]

This further exploration into the recovery of phosphorus from sludge emphasizes the development of innovative approaches aimed at addressing the issues concerning the depletion of resources and the management of waste. The sophisticated precipitation and ion exchange techniques had re-envisioned the waste as a valuable resource [42], [45]. Such advancement helps the proper management of natural resources as stated in this research that the waste by-products could help meet the challenges affecting agriculture around the world.

Although precipitation and ion exchange show strong technical performance, scale-up is often constrained by chemical inputs, regeneration needs, and plant-integration requirements. Chemical precipitation incurs ongoing reagent costs and downstream handling of the recovered product, while ion exchange requires resin inventory, regeneration, and eluant management, which adds to both capital and operating costs [39–41, 43–44]. Reviews indicate that viability improves at facilities with higher phosphate concentrations and when recovery is coupled with energy generation and/or nutrient reuse, creating revenue offsets and avoided disposal charges [39–41]. Experience in Europe shows that clear regulations, quality standards, and market access are key to making sludge projects feasible, with several municipal plants reporting positive results [39, 41]. Overall, progression from pilot to full-scale typically requires supportive policy, financing incentives, and close integration with existing wastewater infrastructure [40, 45].

3.2 Valorization into Bio-based Materials

Valorization of sludge into bio-based material is the process of transforming the sludge into valuable products. This perspective acknowledges the use of sludge in the generation of bio-based products or materials including biochar, bioplastic and other construction materials. Such a transformation also leads to the waste minimization and the use of renewable resources rather than non-renewable fossil-based materials in production, thereby supporting the principles of sustainable and circular economy.

One of the notable applications of sludge is its conversion to biochar through pyrolysis as illustrated in Figure 4. Pyrolysis is a process that involves the thermal decomposition of organic material under limited oxygen conditions [38]. In a fixed-bed reactor, this process yields biochar, gases, and bio-oil. Biochar rich in carbon (C), nitrogen (N), and potassium (K), works well as organic manure, while the gases and bio-oil can be utilized as fuel [46]. Additionally, flash pyrolysis in a conical spouted bed reactor, achieved high liquid yields of 77 wt.% dry ash-free at 500°C while lower temperatures such as 450°C improve the fuel properties [47]. Higher temperatures reduce volatile elements but increase stable aromatic carbon, ash, and concentrations of nutrients and poisonous elements like lead (Pb) and cadmium (Cd). These are the qualities that are affected by pyrolysis temperature. Elevated temperatures also help to stable metals, thereby reducing their toxicity [48].

The resulting biochar from pyrolysis process has been increasingly used for soil amendment, enhancing soil fertility and water retention, and for carbon sequestration, effectively capturing and storing carbon dioxide to mitigate climate change [49]. Zhao *et al.,* (2023) [50] highlight this process as a dual-benefit approach, addressing waste management challenges while contributing positively to environmental conservation efforts. Despite these advancements, problems such as the complex composition of sludge and high energy requirements still exist. To improve waste recycling, future study should strengthen pyrolysis mechanisms, optimize co-pyrolysis with different substances, and address industrial application challenges [51].

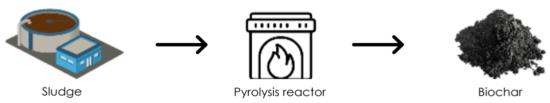


Figure 5 The process of converting sludge to biochar using pyrolysis method

Furthermore, the conversion of sludge into bioplastics presents a viable and sustainable alternative to conventional, fossil-based plastics. In microbial synthesis, certain bacteria are used to synthesize an organic compound in the sludge into polyhydroxyalkanoates (PHAs), which are biodegradable plastics with similar characteristics to ordinary plastics [52]. Figure 6 illustrated the process of PHA production from waste activated sludge.

As stated by Liu *et al.,* (2019) [28], this process has relatively less environmental degradation impacts compared to other methods including formation of poly (p-phenylene), polylactic acid (PLA), and formic acid diol ester (PTT), which are synthesized through chemical processes. More specifically, Zhang *et al.,* (2024) [53], explain that this novel idea helps remove sludge from landfills and eliminate the use of petrochemicals; thus, the benefits of biotechnology for the development of effective approaches to sustainable resource management can be called into question. PHA produced from activated sludge can be used in resource recovery and waste reduction thereby reducing the use of petroleum-based plastics. This does not only solve the problem of waste disposal but also provides environmentally friendly ideas to deal with the challenge of waste management. Table 2 highlights the benefits and challenges of technologies applied for resource recovery from sludge.

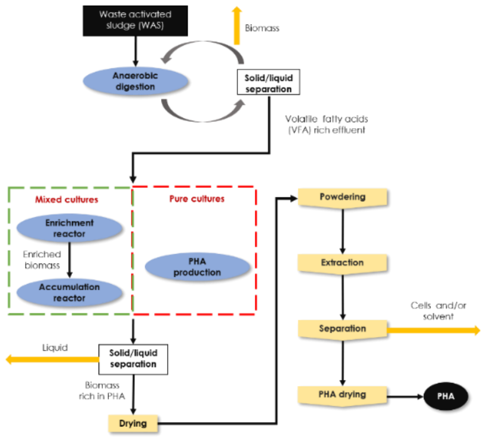


Figure 6 Production of PHA involving both the mixed culture and pure culture approaches for PHA accumulation and extraction [53]

Despite their promise, sludge-derived bioplastics such as polyhydroxyalkanoates (PHAs) face limitations that hinder large-scale adoption. Production is resource intensive, particularly microbial cultivation and solvent- or energy-intensive downstream recovery, resulting in costs that are approximately three to five times higher than conventional petroleum-based plastics [53]. Scaling from laboratory to industrial operation presents further challenges, including maintaining stable microbial performance, optimising nutrient conditions, and ensuring efficient downstream processing [52, 53]. The heterogeneity of sewage sludge also introduces variability in feedstock quality, affecting yields and polymer characteristics [52]. Although pilot-scale demonstrations in Europe and China have shown technical feasibility [28, 53], commercial deployment remains largely confined to niche markets due to high production costs and process-control constraints [53]. Addressing these challenges will require innovations in process optimisation, co-product strategies (e.g., coupling PHA recovery with energy or nutrient recovery), and supportive policies that incentivise adoption [52, 53].

Table 2 Overview of the benefits and challenges of technologies in phosphorus recovery and valorization into bio-based materials for resource recovery from sludge

Technology	Key Processes /Mechanisms	Main Findings	Benefits	Challenges	References
Phosphorus Recovery	Advanced Precipitation Technique - Chemical treatment with salts (e.g., MgCl2) to form struvite for fertilizer production	Efficient phosphorus recovery from sludge, transforms waste into fertilizer (struvite)	Reduces environmental impact (eutrophication), decreases reliance on mined phosphate rock	Potential environmental risks like heavy metals in sludge, high treatment costs	[38], [40], [41], [42]
	Ion Exchange - Use of ion exchange resins/membranes to selectively remove phosphorus ions	High selectivity and efficiency for phosphorus recovery, especially from extracellular polymeric substances (EPS)	Controlled phosphorus recovery, more pure for agriculture or fertilizer production	Complex setup for ion exchange systems	[43], [44]
Valorization into Bio-based Materials	Biochar Production via Pyrolysis - Thermal decomposition of sludge under limited oxygen conditions	Yields biochar, gases, and bio-oil, enhances soil fertility, water retention, and carbon sequestration	Reduces waste, promotes carbon capture, supports climate change mitigation	Complex sludge composition, high energy requirements for pyrolysis process	[46], [47], [49], [50]
	Bioplastics Production (PHAs) - Microbial synthesis of PHAs from organic matter in sludge	Produces biodegradable plastics, lowers reliance on fossil-based plastics	Sustainable, reduces sludge in landfills, decreases petrochemical use	High energy requirements, optimization of microbial synthesis needed for large-scale production	[28], [52], [53]

4.0 ENVIRONMENTAL IMPACT MITIGATION

4.1 Innovations in Sludge Stabilization and Pathogen Inactivation

Technological advancements over the years have seen a focus on improving the methods of handling sludge which is a nutrient dense material derived during wastewater treatment. This by-product however, also contains heavy metals and potential pathogen [54], [55]. The goal of these innovations is twofold: to immobilize heavy metals, thereby preventing their leaching into the environment, and to inactivate pathogens, ensuring the sludge is safe for disposal or use in applications such as soil amendment. These are important in reducing the environmental and health impacts that are occasioned by sludge disposal.

One of the major targeted strategies is to immobilize heavy metals within sludge which intends to positively impact the bioavailability of contaminants. This method reconditioned electroplating sludge (ES) with biochar (BC) and iron sulfide (FeS); hence, decreasing the leaching aspect of heavy metals, which includes chromium, copper, nickel, lead, and zinc illustrated in Figure 7 [56]. Some of the qualitative methods that have been recognised to be effective include use of lime or any other alkaline material [57], [58]. Through raising the sludge pH, these treatments cause the metals to dissolve in less soluble forms hence being trapped in the sludge matrix. Dhokpande *et al.*, (2024) [59], in their study, has explained the usefulness of such stabilization techniques in reducing the threat that comes with the presence of heavy metals showing how such techniques are useful in making sludge safe for management and utilization.

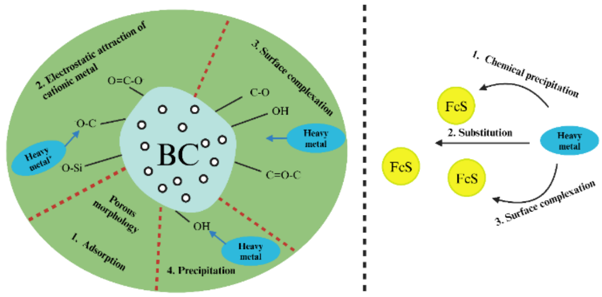


Figure 7 Mechanisms of heavy metals immobilization by biochar (BC) and iron sulfide (FeS) from electroplating sludge [56]

The use of alkaline materials in sludge stabilization can immobilize the heavy metals, improves the sludge stability and significantly reduces the odour. Among them, lime has been popularly adopted owing to its accessibility and relatively low cost. The process requires the determination of lime doses so that suitable pH is attained for the precipitation of the heavy metals to reduce their leachability and harm to the environment [60], [61].

Apart from the immobilization of heavy metals, much effort has been made toward the deactivation of pathogens in the sludge. Some of the new techniques which can be used include ultraviolet (UV) irradiation and ozonation. These techniques have the further advantage of being able to lower pathogen levels without adding further chemicals to the sludge so making the final product acceptable for many uses. Ghodeke *et al.,* (2021) [46] have pointed that these techniques serve well in the promotion of microbiological safety of the treated sludge. Ultraviolet irradiation uses the ability of UV light to alter the DNA structure of microbes and cause them to be non-viable and incapable of reproduction [62]. The benefits of this technique include the fact that the process can be completed rather rapidly and most of the chemical residue remains in the solution after filtration. In the same way, ozonation is the process of using the ozone gas, a very powerful oxidizing agent which is capable of inactivating the pathogens by oxidation mechanisms [63]. Both techniques have been acclaimed for their effectiveness in attaining a high level of disinfection which has helped much in the safety of sludge for disposal or for re-use. Besides, another study done on sludge treatment in South Korea showed that odor elimination of sludge dryers was significantly improved through the further improvement of adding UV light with nonthermal plasma (NTP) and including a scrubber in the sludge treatment process in additional to dust as well as ammonia odor elimination [64]. These odors from sludge are normally as a result of microbial actions. Tian *et al.,* (2015) [65], in another research described how the ultrasonication-ozonation (ULS-Ozone) pre-treatment impacted on sewage sludge anaerobic digestion; causing an increase in biogas production and reduce sludge retention time. Cosgun and Semerci (2019) [66] noted that sludge solubilization and nutrient release were maximum under low pH and when a microwave and ozone treatment was applied.

These innovations and adaptations in sludge technologies: the process of immobilizing heavy metals and inactivating pathogens, for the protection of the environment and public health are major achievements. These technologies help to solve major problems associated with sludge management by making the material less hazardous to the environment and facilitating more effective waste disposal. It is evident that constant fine tuning and implementation of these methods are essential in proper sludge management hence the importance of technology in enhancing environmental conservation and health safety.

4.2 Addressing Emerging Contaminants

The term emerging contaminants refers to the substances that are not commonly monitored but have the potential to pose risks to human health and the environment when present in water, soil, and other environmental media. These include pharmaceuticals (i.e. medicine, drugs), personal care products (i.e. shampoos, lotions, and cosmetics), and microplastics which can be persistent, bioactive and may elicit an adverse effect at very low concentrations. Currently, concerns have emerged on the presence of PPCPs, pharmaceuticals and Microplastics in wastewater treatment sludge resulting from enhanced detection rates. Most of these contaminants are persistent, bioactive and can affect aquatic life as well as human beings when not properly treated before disposal of sludge or application. Due to their large, chemically varied structures and broad range of physicochemical properties, their treatment is more difficult, and the practical applicability of standard methods requires the introduction of new, more effective, and specialized technologies to remove them efficiently.

One method that appears to be reliable to eliminate organic contaminants from sludge is activated carbon adsorption [67]. In this method, the particles get trapped in the surface area and porous nature of the activated carbon thus effectively removing contaminants from the sludge matrix. The strength of this method is based on the extremity that it can degrade a very broad spectrum of compounds with high concentrations and those that are not easily degradable by way of biological processes. By incorporating activated carbon treatment into sludge management processes, treatment facilities can significantly reduce the concentration of harmful contaminants, thus mitigating their potential environmental impact. However, the selectivity of traditional activated carbon for particular contaminants is low. To increase the selectivity and adsorption capacity, Allahkarami and Monfared (2024) [68] develop composites based-activated carbon, that can improve the performance and enable more accurate and efficient removal of contaminants during wastewater treatment by modifying variables such as pH, contact time, and temperature. On the other hand, research on adsorbents derived from biomass offers important insights to improve wastewater treatment costs and sustainability. The established effectiveness of activated carbon combined with strategically chosen, affordable biomass adsorbents can maximize wastewater treatment on a wide scale for improved environmental and financial outcomes [69]. Additionally, converting waste into sludge-based activated carbon (SBAC) provides a closed-loop method that transforms waste into a useful resource which further enhances the wastewater treatment's sustainability and efficacy, while also maximizing resource efficiency [70].

Advanced oxidation processes (AOPs) represent another innovative approach to contaminant removal, characterized by the generation of highly reactive species, such as hydroxyl radicals, capable of degrading complex organic molecules [71]. Techniques such as ozonation, photocatalysis, and Fenton's reaction fall under this category, offering the potential to break down even the most stubborn contaminants, including microplastics. However, due to the increased hydroxyl radical production, it was found that the combination use of ultrasonic (US), ultraviolet (UV), and hydrogen peroxide (H_2O_2) with TiO_2 nanoparticles was more successful than using AOPs alone [72]. AOPs also enhance sludge dewatering since it produces free radicals for sludge reduction and micropollutant removal that enhances sludge treatment, disposal, and environmental protection [73]. In general, AOPs are applauded for their effectiveness in converting toxic 'agents' into less toxic or degradable substances to improve the quality of the treated sludge.

Another method employed in the treatment of emerging contaminants is enzymatic treatment. This method uses specific enzymes to act as catalysts and break down contaminants into smaller molecules. This method is slightly different, more specific to certain pollutants as enzymes affect certain types of bonds within a molecular structure [74]. Pharmaceutical and personal care products are most suitable for enzymatic treatments since they are mostly chemically complex and hence challenging to be degraded through other means. The biocompatibility and specificity of enzymes also helps to reduce the formation of deleterious by-products, thus the process is environmentally friendly for sludge treatment [75-78].

The integrated use of activated carbon adsorption, advanced oxidation processes, and enzymes as treatments provide multipronged strategy to tackle the diverse sources of contamination in sludge. A study by Liu et al., (2022) [70], indicates the need to enhance the outcomes of these methods so that they may be efficient and less costly. Treatment processes have to be customized based on the characteristics of the sludge and the type of contaminants present in it in order to achieve a high level of removal and minimize pollution.

With the increasing need for better sludge treatment techniques, there is a need to develop these advanced methods to operational optimality, and handle issues pertaining to cost and pollution. Further, the utilization of synergistic treatment methods of various technologies could provide a better solution to the elimination of the more challenging pollutants. Clarifying possibilities to reclaim valuables contained in the sludge residual from the treatment step may support the enhancement of sludge management sustainability and profitability. Table 3 outlines the major technological advancements in sludge treatment, highlighting their benefits and challenges in mitigating environmental impacts.

Beyond contaminant-targeted treatments, several sludge processing routes also contribute to sustainable resource management through renewable energy recovery. One of the most important applications of sludge treatment is its role in renewable energy generation [12]. Anaerobic digestion produces biogas, a renewable source of methane that can be used for heat and electricity or upgraded to biomethane for vehicle fuel [14]. Thermal treatments such as pyrolysis and gasification can convert sludge into bio-oil, syngas and biochar, providing multiple energy vectors [46–48]. Additionally, co-incineration of sludge with municipal solid waste is increasingly adopted in Europe and East Asia, reducing landfill burden while recovering energy [11]. These renewable-energy applications position sludge not as a liability but as a resource that supports sustainable development and the circular economy.

Table 3 Key technological advancements along with its benefits and challenges for environmental impact mitigation in sludge treatment

Focus Area	Technological Approach	Main Findings	Benefits	Challenges	References
Heavy Metals Immobilization	Biochar (BC) and Iron Sulfide (FeS) Treatment	Reduced leachability of heavy metals (Cr, Cu, Ni, Pb, Zn) from electroplating sludge [56].	Reduces heavy metal contamination, supports environmental safety.	High material and process costs, requires optimization for various sludge types.	[56], [57], [59]
	Lime Treatment	Precipitation of heavy metals through pH elevation; immobilizes metals in sludge matrix [57], [58].	Low-cost, enhances sludge stability, reduces odor, and improves handling.	Requires careful dosing to ensure optimal pH and treatment efficiency.	[57], [58], [59]
Pathogen Inactivation	Ultraviolet (UV) Irradiation	Effective in pathogen reduction without leaving chemical residues; improves microbiological safety of sludge [62].	Fast, efficient disinfection method, no chemical residues.	High initial cost, requires regular maintenance for optimal performance.	[62], [63], [64]
	Ozonation & Ultraviolet (UV)/Non-Thermal Plasma (NTP)	Enhanced sludge drying and odor reduction; reduced dust and ammonia odors [64].	Significant odor and pathogen reduction, improved safety and usability of sludge.	Ozone generation requires careful control; potential formation of by-products.	[64], [65]
	Ultrasonication-Ozonation (ULS-Ozone)	Increased biogas output in anaerobic digestion, reduced sludge retention time [65].	Increases energy efficiency and resource recovery from sludge.	Energy-intensive process, may require combination with other techniques for full efficacy.	[65], [66]
Emerging Contaminants (Pharma-	Activated Carbon Adsorption	Efficient removal of pharmaceuticals and personal care	Effective in sequestering a wide range of	Low selectivity for specific contaminants,	[67], [68], [69]

Focus Area	Technological Approach	Main Findings	Benefits	Challenges	References
ceuticals, Personal Care Products)		products from sludge; customizable adsorption properties [67].	organic contaminants.	requires regeneration or replacement.	
	Advanced Oxidation Processes (AOPs)	Successful degradation of organic contaminants and microplastics via hydroxyl radicals, especially with TiO2 [72].	High efficiency in degrading persistent pollutants, improved sludge dewatering.	High energy consumption, potential secondary pollution from radical generation.	[71], [72], [73]
Sustainability and Resource Recovery	Sludge-Based Activated Carbon (SBAC)	Converting sludge into activated carbon improves both sludge management and contaminant removal [70].	Supports circular economy, reduces waste and increases sustainability.	Optimization needed to enhance cost-effectiveness and scalability.	[69], [70], [74]
Enzymatic Treatment	Targeted Enzyme Catalysis	Selective breakdown of pharmaceuticals, minimizes harmful by-products and ensures more complete degradation [74].	Environmentally friendly, highly specific to contaminants.	High operational costs, requires careful selection of enzymes for different contaminants.	[74], [75], [76]

5.0 REGULATORY FRAMEWORKS AND SUSTAINABILITY CONSIDERATIONS

Over the years, legal and regulatory frameworks for managing sewage sludge have evolved in recognition of increasing concern on environmentalism and health-wise. These frameworks are useful in establishing guidelines in handling sludge treatment, disposal as well as land application to ascertain that practices being adopted are safe, environmentally sound as well as sustainable. With such regulations in place, there is pressure to develop new technologies and methods of sludge handling and disposing that will enhance efficiency as well as reduced polluting impact on the environment, and so plays a role in guiding the industry towards better and cleaner ways of managing wastewater by-products.

A review of the currently existing laws, as pointed out by Braine *et al.,* (2024)[79], shows a progressive shift towards higher requirements for land utilization and disposal of sludge. These improved standards are meant to reduce potential environmental pollution and adverse health effects, issues regarding heavy metals, pathogens, and new challenges like pharmaceutical residues and microplastics. The increase in restrictions serves as a reminder of the need to advance in technological integration and come up with new ways of dealing with waste and recovering resources therefrom.

As a result of these regulations there has been a drive for innovation regarding sludge treatment technologies as well as the technologies used in the recovery of resources from the sludge. Some of the available technologies are advanced oxidation processes, membrane filtration and nutrient recovery systems in order to meet and even surpass existing regulatory requirements. These new technologies not only focus on the optimization of the sludge treatment process but also strive toward the utilization of sludge as economic resources for the generation of energy, as soil fertilizers, or as a source of materials.

Sustainability assessments using cost and benefit analysis, life cycle analysis, and other tools should be employed to evaluate environmental and economic viability of sludge treatment options. As highlighted by Patel *et al.,* (2022) [80], these assessments provide an integrated evaluation of the effects of sludge management measures from the life cycle perspective and assist stakeholders to make decisions concerning the sludge management practices taking into account both the advantages in terms of environmental conservation and the costs. Such measurements help balance the regulatory compliance with conditions reflecting the sustainability by encompassing an overall footprint, which makes the choice of treatment and disposal options more suited to reach sustainability objectives.

The interaction between the legal requirements, advanced technology solutions, and sustainability evaluations is vital to the development of sludge management. Regulations act as an important factor that requires innovation because by establishing standards that the treatment technologies must achieve or surpass. Consequently, sustainability assessment provides the method for reviewing the efficiency and sustainability of these innovations and recognizing the compliance of the sludge management practices with the existing legal requirements and principles of sustainable development.

From the future perspective it is possible to state that the changes of the regulatory environments will have the further impact on the development of sludge management practices. The stakeholders such as policymakers, researchers and industrial practitioners should ensure that the regulations are up to date for current environmental issues and scientific discoveries. At the same time, continuous capital investments need to be made for maintaining and enhancing the research and development that is required to develop the new treatment and resource recovery technologies to meet such standards. As sludge management enters a new era of regulatory rigor and innovation, sustainability assessments will remain indispensable in navigating the path towards environmentally sound and economically viable solutions [81].

6.0 CHALLENGES IN SLUDGE MANAGEMENT

Sludge, a byproduct of wastewater treatment, presents some challenges in environmental management. While rich in nutrients beneficial for agriculture, its complex composition and emerging contaminants require careful handling. Balancing economic considerations with sustainable practices is crucial in its effective management and disposal.

Sludge is a complex blend of organic carbon compounds, phosphorous, nitrogen-containing compounds, toxic pollutants (heavy metals, polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs)), pathogens, and inorganic compounds [82]. Although sludge is a valuable renewable source of nutrients, advancements in technology and analytical methods have led to the identification of new contaminants in sludge, disrupting environmental equilibrium. For instance, the pharmaceuticals and personal care products are increasingly overshadowed by households, with concentrations ranging from a few mg/kg to g/kg. Also, various contaminants and heavy metals present in sewage sludge restrict its use in agriculture due to the elevated levels of antibiotics associated with antibiotic-resistant bacteria. Moreover, the traditional sludge treatment processes, such as anaerobic digestion, composting, and thermal carbonization, do not guarantee contaminant-free, high-quality end products [83].

The economic dimensions of sludge management in wastewater treatment have garnered increasing attention due to the substantial costs involved and the critical role of efficient resource utilization in sustainable development. For instance, in the sludge treatment, cost constitutes a large proportion of the total cost, which could be over fifty percent. In contrast to the small proportion of the volume of sludge in the treated wastewater, it may take up to half of the overall operating costs because of the complexities associated with the management, treatment and disposal of this substance [84]. This aspect has further been compounded by a ban on traditional type of recycling practices, including direct use of residues in agriculture and other forms of land use, which has vitalized the need for more efficient and cost effective methods of recycling in order to obtain the highest percentage of useful material and energy recovery possible in sustainable manner [85]. Based on the current options for sludge recovery and disposal, Ferrentino *et al.,* (2023) [86], mentioned that central expenditures per disposal of sewage sludge in Europe varies between EUR 160 to 310 per ton of dry sludge but differs from one country to another. Thus, sludge disposal accounts for about 20 - 65 per cent of the total operating cost of different wastewater treatment plants. Hence the issues of management and disposal of the sewage sludge has attracted more attention from the environmental as well as the business communities, motivating scientist to engage in research that would come up with technologies as well as solution that would reduce the output of the sludge by say a significant proportion.

Given the substantial share of total operating costs attributed to sludge handling and disposal, targeted funding and incentives are pivotal to de-risk the adoption of innovative technologies. To advance innovation in sludge management, funding mechanisms should be leveraged at both national and international levels. At the national scale, Malaysia provides competitive research grants such as the Fundamental Research Grant Scheme (FRGS) and the Long-Term Research Grant Scheme (LRGS) under the Ministry of Higher Education (MOHE). In addition, the Malaysian Green Technology and Climate Change Corporation (MGTC) under the Ministry of Natural Resources, Environment and Climate Change (NRECC) offers green financing and fiscal incentives to industries adopting sustainable technologies. Internationally, competitive research programs and capacity-building grants such as Horizon Europe, UN SDG–aligned initiatives, and the Global Environment Facility (GEF) support sustainable waste and resource management. Furthermore, multilateral development finance from the World Bank and the Asian Development Bank (ADB) has enabled large-scale wastewater and sludge projects in developing regions. Aligning sludge-management projects with these schemes can reduce financial barriers, attract industrial participation, and accelerate the transition of laboratory-scale innovations to industrial-scale applications in line with circular-economy objectives.

Understanding public perception of sludge management is important for formulating policies and making decisions. This comprises working with the communities, delivering the educational sessions, and ensuring necessary interaction. One significant issue that has been encountered in many countries is the observed reluctance to adopt more sludge, which is mainly attributed to perceived dangers affecting health and the environment. According to Ekane *et al.,* (2021) [87], public acceptability of sewage sludge is generally poor due to uncertainties of its composition, where it may have components such as microplastics, per- and poly-fluoroalkyl substances (PFAS), and its potential effects. Along these, there is skepticism regarding the application of sewage sludge on crops and this results in avoidance of the practice particularly on food crops. This may be due to perceived risks, lack of knowledge about regulations, lack of trust in quality standards, safety and possible negative impact on a company's image.

Several countries have successfully implemented sludge-management policies that not only improve technical efficiency but also enhance public confidence [79]. For instance, the European Union Sewage Sludge Directive (86/278/EEC) sets strict limit values for heavy metals and microbiological safety, which has increased acceptance of land application in agriculture [82]. In Japan, national recycling policies promote the conversion of sludge into building materials and fertilisers, with high recycling rates reported in several municipalities. In the United States, the EPA Part 503 Rule regulates biosolids land application and treatment classes, ensuring that treated sludge meets safety standards and supporting agricultural reuse. Closer to Malaysia, Singapore's advanced water-recycling (NEWater) and sludge-to-energy initiatives show how robust treatment and sustained public education can foster confidence in resource recovery. These examples highlight that transparent regulations, rigorous quality standards, and effective public communication are essential to improve the perception and acceptability of sludge-management practices [87].

In conclusion, sludge management is a complex task that is associated with environmental, economic and social issues. Although sludge contains useful nutrients, emerging contaminants along with the changing perception of the public prevents its application. The high costs of treatment underscore the need for proper strategies which are sustainable. Therefore, any solutions must focus on the principles of transparency, enhancement of knowledge in society, and continuous research on the effects of the substances on the people and the environment. Such challenges point to the need to develop and implement efficient and sustainable strategies of managing sewage sludge to minimize adverse effects on the environment, control costs and enhance safety.

7.0 FUTURE PERSPECTIVES

The prospects of sludge management in wastewater treatment are quite promising. It is also predicted that future research will be directed towards improving the methods of processing and recovering the solid resources; the enhancement of energy efficiency; as well as the reduction of the negative effects on the environment when handling sludge. The adoption of alternative technologies and their interaction with other processes will most probably determine how this sector will develop in the future. In this context, the constant change and development of concepts concerning sludge management, as well as the identification of targeted prospects toward sustainability in wastewater treatment, is vital.

At present, there is a legal period of sludge land application on steady increase, backed by good research work, improved sludges, and effective public awareness. This increasing tendency is expected to progress as more studies establish the efficiency of using sludge as an organic manure. It gets more and more important to recover these minerals from sludge as the demand for phosphorus and nitrogen grows [88]. Such an approach is in compliance with circular economy principles and can contribute to the reduction of the need for additional supplies. Sludge management techniques are also beginning to emphasize energy recovery from sludge. The need for employing sewage sludge as an agricultural fertilizer is growing due to calls for sustainable development and rising chemical fertilizer costs [89]. However, in order to prevent any negative effects on the soil environment and public health, it is imperative that the qualities of sewage sludge be carefully evaluated before applying it. A viable technique for lowering sludge's moisture content and keeping its organic matter content high is deep dewatering of sludge with chemical conditioning reagents, which is advantageous for composting treatment [90].

When it comes to producing renewable energy and managing waste sustainably, Anaerobic digestion (AD) technology is undeniably having a lot of potential to address pressing environmental and sustainability issues as mentioned in section 2.1. Although AD of sewage sludge is a common approach for biogas and digestate production, the digestate quality is deteriorated by heavy metals in sewage sludge, which calls for an initial plasma pyrolysis treatment. This method uses less acreage and produces useful syngas, hydrogen, and char while lowering the volume of sewage sludge. Despite being expensive and energy-intensive, the syngas, hydrogen, and char produced make it cost-effective. Rich in vital nutrients, char can be added to AD or used as an organic fertilizer. The most effective way to make sludge treatment more sustainable and cost efficient is to incorporate it with other waste management or industrial processes. This is supported by Giwa *et al.,* (2023) [91], the integration of both AD and plasma pyrolysis is a sustainable long-term solution to deal with sewage sludge and open up possibilities of utilization of byproducts and new applications.

8.0 CONCLUSION AND FUTURE DIRECTIONS

The landscape of sludge research is marked by rapid advancements and emerging challenges. It is suggested that future studies should focus on the design and implementation of comprehensive treatment systems that are effective, environmentally friendly, and cost effective. The exploration of new and innovative ways of recovering resources from sludge together with progress in the treatment technologies will be vital in managing the complex issues involved in sludge handling. Academic institutions, industries and government regulatory agencies need to work hand in hand to foster innovation and proper management of sludge.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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