Issue No. 2 · 2026
ADVANCED STUDIES
IN ARCHITECTURE AND CIVIL ENGINEERING
(ASACE)

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

UDC 628.31
Review article

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MODERN APPROACHES TO THE TREATMENT AND UTILIZATION OF WASTEWATER SLUDGE FROM LIGHT INDUSTRY ENTERPRISES: A REVIEW

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ABSTRACT

Introduction. Industrial wastewater generated by light industry enterprises contains a considerable amount of suspended solids, organic contaminants, surfactants, dyes, and toxic compounds that contribute to the formation of large volumes of sludge during wastewater treatment processes. The management, dewatering, stabilization, and disposal of sludge remain major environmental and economic challenges for wastewater treatment facilities. This review summarizes recent advances in sludge treatment and utilization technologies applied to industrial wastewater treatment systems, with particular emphasis on sludge generated from textile and light industry enterprises. **Materials and Methods.** Conventional sludge treatment methods, including mechanical dewatering, coagulation, flocculation, filtration, and thermal conditioning, are discussed together with modern sustainable approaches such as microwave-assisted oxidation, electro-dewatering, advanced oxidation processes, and environmentally friendly flocculants. The role of extracellular polymeric substances (EPS) and bound water in limiting sludge dewaterability is also analyzed. **Results and Discussion.** Recent international studies demonstrate that optimization of conditioning methods can reduce sludge moisture content by 20-60%, decrease filtration resistance, and improve sludge stabilization efficiency. In addition, resource recovery strategies including composting, biochar production, and sludge reuse in construction materials are reviewed. **Conclusions.** The analysis indicates that integrated treatment technologies combining chemical, thermal, and biological approaches provide the highest efficiency for sludge reduction and reuse. Future research directions should focus on energy-efficient treatment systems, circular economy principles, and environmentally sustainable sludge management.

KEYWORDS: industrial wastewater; sludge treatment; sludge dewatering; activated sludge; textile industry; wastewater treatment; sludge utilization; sustainable technologies; EPS; resource recovery.

FOR CITATION:

Taubaldy M.S., Niyetbay S.E. Modern approaches to the treatment and utilization of wastewater sludge from light industry enterprises: a review. Advanced Studies in Architecture and Civil Engineering. 2026; 1 (2): 54-65.

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(ASACE)
ISSN 3134-8475 (Print)
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1 INTRODUCTION

Industrial wastewater generated by textile and light industry enterprises contains significant concentrations of suspended solids, dyes, surfactants, heavy metals, and organic contaminants that contribute to the formation of large amounts of sludge during treatment processes. According to He et al. [1], activated sludge generated during industrial wastewater treatment contains complex organic and inorganic contaminants that negatively affect sludge dewatering performance. Recent studies by Yang et al. [2] demonstrated that extracellular polymeric substances and internal bound water significantly limit sludge dewatering efficiency in activated sludge systems. Xia et al. [3] further investigated heavy metal distribution in dewatered activated sludge and emphasized the environmental risks associated with sludge disposal and reuse. Similar findings were reported by Demir and Pakdil [4], who analyzed electro-dewatering processes and demonstrated that sludge treatment technologies strongly influence volatile contaminant migration and sludge stabilization efficiency.

Sludge management remains one of the most expensive stages of wastewater treatment plant operation, accounting for up to 50–60% of total operational costs. Rahmani et al. [5] reported that sludge treatment and conditioning processes require considerable operational and energy expenditures, particularly for high-moisture industrial sludge systems. AbuSeif et al. [6] also demonstrated that optimization of sludge conditioning strategies can substantially reduce operational costs while improving sludge dewatering efficiency.

The rapid development of industrial production and urbanization has significantly increased the generation of industrial wastewater and sludge worldwide. Enterprises of the textile and light industries consume large quantities of water during dyeing, washing, bleaching, and finishing processes, resulting in wastewater containing suspended solids, dyes, surfactants, heavy metals, and organic contaminants. During biological and physicochemical wastewater treatment, significant amounts of sludge are produced as a byproduct.

In practical wastewater treatment operation, sludge management remains one of the most complicated stages because large sludge volumes require additional treatment, transportation, conditioning, and disposal processes. Leskokalayeh and Pirouzi [7] emphasized that conventional sludge treatment methods often require high chemical consumption and additional operational costs. Rumky et al. [8] reviewed recent electrochemical sludge dewatering technologies and concluded that conventional mechanical treatment methods are frequently insufficient for efficient bound water removal. Pirouzi et al. [9] further noted that sludge morphology, extracellular polymeric substances, and filtration resistance strongly influence sludge dewatering efficiency. In addition, Hatamifar and Gholikandi [10] demonstrated that combined bentonite and poly aluminum chloride systems significantly improve sludge thickening and dewatering performance.

Recent international studies have increasingly focused on advanced sludge conditioning technologies, sustainable treatment approaches, and resource recovery systems. Zhang et al. [11] investigated environmentally friendly sludge conditioning materials based on modified chitosan and coconut shell composites and reported improved sludge dewatering performance. Sun et al. [12] emphasized the environmental importance of sludge reduction technologies for minimizing greenhouse gas emissions and improving wastewater treatment sustainability. Hämäläinen et al. [13] investigated hydrothermal carbonization technologies and demonstrated their potential for simultaneous energy and nutrient recovery from sewage sludge. Wang et al. [14] reported that carbon source recovery from waste sludge can significantly reduce greenhouse gas emissions in industrial wastewater treatment plants.

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ISSN 3134-8475 (Print)
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Kadri et al. [15] demonstrated that sludge morphology strongly affects the energy demand of centrifugal dewatering systems, while Sodhi et al. [16] investigated activated sludge characteristics and their influence on sludge minimization and nitrogen removal efficiency in industrial wastewater treatment systems.

Despite significant progress in sludge treatment technologies, many industrial wastewater treatment systems still experience insufficient dewatering efficiency, high operational costs, and environmental limitations associated with sludge disposal. Furthermore, the applicability of advanced sludge conditioning technologies for wastewater treatment systems of textile and light industry enterprises remains insufficiently summarized in recent review studies.

The aim of this review is to evaluate modern sludge treatment and utilization approaches reported in recent international studies and to analyze their applicability for wastewater treatment systems of textile and light industry enterprises.

2 METHODS AND MATERIALS

This review was conducted based on the analysis of recent international scientific publications related to sludge treatment, sludge dewatering, and resource recovery technologies applied in industrial wastewater treatment systems of textile and light industry enterprises. Scientific articles indexed in ScienceDirect, Scopus, Web of Science, Google Scholar, and eLibrary databases and published between 2020 and 2026 were selected in order to ensure the relevance and scientific reliability of the reviewed information.

The literature selection focused on studies investigating conventional sludge treatment technologies, advanced sludge conditioning methods, and sustainable sludge utilization approaches. Particular attention was given to studies related to activated sludge dewatering, extracellular polymeric substances (EPS), bound water removal, filtration resistance reduction, and environmentally sustainable treatment technologies.

The reviewed studies included investigations of centrifugation, filter press dewatering, belt press systems, microwave-assisted sludge conditioning, electro-dewatering, thermally activated oxidation processes, alkaline conditioning, and environmentally friendly flocculants. The selected technologies were comparatively evaluated according to sludge moisture reduction, dewatering efficiency, filtration performance, energy demand, chemical consumption, environmental sustainability, and resource recovery potential.

Comparative analysis of recent international studies was performed using the operational and technological indicators reported in the selected articles. Conventional sludge treatment methods were compared with advanced sludge conditioning technologies in order to evaluate their practical applicability, operational limitations, and environmental performance for wastewater treatment systems of textile and light industry enterprises.

Particular emphasis was placed on modern sustainable sludge treatment approaches, including microwave-assisted conditioning and electrochemical sludge dewatering technologies, due to their high sludge dewatering efficiency and resource recovery potential. Microwave-assisted conditioning technologies were analyzed as advanced methods for enhancing bound water release and extracellular polymeric substance destruction during sludge treatment processes.

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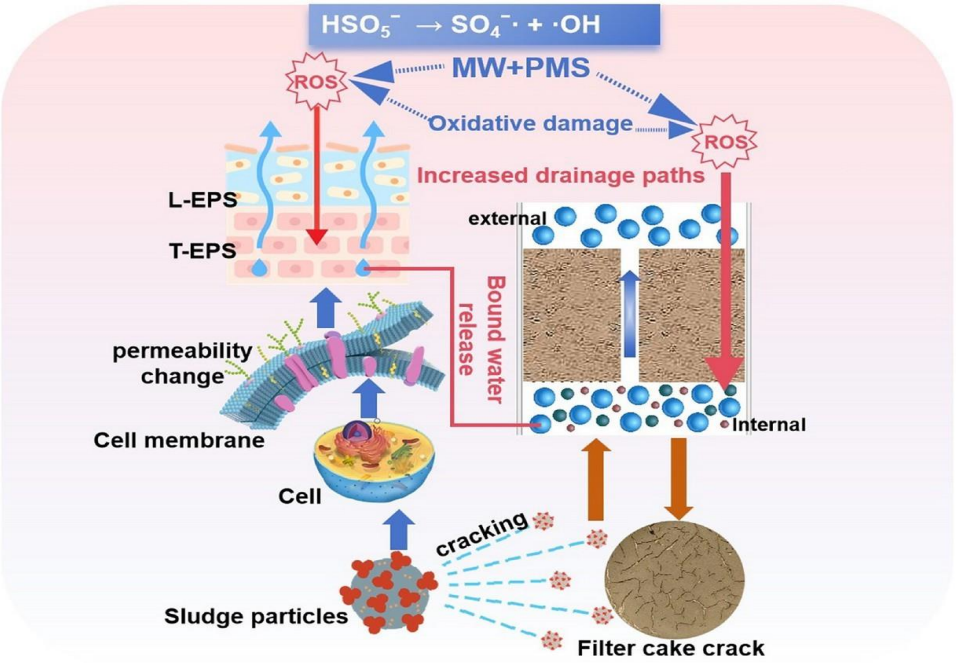


Fig. 1. The proposed mechanism of MW coupled PMS activation on enhancing sludge dewatering reproduced from Yang CX, Dong KY, Chen KY, et al. [2]. (Original figure used: Fig. 7)

Electrochemical sludge treatment technologies were comparatively evaluated according to moisture reduction efficiency, sludge filtration performance, energy demand, and operational sustainability. The reviewed studies demonstrated that electrochemical treatment processes improve water migration, reduce sludge volume, and enhance sludge stabilization efficiency compared to several conventional dewatering methods.

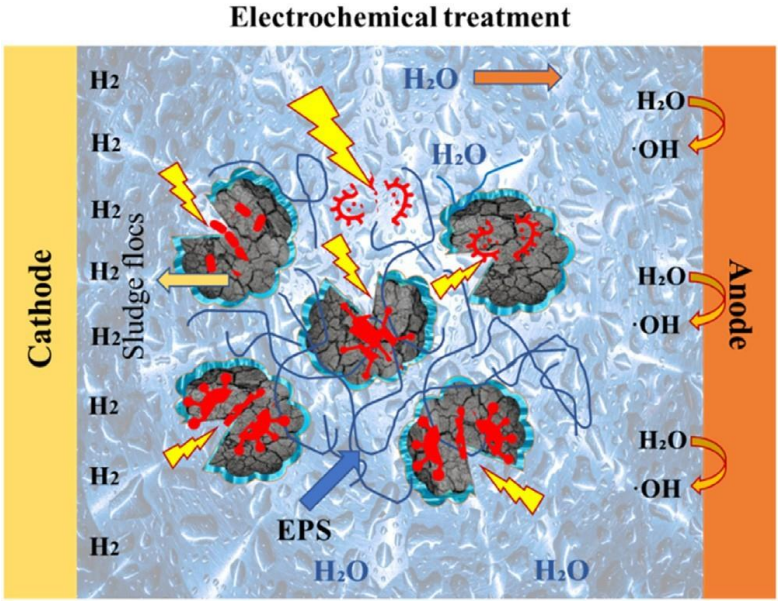


Fig. 2. Electro-chemical treatment for treating sludge materials reproduced from Rumky J, Deb A,

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ISSN 3134-8483 (Online)

Shim MJ, et al. [8]. (Original figure used: Fig. 5)

The obtained analytical results were further interpreted from the perspectives of environmental sustainability, sludge volume reduction, energy efficiency, and circular economy principles.

3 RESULTS AND DISCUSSION

Characteristics of Sludge Generated from Industrial Wastewater

Sludge generated during treatment of industrial wastewater from textile and light industry enterprises contains organic pollutants, suspended solids, dyes, surfactants, oils, heavy metals, microorganisms, and chemical additives.

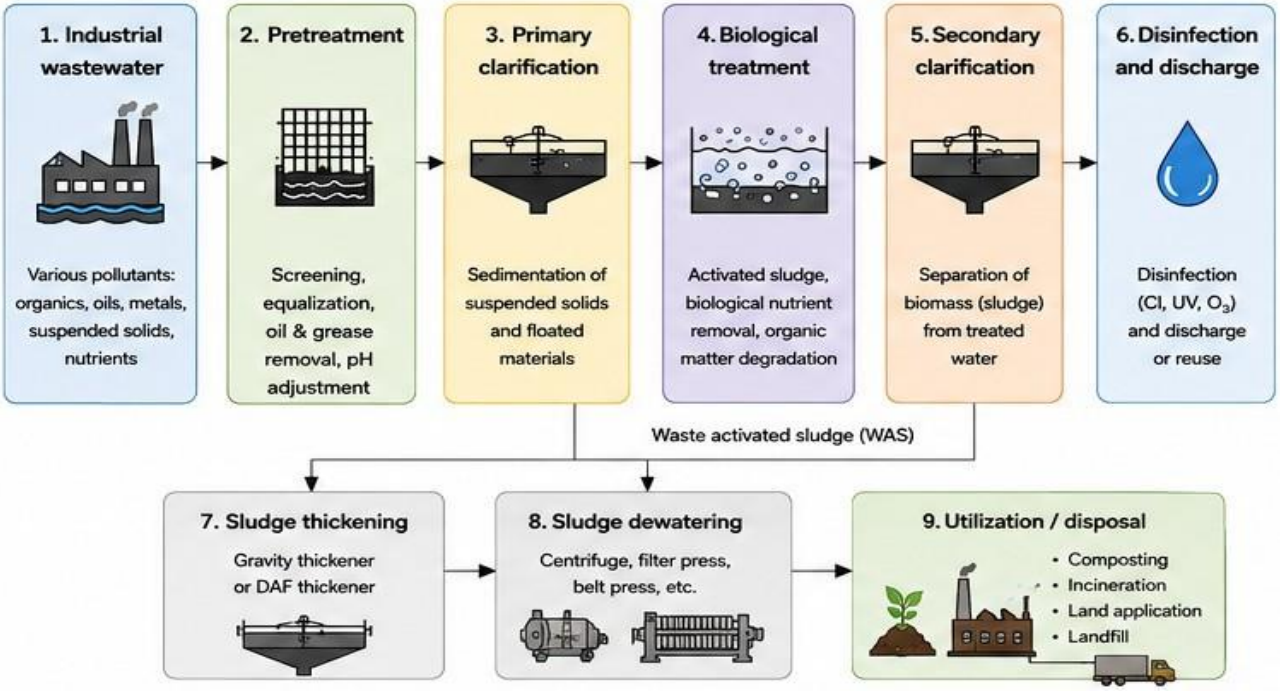


Fig.3. Conventional stages of industrial wastewater treatment and sludge managemen

The composition and properties of sludge depend on wastewater characteristics, treatment technology, and operating conditions.

A major problem in sludge treatment is the extremely high moisture content of raw activated sludge, which may reach 95–99% depending on wastewater characteristics and treatment conditions.

Water contained within sludge exists in several forms, including free water, interstitial water, surface water, and bound water. Bound water is strongly associated with extracellular polymeric substances and microbial cells, making deep dewatering difficult.

Many researchers consider extracellular polymeric substances (EPS) to be one of the main factors limiting sludge dewatering efficiency.

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ISSN 3134-8475 (Print)
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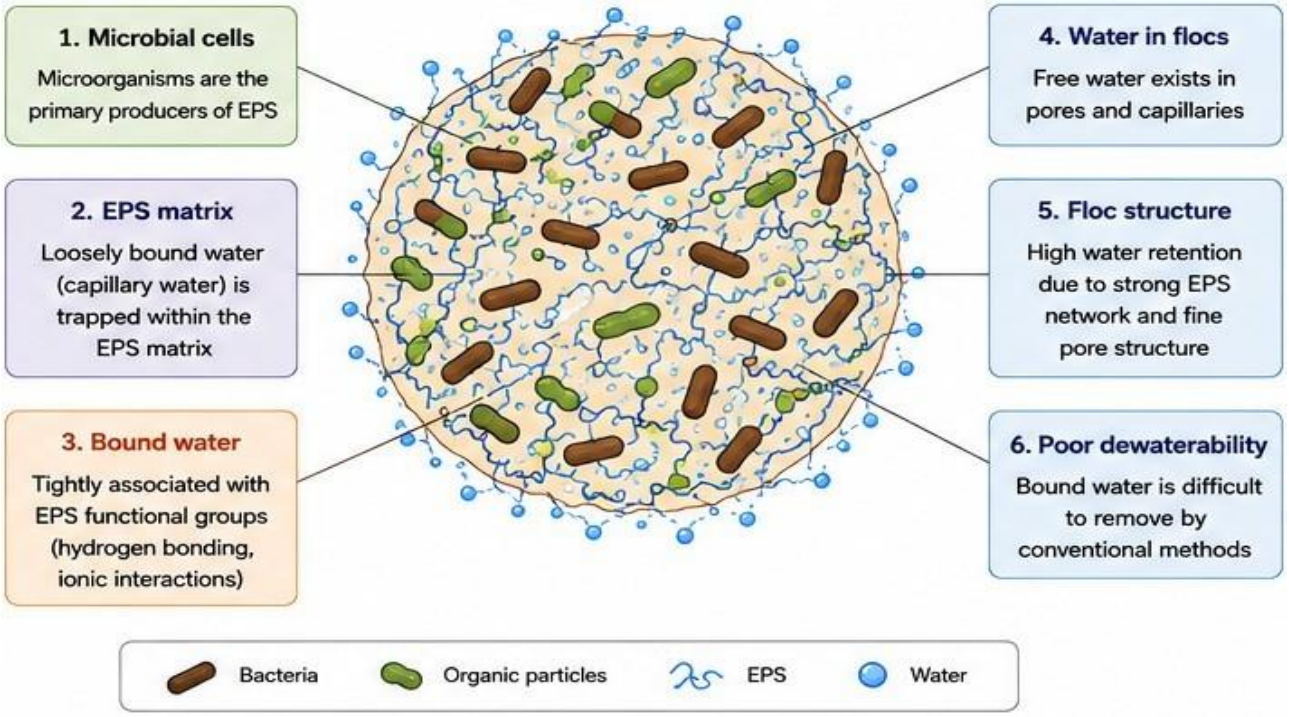


Fig. 4. Mechanisms of EPS formation and bound water retention in sludge flocs

EPS contain proteins, polysaccharides, lipids, and humic substances that form a stable hydrophilic matrix around sludge flocs. This matrix retains large amounts of water and increases filtration resistance.

Recent studies demonstrate that destruction or modification of EPS structure significantly improves sludge dewatering efficiency.

Conventional Sludge Treatment and Dewatering Methods

Recent review studies emphasize that sludge dewatering efficiency strongly depends on sludge physicochemical characteristics, moisture distribution, extracellular polymeric substances (EPS), particle morphology, and operational conditions. Mechanical dewatering technologies remain the most widely applied approaches because of their operational simplicity and scalability. However, the removal of bound water remains a major challenge in sludge treatment systems.

Recent engineering analyses demonstrated that sludge morphology significantly affects energy requirements during centrifugation and filtration processes. Activated sludge with different floc structures and particle characteristics requires different operating conditions and energy consumption levels to achieve similar dewatering efficiencies.

Traditional sludge treatment methods include:

- gravity thickening;
- flotation;
- centrifugation;
- filter press dewatering;
- vacuum filtration;
- coagulation and flocculation;
- thermal conditioning.

Mechanical sludge dewatering methods are still widely used in industrial practice because they are relatively simple to operate and economically accessible for many treatment plants. However, mechanical treatment alone often cannot reduce sludge moisture content below 75–80% due to the presence of bound water.

Chemical conditioning using coagulants and flocculants is one of the most common methods for improving sludge dewaterability. Ferric chloride (FeCl3), aluminum sulfate, polyaluminum chloride, and cationic polyacrylamide (CPAM) are among the most frequently used reagents.

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ISSN 3134-8475 (Print)
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Recent studies indicate that low-dose CPAM conditioning can reduce sludge cake moisture from more than 80% to approximately 22-30% under optimized conditions. Furthermore, combined coagulation and acidification methods improve floc formation and release bound water from sludge flocs.

Table 1. Conventional sludge dewatering technologies

Technology	Advantages	Disadvantages
Centrifugation	Fast operation	High energy consumption
Filter press	High dewatering efficiency	Maintenance costs
Vacuum filtration	Continuous operation	Limited efficiency
Chemical coagulation	Improved floc formation	Chemical consumption
Thermal conditioning	Enhanced moisture removal	Energy-intensive

The comparative analysis presented in Figure 5 demonstrates that advanced sludge conditioning technologies, particularly microwave conditioning and electro-dewatering, provide significantly higher sludge dewatering efficiency compared to conventional mechanical treatment methods. The obtained results indicate that advanced treatment approaches improve bound water removal and enhance sludge stabilization performance, making them promising alternatives for sustainable industrial wastewater sludge management.

Advanced Sludge Conditioning Technologies

Recent international review studies indicate that advanced sludge conditioning technologies are increasingly focused on improving dewatering efficiency while simultaneously reducing operational costs, greenhouse gas emissions, and environmental impacts.

The transition from conventional sludge disposal toward sustainable sludge management and resource recovery systems has become one of the main directions in wastewater engineering.

Electrochemical and electro-dewatering technologies have recently attracted considerable scientific attention because they combine moisture reduction, sludge volume minimization, and resource recovery in a single process. These technologies facilitate the removal of free and bound water through electric field-driven migration and EPS disruption, significantly improving sludge filtration characteristics.

Advanced Oxidation Processes

Advanced oxidation technologies are currently regarded as promising methods for improving sludge conditioning and enhancing dewatering performance. These processes generate highly reactive radicals capable of degrading extracellular polymeric substances and destroying sludge floc structures.

Thermally activated persulfate systems have recently demonstrated high efficiency for industrial sludge dewatering. Under optimized conditions, specific resistance to filtration reduction above 70% has been reported. Sulfate radicals and hydroxyl radicals contribute synergistically to EPS destruction and bound water release.

Microwave-assisted oxidation technologies have also shown promising results. Coupling microwave irradiation with peroxymonosulfate activation significantly enhances internal bound water removal and reduces sludge moisture content.

Electro-dewatering

Electro-dewatering technologies have recently gained attention because they improve sludge filtration performance while reducing sludge volume and transportation

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requirements. Application of electric fields accelerates water migration and improves sludge filtration characteristics. In addition to moisture reduction, electro-dewatering contributes to partial removal of volatile contaminants and improves sludge stabilization.

Environmentally Friendly Flocculants

Recent international studies emphasize the development of environmentally friendly coagulants and natural flocculants. Chitosan, natural polymers, and combined organic-inorganic coagulants reduce chemical consumption and improve sludge dewaterability.

Combined ferric chloride and natural polymer systems have demonstrated moisture removal efficiencies exceeding 85% under optimized conditions.

Recent studies also investigated innovative sludge conditioning materials such as bentonite-poly aluminum chloride (PAC) systems and environmentally friendly natural composites. Bentonite and PAC combinations demonstrated filtration time reductions of up to 90% and specific resistance to filtration reductions exceeding 70%, indicating strong potential for practical wastewater sludge treatment applications.

Sustainable natural polymer-based conditioners have also shown promising performance. Coconut shell-based composite materials coupled with modified chitosan significantly improved sludge dewatering rates while simultaneously reducing organic contaminants in sludge filtrate.

Table 3. Modern sludge conditioning technologies

Technology	Main mechanism	Reported efficiency
Thermally activated persulfate	EPS oxidation	SRF reduction >70%
Microwave-assisted oxidation	Bound water release	Moisture reduction to 64–70%
Electro-dewatering	Electric field water migration	Improved filtration efficiency
Natural flocculants	Charge neutralization	Reduced chemical demand
DES-based conditioning	EPS disruption	CST reduction up to 69%

Sludge Utilization and Resource Recovery

Modern sludge management concepts are increasingly based on circular economy principles, carbon neutrality, and resource recovery.

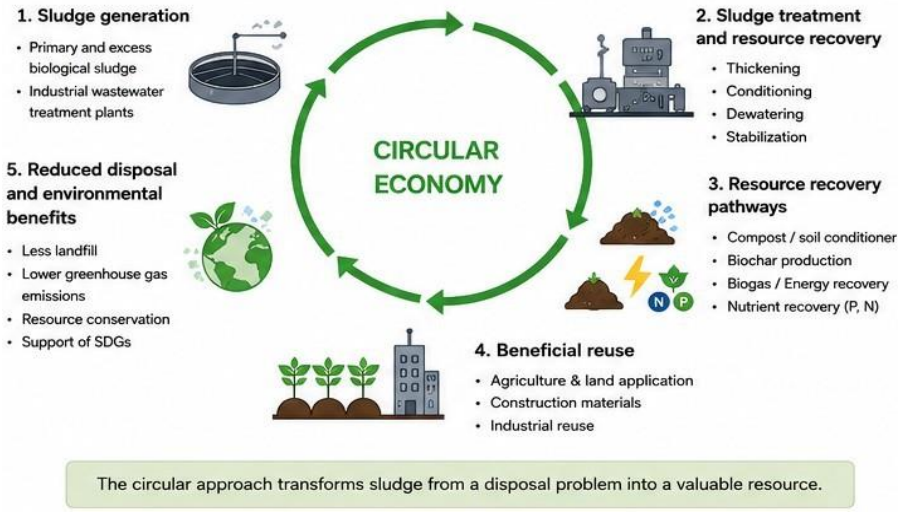


Fig. 6. Sludge management in a circular economy framework

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ISSN 3134-8475 (Print)
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Instead of considering sludge solely as waste, recent studies evaluate sludge as a valuable source of carbon, nutrients, energy, and reusable materials.

Hydrothermal carbonization technologies have recently attracted considerable interest because they enable simultaneous energy and nutrient recovery from dewatered sludge. Hydrothermal treatment converts sludge into hydrochar while preserving a large proportion of phosphorus and carbon resources. Recent investigations reported that hydrochar retained up to 92% of phosphorus and 87% of the original energy content from sewage sludge digestates.

Pilot-scale studies on industrial wastewater treatment systems further demonstrated that carbon source recovery from waste sludge can substantially reduce greenhouse gas emissions and external carbon consumption. Recovery and reuse of sludge-derived carbon sources reduced indirect greenhouse gas emissions by more than 8% while simultaneously lowering sludge generation.

Environmental sustainability of sludge treatment systems has become increasingly important due to growing concerns regarding greenhouse gas emissions and climate change. Carbon footprint analyses demonstrated that optimized sludge reduction technologies can reduce greenhouse gas emissions by 12–17% compared to conventional activated sludge systems.

Current sludge management strategies are no longer focused only on disposal. Modern approaches increasingly aim to recover energy, nutrients, and reusable materials from sludge. Instead of direct disposal, sludge can be reused after stabilization and dewatering.

Potential sludge utilization pathways include:

- compost production;
- agricultural soil amendment;
- biochar production;
- production of construction materials;
- energy recovery;
- anaerobic digestion.

Biocomposting technologies are widely applied for sludge stabilization and volume reduction. During composting, organic matter decomposition and pathogen reduction occur simultaneously. Recent engineering solutions propose combined sludge composting with plant waste and food waste additives.

Thermal treatment and pyrolysis technologies are also gaining attention because they produce biochar and reduce sludge volume significantly.

Table 4. Sludge utilization approaches

Utilization method	Advantages	Limitations
Composting	Nutrient recovery	Odor generation
Biochar production	Carbon recovery	High temperature required
Construction materials	Waste reuse	Heavy metal limitations
Anaerobic digestion	Biogas production	Process complexity
Agricultural application	Soil improvement	Contaminant control needed

Challenges and Future Perspectives

Despite significant progress in sludge treatment technologies, several challenges remain:

- high energy consumption;
- large chemical demand;
- management of heavy metals;
- sludge disposal costs;
- greenhouse gas emissions;
- environmental safety concerns.

Based on the reviewed studies, future sludge treatment systems should combine:

- sustainable conditioning technologies;

ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

- energy-efficient processes;
- low-cost reagents;
- advanced oxidation methods;
- resource recovery strategies.

The reviewed studies suggest that integrated treatment systems combining chemical, thermal, and biological methods may provide the highest sludge treatment efficiency while reducing environmental impact and operational costs.

4 CONCLUSION

Sludge generated during treatment of industrial wastewater from textile and light industry enterprises represents a major environmental and engineering challenge because of its high moisture content, complex composition, and significant disposal costs.

Analysis of recent international studies demonstrates that conventional mechanical dewatering methods alone are insufficient for achieving deep sludge dewatering due to the strong retention of bound water within extracellular polymeric substances.

The analyzed studies demonstrate that modern conditioning technologies can significantly improve sludge dewatering and stabilization efficiency. Advanced oxidation systems, including thermally activated persulfate and microwave-assisted oxidation, can reduce filtration resistance by more than 70% and decrease sludge moisture content to approximately 65-70%. Chemical conditioning using optimized flocculants and coagulants also substantially enhances sludge dewaterability while reducing energy consumption.

Recent studies further indicate that integrated sludge treatment systems combining chemical, thermal, and biological approaches provide the highest overall performance. Resource recovery technologies such as composting, biochar production, and sludge reuse in construction materials support circular economy principles and reduce environmental impacts.

Future investigations should primarily focus on low-energy and environmentally safe sludge treatment technologies capable of reducing sludge generation, minimizing greenhouse gas emissions, and improving resource recovery efficiency.

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ISSN 3134-8475 (Print)
ISSN 3134-8483 (Online)

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used [tool name, version] solely for language editing and grammar checking. The authors reviewed and edited the output and take full responsibility for the scientific content, analyses, interpretations and conclusions of the article.

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AUTHORS CONTRIBUTION

Taubaldy M. S. – literature review; analysis of international scientific publications; article writing; preparation of tables and figures; systematization of sludge treatment technologies; manuscript editing.
Niyetbay S. E. – scientific supervision; research concept development; methodology improvement; scientific consulting; review and editing of the manuscript; final approval of the article..

The article was submitted 15 April 2026; approved after reviewing 30 April 2026; accepted for publication 10 May 2026.