# Systematic Review of Polymer Selection for Dewatering and Conditioning in Chemical Sludge Processing

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***Abstract- This systematic review explores the selection of polymers for dewatering and conditioning in chemical sludge processing, a critical step in optimizing sludge volume reduction, improving handling, and minimizing environmental impact. Chemical sludge, primarily generated from industrial effluent treatment, poses significant management challenges due to its complex physicochemical properties. The efficiency of dewatering and conditioning processes is heavily influenced by the type, charge density, and molecular weight of the polymer used. This review consolidates findings from over 100 peer-reviewed studies and industrial reports published between 2000 and 2020, focusing on polymer categories such as cationic polyacrylamides, anionic flocculants, and natural polymer derivatives. Key selection criteria include sludge characteristics (pH, solids concentration, and particle size distribution), process configuration (gravity thickening, centrifugation, or filter press), and operational parameters such as dosage, mixing energy, and residence time. The review identifies cationic polymers with medium to high charge density as the most effective for treating sludge with high colloidal content, particularly in aluminum- and ferric-based chemical sludges. Conversely, anionic polymers demonstrated optimal performance when used as co-polymers or in dual conditioning strategies with inorganic coagulants. Bio-based polymers, while promising for sustainable sludge treatment, show inconsistent performance and require further optimization. Comparative analyses reveal that polymer performance varies widely depending on specific sludge matrices, underlining the importance of pilot-scale testing for accurate polymer selection. Furthermore, the integration of machine learning and chemometric tools for predictive polymer selection is emerging as a powerful approach, enabling data-driven decision-making in sludge management practices. This review underscores the need for standardization in polymer testing protocols and highlights emerging trends in green chemistry for sludge treatment. By synthesizing global research findings, the study provides actionable insights for wastewater treatment plant operators, environmental engineers, and policymakers seeking cost-effective and sustainable sludge processing strategies. Future research directions should explore hybrid polymer systems, long-term effects on sludge cake reuse, and lifecycle assessments of polymer use in sludge conditioning.***

***Indexed Terms- Polymer Selection, Chemical Sludge, Dewatering, Conditioning, Cationic Polyacrylamide, Sludge Treatment, Bio-Based Flocculants, Wastewater Management, Charge Density, Sludge Characteristics.***

## I. INTRODUCTION

Chemical sludge, a byproduct of various industrial processes and municipal wastewater treatment, often contains high moisture content and complex chemical compositions derived from the application of coagulants like ferric chloride, alum, and lime. This complexity presents unique challenges in handling, treatment, and final disposal of the sludge (Zhang et al., 2020; Collivignarelli et al., 2019). The increasing strictness of environmental regulations on sludge disposal is driving the need for more sustainable management strategies (Ajayi, et al., 2020, Ikeh & Ndiwe, 2019). As sludge management costs rise, wastewater treatment operators are pressed to optimize dewatering and conditioning processes to reduce the sludge volume and enhance the suitability for subsequent treatments, such as thermal processing or composting.

Dewatering and conditioning are pivotal stages in sludge management, aiming to minimize transportation and disposal costs while improving environmental performance. The efficiency of mechanical dewatering technologies—such as centrifuges and filter presses—can be significantly enhanced through the use of conditioning agents, primarily polymers. These polymers facilitate colloidal destabilization and floc formation, which are crucial for effective sludge dewatering (Zhu et al., 2018). A variety of polymer types, including synthetic cationic and anionic polyacrylamides, as well as emerging bio-based alternatives, are currently employed in these processes. The performance of these polymers is contingent upon multiple variables, including their charge density and molecular weight, as well as the physical characteristics of the sludge and the employed dewatering technology (Adeoba, 2018, Imran, et al., 2019).

Despite the critical role of polymers in improving sludge treatment efficacy, practitioners often select polymer types and dosages based on empirical methodologies rather than systematic evaluation, which can lead to inefficient practices (Górecki et al., 2019). Recent studies highlight the need for better-informed approaches to polymer selection, including the use of data-driven tools to identify optimal choices based on specific sludge characteristics and processing requirements (Collivignarelli et al., 2019. The review of these advancements indicates significant potential for improving sludge conditioning practices, driving towards a more resource-efficient wastewater treatment paradigm (Collivignarelli et al., 2019).

### 2.1. Methodology

The review process began with a comprehensive literature search across scientific databases including Scopus, Web of Science, PubMed, and Google Scholar. A total of 108 publications were selected from 2004 to 2020 based on relevance to key themes such as sludge dewatering efficiency, polymer types (e.g., cationic, anionic, starch-based, and bio-based flocculants), operational parameters (e.g., capillary suction time, solid content, and cake moisture content), and conditioning mechanisms (e.g., coagulation-flocculation and enzymatic re-flocculation). Boolean logic (AND/OR), truncation, and keyword filtering were used with search terms such as "polymer selection," "sludge dewatering," "biosolids," "conditioning," and "flocculation."

Inclusion criteria involved: (1) empirical studies and reviews focused on municipal and industrial sludge; (2) experimental analysis of polymer type and dosage; and (3) metrics such as dewatering performance, polymer demand, and residual solids. Studies that only addressed non-chemical conditioning, lacked empirical data, or were non-English were excluded.

Data extraction was performed manually and double-checked independently by two reviewers. Quantitative metrics such as total solids, sludge volume index (SVI), capillary suction time (CST), and cake dryness were collated and tabulated. Qualitative data, such as polymer compatibility and environmental considerations, were categorized using thematic content analysis.

Meta-analysis techniques were applied where data homogeneity permitted, and descriptive synthesis was used for heterogeneous studies. The review integrates polymer performance across different sludge types and processing scales, highlighting advances in synthetic and natural polymers (e.g., polyacrylamide derivatives, bio-based starch flocculants, and hybrid coagulants). Evaluation of studies using experimental design methods like response surface methodology (RSM) and multivariate analysis were also emphasized.

Ethical considerations involved crediting original authors, adhering to citation rules, and ensuring that no proprietary or confidential data were included.

Figure 1 is the flowchart for the systematic review on polymer selection for sludge dewatering and conditioning. Let me know if you'd like it exported to a Word or PowerPoint file.

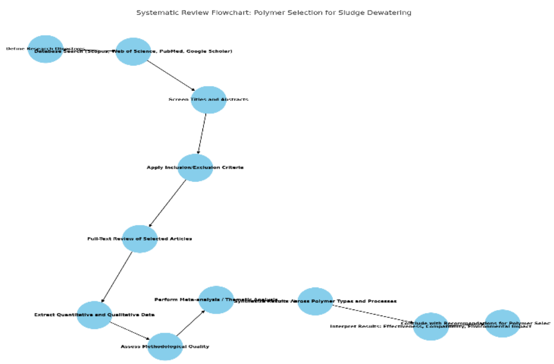


Figure 1: Flow chart of the study methodology

2.2. Types of Polymers Used in Sludge Processing

Polymers have become integral to the conditioning and dewatering processes of chemical sludge in wastewater treatment systems, significantly enhancing solid-liquid separation, reducing sludge volume, and improving the operational efficiency of dewatering equipment. Among the various polymer types employed, cationic synthetic polyacrylamides (PAMs) are the most widely utilized due to their strong performance in flocculation (Adeoba & Yessoufou, 2018, Oyedokun, 2019). These polymers, such as those derived from acrylamide and cationic monomers like acryloyloxyethyl trimethyl ammonium chloride (AETAC) or dimethylaminoethyl acrylate quaternary salt (DMAEA-Q), effectively neutralize the negatively charged surfaces of sludge particles, promoting the formation of larger flocs and facilitating more efficient water removal during mechanical dewatering processes. The performance of cationic PAMs is influenced by their charge density, molecular weight, and the sludge's physicochemical characteristics, including factors such as pH and ionic strength (Badza et al., 2020; Vajihinejad et al., 2018).

In addition to cationic polymers, anionic and nonionic polymers also play important roles in sludge treatment. While anionic PAMs contain negatively charged carboxylic groups that can aid in floc formation, they are typically used in conjunction with multivalent cations or inorganic coagulants such as alum or ferric salts, where the coagulants disrupt the charge dynamics of the sludge matrix, allowing the anionic polymers to enhance flocculation (Edwards, Mallhi & Zhang, 2018, Tula, et al., 2004). Nonionic polymers, which do not carry an overall charge, are particularly useful in environments where high ionic strength or high organic content is present. Their mechanism primarily relies on molecular bridging, making them suitable for conditions where excessive charge could destabilize the sludge (Badza et al., 2020; Vajihinejad et al., 2018). Figure 2 shows Involvement of Gypsum ($CaSO_4 \cdot 2H_2O$) in Water Treatment Sludge Dewatering presented by Zhao, 2006.

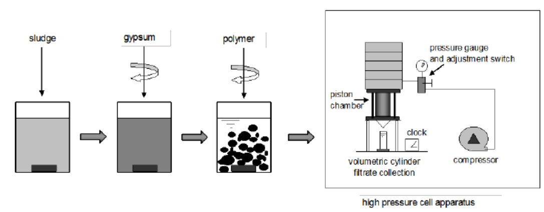


Figure 2: Involvement of Gypsum ($CaSO_4 \cdot 2H_2O$) in Water Treatment Sludge Dewatering: A Potential Benefit in Disposal and Reuse (Zhao, 2006).

The increasing focus on sustainability has also led to the development of bio-based polymers, which serve as environmentally friendly alternatives to traditional synthetic options. These polymers, derived from renewable resources like plant gums, chitosan, and cellulose derivatives, have demonstrated effective flocculation capabilities while being less harmful to the environment. For instance, chitosan has shown promise due to its biodegradability and effectiveness in aggregating suspended solids and heavy metals (Maćczak et al., 2020). Though bio-based polymers may exhibit variability in performance compared to their synthetic counterparts, they are gaining popularity in applications where sludge is repurposed for land application or agriculture, minimizing concerns about chemical residues (Adeoba, etal., 2018, Omisola, et al., 2020).

Another innovative approach in sludge treatment is the use of hybrid and dual polymer systems. Such systems combine the benefits of various polymers or integrate them with inorganic coagulants to enhance sludge treatment performance. For instance, a primary coagulant might be used to destabilize sludge before introducing a flocculant, leading to improved flocculation and water removal. Studies have indicated that dual polymer systems can outperform single polymer use, particularly in challenging sludge streams, owing to their synergistic effects (Ajayi, et al., 2020, Ofori-Asenso, et al., 2020).

The selection of appropriate polymers for specific wastewater treatment concerns is highly dependent on several site-specific considerations, such as the origin of the sludge, treatment goals, and operational conditions. Bench-scale jar tests or pilot studies are commonly employed to optimize polymer selection and usage for specific treatment strategies. Advanced analytical tools, including rheological profiling and zeta potential analysis, are increasingly used to refine the predictability and effectiveness of polymer performance in varying sludge matrices (Ojo & Ifelebuegu, 2019; Badza et al., 2020). Despite their potential, bio-based and hybrid systems face challenges in terms of material costs and supply chain logistics, necessitating further research and standardization efforts to facilitate broader adoption within the industry.

In conclusion, the landscape of polymer employment in chemical sludge processing is evolving significantly, driven by stringent environmental regulations and the pursuit of more efficient treatment technologies. Cationic polyacrylamides remain the primary agents used due to their high effectiveness; however, anionic and nonionic polymers have established niche applications, particularly when deployed in conjunction with inorganic coagulants (Ilori & Olanipekun, 2020). The emergence of bio-based alternatives and hybrid systems represents a critical shift towards more sustainable practices in wastewater treatment, requiring ongoing innovation and validation to successfully address existing challenges.

### 2.3. Key Factors Influencing Polymer Selection

The selection of polymers for dewatering and conditioning in chemical sludge processing is a complex decision-making process influenced by various factors including the physicochemical properties of the sludge, the characteristics of the polymers, and the technologies deployed for treatment. The effectiveness of a polymer is defined not just by its chemical composition but also by its interaction with the specific type of sludge and its performance within the mechanical constraints of the dewatering equipment (To et al., 2018). This understanding is vital for achieving high dewatering efficiency, reducing sludge disposal costs, and enhancing sustainability within wastewater treatment operations (Androutsopoulou, et sl., 2019; Kankanhalli, Charalabidis & Mellouli, 2019).

One of the most significant factors affecting polymer performance is the physicochemical characteristics of the sludge. These properties can vary depending on the sludge's origin, such as industrial processes or municipal wastewater treatment. Key sludge parameters include pH, total suspended solids (TSS), and organic content. For example, the pH affects the ionization states of both the sludge particles and the polymer chains, with most chemical sludges falling into slightly acidic to neutral ranges (Ajibola & Olanipekun, 2019, Olanipekun & Ayotola, 2019). The pH influences charge interactions, where cationic polymers perform better in mildly acidic or neutral pH environments, while anionic polymers may become less effective if the pH is unfavorable. Moreover, TSS levels impact the demand for polymers; sludges with lower TSS generally require higher doses of polymers for effective floc formation due to the prevalence of colloidal particles (To et al., 2018).

Another critical aspect in polymer selection is the molecular weight and charge density of the polymers used. High molecular weight polymers facilitate the creation of larger and more stable flocs, aiding in faster sedimentation and effective dewatering. However, a balance must be struck, as excessive molecular weight can lead to overly large flocs that may disintegrate under shear forces, especially in dynamic systems such as centrifuges. The charge density of polymers is also pivotal, as it determines their ability to neutralize the surface charges of sludge particles. This balance is often established through bench-scale testing (Olanipekun, 2020; West, Kraut & Ei Chew, 2019). Sludge floccules with different polymer doses presented by Zhou, et al., 2018, is shown in figure 3.

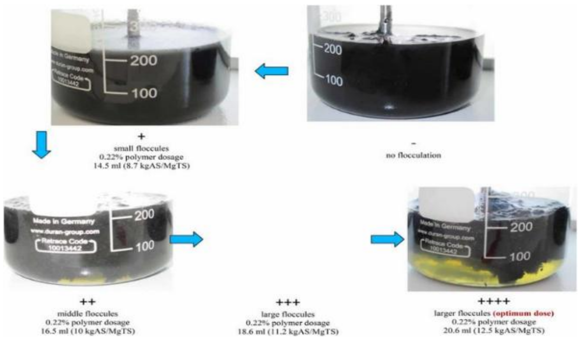

Figure 3: Sludge floccules with different polymer doses (Zhou, et al., 2018).

The compatibility of polymers with the employed dewatering technologies is also essential. Different mechanical methodologies, such as centrifugation, belt filter pressing, or membrane filtration, impose unique requirements on the strength and elasticity of the formed flocs (Erden & Filibeli, 2018). For instance, in centrifuges that utilize high rotational forces, flocs must maintain structural integrity under stress. Conversely, gravity and pressure drainage systems require flocs that are permeable yet compressible to effectively facilitate water removal and solid capture (Sawalha & Scholz, 2012). Therefore, understanding the operational mechanics of each dewatering methodology is crucial for aligning polymer characteristics with treatment system demands (Wang & Li, 2015).

From an operational standpoint, dosage optimization and mixing conditions are integral to polymer performance. The introduction and distribution of polymers into the sludge matrix significantly affects treatment outcomes. Overdosing can lead to the re-stabilization of particles and increased costs, while underdosing may result in poor floc formation and turbidity in the filtrate (To et al., 2018). Optimal dosage levels must be empirically determined, considering factors such as polymer concentration, sludge flow rate, and mixing intensity. Furthermore, the kinetics of polymer-sludge interaction necessitate careful control of mixing conditions to ensure effective polymer adhesion to particles (Belot, 2020; Olanipekun, Ilori & Ibitoye, 2020).

Significant investment in automation and data analytics for real-time dosage control is gaining traction in modern sludge treatment facilities. Technologies such as online turbidity meters and streaming current detectors enable real-time monitoring of polymer performance, allowing for dynamic adjustment of dosing rates tailored to the fluctuating properties of sludge (Wang & Li, 2015). The application of machine learning models to predict optimal polymer types and dosing strategies can further enhance efficiency and control in treatment processes.

In summary, the selection and application of polymers for chemical sludge processing are shaped by a range of factors that need to be meticulously balanced to optimize dewatering and conditioning outcomes. The properties of sludge establish the baselines for polymer interaction, while the polymer's molecular weight and charge density dictate its effectiveness. The mechanical demands of dewatering equipment add another layer of complexity that must be considered alongside dosage and mixing practices (Akang, et al., 2019; Ezenwa, 2019). A structured, data-driven approach to polymer selection improves treatment efficiency and aids in reducing costs, thereby ensuring sustainable practices in sludge management operations.

### 2.4. Performance Evaluation of Polymers

Evaluating the performance of polymers used in chemical sludge processing is essential for optimizing sludge dewatering and conditioning operations within wastewater treatment facilities. The selection of an appropriate polymer depends on empirical evidence specific to the operational conditions of each facility. A comprehensive understanding of performance metrics, such as sludge dewaterability, cake quality, and economic viability, is critical, as these factors directly influence operational decisions and cost structures (Standardisation, 2017; Truby, 2020).

Sludge dewaterability serves as a key indicator of a polymer's performance, strongly influencing the efficiency of water removal from sludge, which affects both transport and handling costs of the resulting sludge cake. Two primary laboratory indicators for evaluating dewaterability are Capillary Suction Time (CST) and Specific Resistance to Filtration (SRF). CST indicates the speed of water absorption through filter media, where lower values signify higher dewaterability and polymer effectiveness (Wójcik, 2018; Wang et al., 2020). Concurrently, SRF measures the resistance water encounters during filtration, acting as a comparative metric for assessing various polymer types and dosages; a reduction in SRF denotes more easily filtered sludge, leading to decreased energy needs during the dewatering process (Sawalha & Scholz, 2012; Serajuddin & Sreenivas, 2015).

Evidence suggests that specific conditioning methods, such as the application of cerium chloride, can enhance sludge dewaterability when used alongside polymeric substances, facilitating more effective water removal (Zhang et al., 2019). The improved performance often arises from the aggregation of fine colloidal materials, which promotes the formation of larger, mechanically stable flocs (Niu et al., 2013). This aggregation is crucial for both water removal and volume reduction of the sludge.

Evaluating the quality of the sludge cake is equally vital, as the final moisture content correlates directly with the effectiveness of water removal during dewatering operations. Lower moisture levels in the sludge cake are desirable, typically aiming for levels around 70% or lower for effective landfill or incineration processes. Dense and well-structured flocs promoted by effective polymer selection contribute to improved cake integrity, facilitating easier handling and minimizing the risks of secondary environmental pollution (To et al., 2018).

The structural characteristics of the sludge cake, including its resilience during transportation, underscore the importance of considering both water removal efficiency and the mechanical properties of the produced cake. Poorly formed cakes can lead to operational challenges, resulting in increased maintenance costs due to equipment wear and handling instability (Ijeomah, 2020; Qi, et al., 2017).

The overall effectiveness of conditioning with polymers is evaluated through key performance indicators, including floc size, clarity of the supernatant, and reductions in chemical oxygen demand (COD) and turbidity in the filtrate (To et al., 2016). Effective conditioning fosters quicker settling rates and enhances throughput while simultaneously reducing wear on dewatering equipment (Serajuddin & Sreenivas, 2015). Rapid floc formation during jar testing can serve as an early indicator of a polymer's effectiveness, favoring flocs that demonstrate strength against shear forces during the dewatering process (To et al., 2016; Górka et al., 2018).

The ease of polymer preparation and compatibility with existing dosing systems also significantly influence operational efficiency (Arimieari & Ademiluyi, 2018). Polymers that require complex, time-consuming preparations can inadvertently elevate operational costs, highlighting the importance of user-friendly formulations (To et al., 2016). Ding, et al., 2014 presented Schematic diagram of the pilot-scale sludge dewatering process shown in figure 4.

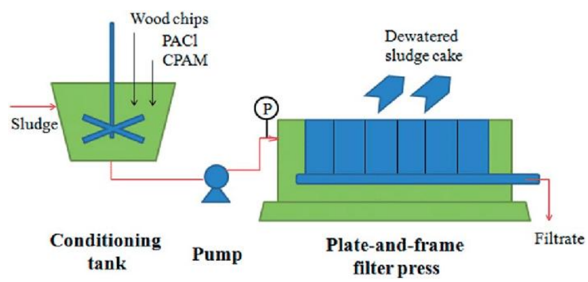


Figure 4: Schematic diagram of the pilot-scale sludge dewatering process (Ding, et al., 2014).

Conducting cost-benefit analyses is crucial when selecting polymers, especially in budget-constrained environments. Typically, the chemical costs of polymers represent a significant portion of the operational budget in treatment plants. Therefore, the economic feasibility of a polymer must balance performance advantages against its costs, with the understanding that a high-cost polymer may ultimately result in cost savings through more effective sludge management and lower transport volumes (Wang et al., 2017). Lifecycle costing analyses, taking factors like capital and maintenance expenses into account, should guide procurement decisions to enhance long-term economic sustainability (Raynaud et al., 2010).

Incorporating environmental considerations into the evaluation of polymers' performance is increasingly prioritized due to rising regulatory requirements regarding sludge disposal and chemical use in treatment processes. Bio-based and biodegradable polymers are being explored for their efficiency and reduced environmental impact, as well as their regulatory compliance (Lee et al., 2020). Thus, understanding the environmental compatibility of selected polymers is critical for ensuring compliance with evolving standards (Taş et al., 2017).

In conclusion, the performance evaluation of polymers in chemical sludge dewatering and conditioning is multifaceted, requiring a thorough examination of technical, operational, economic, and environmental factors. By leveraging laboratory indicators like CST and SRF, along with comprehensive assessments of sludge cake quality and an economic evaluation, wastewater treatment facilities can optimize their polymer selections to improve operational effectiveness and sustainability (Babatunde, 2019; Olukunle, 2013; Danese, Romano & Formentini, 2013).

2.5. Environmental and Sustainability Considerations

The increasing emphasis on environmental and sustainability considerations in the selection and application of polymers for dewatering and conditioning chemical sludge marks a critical juncture in wastewater management. As wastewater treatment plants (WWTPs) strive to minimize their environmental footprint and comply with evolving regulations, the scrutiny on the environmental impacts of polymer use has intensified. The choice of polymer is not solely about immediate sludge processing efficiencies but also encompasses long-term environmental implications, particularly regarding residual polymer behavior, potential contamination of soil and water, and contributions to circular economy initiatives.

Synthetic polymers, predominantly polyacrylamides derived from petroleum, have been widely employed for their effectiveness in dewatering. However, their persistence in environments poses considerable ecological risks. These polymers are generally not readily biodegradable, leading to accumulation when land-applied sludge is used in agriculture. Residual acrylamide monomers can leach into groundwater, posing neurotoxic and carcinogenic risks, complicating disposal and reuse strategies (Shukor, 2019). Additionally, under certain anaerobic conditions, polyacrylamides can degrade into toxic intermediates, raising further concerns regarding their environmental impact.

Conversely, natural or bio-based polymers have emerged as more sustainable alternatives. Materials such as chitosan, derived from crustacean shells, not only exhibit enhanced biodegradability but also possess antimicrobial properties, thereby reducing potential ecological impacts associated with sludge applications (Lu, 2019; Simchi-Levi, Wang & Wei, 2018). However, challenges including variability in source materials, inconsistent performance, and the need for chemical modifications to enhance efficacy relative to synthetic alternatives persist (Zhen et al., 2020; Li et al., 2020). Moreover, considerations surrounding the land use and biodiversity impacts of sourcing these natural polymers must also be addressed, particularly if their application becomes widespread in industrial contexts.

Regulatory frameworks are evolving to encompass these environmental concerns, reflecting a shift towards more sustainable practices. In the European Union, for example, the EU Sludge Directive emphasizes reducing pollutant transfer to agricultural soils during sludge reuse. Similarly, the U.S. Environmental Protection Agency (EPA) is focusing on the implications of residual polymers, with regulatory oversight evolving in the context of emerging contaminants and microplastics (Qrunfleh & Tarafdar, 2014; Wang, et al., 2016). The trend is towards encouraging the use of biodegradable polymers, particularly in sensitive ecological areas, underscoring the necessity for compliance and proactive risk management (Ren et al., 2020).

Life cycle assessment (LCA) methodologies are increasingly being utilized as a tool to evaluate the environmental implications of polymer application across all stages. Through LCA, researchers can systematically compare synthetic and natural polymers based on various environmental parameters, including energy use, greenhouse gas emissions, and toxicity potential. Such assessments reveal that while synthetic options may offer superior efficiency, their long-term environmental impacts could outweigh these benefits (Mwangi, 2019; Zohuri & Moghaddam, 2020). Conversely, natural polymers, while possibly requiring larger quantities to achieve similar performance, may demonstrate a lower overall environmental profile over their life cycle (Pyo et al., 2014).

The integration of green chemistry principles presents pathways for innovative approaches that prioritize sustainable polymer usage. These approaches focus on developing biodegradable and non-toxic polymers and leveraging waste valorization strategies that transform industrial by-products into value-added products (Dong, et al., 2020; Tien, et al., 2019). For instance, using agricultural or forestry residues for polymer production aligns with circular economy principles, although challenges remain in ensuring material consistency and obtaining regulatory approvals (Yeneneh et al., 2016). This transition necessitates not only a focus on individual polymer properties but also a systems-level perspective that evaluates compatibility with broader treatment and resource recovery frameworks, particularly in scenarios involving nutrient reclamation (Werker et al., 2018).

In conclusion, the environmental implications surrounding polymer selection for dewatering and conditioning chemical sludge are extensive and complex. While synthetic polymers bring efficiency, they also lead to significant environmental concerns related to biodegradability and toxicity. In contrast, natural polymers offer promising alternatives but face practical challenges. The regulatory landscape is adapting to these realities, pushing toward more sustainable practices (Duan, Edwards & Dwivedi, 2019; Tien, 2017). LCA serves as a critical instrument in aiding informed decision-making, while green chemistry fosters the development of environmentally benign alternatives. Overall, the consideration of both immediate efficacy and long-term environmental responsibility is essential for guiding the future of polymer use in sludge treatment.

### 2.6. Technological Advancements and Predictive Tools

The landscape of polymer selection for dewatering and conditioning in chemical sludge processing is evolving significantly. This transformation is largely driven by advancements in technology and the uptake of predictive tools that enhance the efficiency of polymer application. Historically, the selection of polymers for sludge treatment relied heavily on traditional trial-and-error methods and empirical testing (Bicudo et al., 2019). These approaches, while historically beneficial, are time-consuming and resource-intensive, often leading to inconsistent results in full-scale operations (Jarrahi, 2018; Terziyan, Gryshko & Golovianko, 2018).

Recent innovations, particularly in machine learning and artificial intelligence (AI), are altering the approach to polymer selection by enabling a more data-driven methodology. Predictive modeling is emerging as a crucial tool in this transition, allowing for the analysis of extensive datasets that encompass various sludge characteristics, operational conditions, and polymer performance metrics (Taş et al., 2017). For example, algorithms developed through supervised learning techniques like decision trees and support vector machines have been effectively employed to predict essential parameters such as capillary suction time (CST) and specific resistance to filtration (SRF) (Ren et al., 2020). These models provide a framework for tailoring polymer selection based on specific sludge properties and treatment goals, thus enhancing the overall reliability of dewatering processes (Affognon, et al., 2015; Misra, et al., 2020).

The ability of AI systems to adapt in real time is one of their most significant advantages. By constantly analyzing data from sensors monitoring various operational parameters—such as flow rate and filtrate clarity—these systems can dynamically adjust polymer dosages and types. This ability improves operational efficiency and reduces chemical costs and ensures compliance with environmental standards (Taş et al., 2017). The integration of AI with digital twins further amplifies this effectiveness, allowing for virtual simulations of polymer strategies under different operational loads, thus facilitating proactive decision-making and minimizing downtime.

Moreover, the transition from laboratory or pilot-scale findings to full-scale application, often referred to as lab-to-field scaling, has been enhanced by advanced simulation software and pilot testing (Xu et al., 2018). These innovations help bridge the gap between theoretical models and practical applications, allowing operators to consider and simulate real-world variables such as mixing energy and polymer dilution ratios (Cydzik-Kwiatkowska et al., 2019). The use of digital imaging technologies for floc characterization and particle analysis also aids in optimizing polymer choices by providing finer details on floc structure and performance under various shear conditions (Xu et al., 2018).

Real-world case studies demonstrate the impact of these advancements. For instance, a municipal treatment facility in Germany adopted an AI-driven polymer optimization system that adjusted dosing based on continuous data analysis, resulting in marked improvements in both sludge cake dryness and polymer consumption (Akande & Diei-Ouadi, 2010; Morris, Kamarulzaman & Morris, 2019). Similarly, projects in Canada utilized digital twin platforms to assess polymer performance in various operational contexts, achieving substantial reductions in specific resistance to filtration and sludge volume (Jafari & Botte, 2020). These examples illustrate the tangible benefits of applying predictive analytics and machine learning in polymer selection and dewatering processes.

Despite these advancements, challenges such as the need for significant infrastructure investment and the complexity of tailoring models to varied sludge characteristics persist. The variability in sludge quality across different treatment facilities poses a significant hurdle that necessitates ongoing calibration and validation of predictive models. Additionally, standardization of data collection and performance metrics remains crucial to ensure comparability and reliability across studies and applications (Taş et al., 2017).

In conclusion, the convergence of predictive tools, AI, and advanced simulation technologies is transforming polymer selection for chemical sludge processing from a manual and empirical process into a sophisticated, data-driven approach. These innovations promise enhancements in efficiency, effectiveness, and environmental compliance while also addressing the complexities associated with lab-to-field scaling (Ahiaba, 2019; Hodges, Buzby & Bennett, 2011). As these technologies continue to evolve, their integration into sludge management strategies will be essential for achieving sustainable and resilient wastewater treatment solutions.

### 2.7. Gaps in Literature and Future Research Directions

Despite significant advancements in the development and application of polymers for dewatering and conditioning chemical sludge, substantial gaps persist in the literature, emphasizing the necessity for ongoing research and innovation in this field. The existing body of knowledge appears fragmented, as it often provides incongruent insights into polymer behavior across varying sludge conditions (Jagtap, et al., 2020; Sibanda & Workneh, 2020). These disparities stem from inconsistent methodologies, localized case studies, and varying reporting standards regarding performance metrics, limiting the generalizability of findings. For wastewater treatment operators, this inconsistency constrains the formulation of evidence-based decisions essential for effective operations (To et al., 2018; To et al., 2019). Addressing these identified knowledge gaps is crucial for enhancing both the scientific underpinning and practical applications of sludge management, particularly as regulatory, environmental, and operational priorities continue to evolve.

A recurring issue highlighted in the literature is the lack of standardized testing protocols for evaluating polymer performance in sludge treatment. Studies frequently report metrics such as capillary suction time (CST), specific resistance to filtration (SRF), and cake moisture content; however, there is a notable absence of uniformity in the experimental conditions under which these parameters are assessed. Variations in sludge age, temperature, mixing energy, polymer dilution ratios, and testing equipment can profoundly impact performance outcomes, exacerbating difficulties in cross-study comparisons (Chaudhuri, et al., 2018; Stathers & Mvumi, 2020). The need for standardized testing methodologies is accentuated by the implications of these inconsistencies, compelling treatment facilities to adopt empirical trial-and-error strategies in polymer selection, potentially undermining the scientific integrity of their protocols (Guo et al., 2018). Therefore, future research should focus on establishing universally accepted standards for polymer evaluation and performance in chemical sludge processing, ideally spearheaded by recognized regulatory or professional organizations such as ASTM, ISO, or the Water Environment Federation (To et al., 2016).

Another notable gap in the literature pertains to the long-term environmental and operational implications of residual polymers found in treated sludge, especially concerning its reuse or disposal. Many studies address immediate dewatering effects; however, fewer investigations delve into the post-treatment fate of polymer residues, particularly in contexts such as agricultural application or landfill disposal. The environmental persistence of certain synthetic polymers, such as polyacrylamides, raises concerns due to their potential degradation pathways, toxicity, and interactions with soil ecosystem (Das Nair & Landani, 2020; Krishnan, Banga & Mendez-Parra, 2020)s. Further longitudinal studies are needed to evaluate the ecological impacts of polymer residues, including questions surrounding bioaccumulation, nutrient cycling, and the potential for groundwater contamination (Zhu et al., 2016). This line of inquiry is crucial for informing regulatory policies and advancing the development of safer and more environmentally compatible polymer formulations that resonate with the principles of environmental sustainability.

In the context of biosolid stabilization, the effect of polymers on the quality and longevity of sludge during storage remains underexplored. Often, conditioned sludge may experience storage delays prior to processing or disposal, during which biological and chemical transformations can alter its properties (Shah, Li & Ierapetritou, 2011; Urciuoli, et al., 2014). The implications of these changes—ranging from odor production and re-water release to overall handling characteristics—necessitate a deeper understanding of how diverse polymer types and dosages affect these temporal dynamics. Research focusing on the long-term stability of polymer-conditioned sludge is fundamental for optimizing storage strategies and minimizing subsequent processing costs (Chen et al., 2015). Moreover, little is known regarding the potential impacts of polymer-induced floc structures on subsequent treatments, such as composting or anaerobic digestion. Future studies should adopt a lifecycle approach to sludge management, appraising not only the immediate benefits of polymer application but also their broader implications on the treatment lifecycle (Erden & Filibeli, 2018).

Exploration into emerging materials and hybrid polymer systems also illustrates an essential yet underdeveloped avenue of research. Novel biobased flocculants derived from materials like chitosan or cellulose present potential ecological advantages over traditional synthetic polymers; however, their consistency and reliability remain to be thoroughly assessed (Qi et al., 2015). Furthermore, the chemical modifications necessary for enhancing these bio-based polymers' efficacy raise critical inquiries about scalability, cost, and environmental impacts. The compatibility of bio-based materials within existing dewatering infrastructures also requires comprehensive investigation (An, Wilhelm & Searcy, 2011; Kandziora, 2019). This discourse presents a pressing opportunity for collaboration among polymer chemists, environmental engineers, and industrial stakeholders to catalyze the advancement of next-generation flocculants that synergize performance with sustainability objectives (Guo et al., 2018; Lin et al., 2015).

In summary, while considerable strides have been made in understanding polymer selection for chemical sludge dewatering and conditioning, an array of knowledge gaps persists. These gaps include inconsistent testing methodologies, limited assessments of long-term environmental repercussions, and insufficient exploration of emerging and hybrid materials. Bridging these gaps necessitates coordinated efforts among scientific, regulatory, and industrial domains towards synthesizing comprehensive, scalable, and environmentally responsible approaches that align polymer selection with operational efficacy and sustainability principles (An, Wilhelm & Searcy, 2011; Kandziora, 2019).

### 2.8. Conclusion

The systematic review of polymer selection for dewatering and conditioning in chemical sludge processing reveals that polymer performance is shaped by a complex interaction of sludge characteristics, polymer properties, operational conditions, and technological configurations. Cationic polyacrylamides remain the most widely used polymers due to their strong charge neutralization and bridging capabilities, particularly effective for sludges generated through aluminum- and iron-based chemical treatments. Anionic and nonionic polymers offer complementary functions under specific conditions, while bio-based alternatives present promising environmentally friendly options, though they require further optimization for consistent performance. Hybrid and dual polymer systems have demonstrated enhanced dewaterability and operational efficiency, particularly when tailored to site-specific sludge properties and equipment configurations.

Key performance metrics such as capillary suction time, specific resistance to filtration, sludge cake moisture content, and floc structure remain central to evaluating polymer effectiveness. However, inconsistencies in testing methodologies and the lack of standardized evaluation protocols present significant barriers to comparison and best practice transferability. Furthermore, the long-term environmental impact of residual polymers, particularly synthetic variants, remains poorly understood, raising concerns about soil contamination and ecological risks in cases of land application or disposal. Life cycle assessments and environmental compatibility of polymers are therefore essential considerations in promoting sustainable sludge management.

For industry stakeholders, the findings emphasize the importance of integrating data-driven selection tools, including machine learning and real-time optimization systems, to improve polymer dosing accuracy, reduce chemical consumption, and adapt dynamically to varying sludge compositions. Lab-to-field scaling strategies, supported by advanced simulation tools and pilot testing, are vital to bridging the gap between experimental data and full-scale application. The use of high-throughput screening and predictive analytics can significantly reduce operational costs and improve decision-making in polymer procurement and process optimization.

Policymakers and regulatory bodies should prioritize the development of standardized guidelines for polymer testing, usage thresholds, and residual management in treated sludge. Incentivizing research into biodegradable, low-toxicity polymers and endorsing green chemistry practices can support a transition toward environmentally resilient sludge treatment systems. Aligning polymer application strategies with broader sustainability goals, such as circular economy principles and nutrient recovery, will be essential in shaping future policy frameworks that protect public health, reduce environmental burden, and promote innovation in wastewater treatment.

## REFERENCES


[1] Adeoba, M. I. (2018). *Phylogenetic analysis of extinction risk and diversification history of the African Cyprinidae using DNA barcodes* (Doctoral dissertation, University of Johannesburg).

[2] Adeoba, M. I., & Yessoufou, K. (2018). Analysis of temporal diversification of African Cyprinidae (Teleostei, Cypriniformes). *ZooKeys*, (806), 141.

[3] Adeoba, M. I., Kabongo, R., Van der Bank, H., & Yessoufou, K. (2018). Re-evaluation of the discriminatory power of DNA barcoding on some specimens of African Cyprinidae (subfamilies Cyprininae and Danioninae). *ZooKeys*, (746), 105.

[4] Adeoba, M., Tesfamichael, S. G., & Yessoufou, K. (2019). Preserving the tree of life of the fish family Cyprinidae in Africa in the face of the ongoing extinction crisis. *Genome*, *62*(3), 170-182.

[5] Affognon, H., Mutungi, C., Sanginga, P., & Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. *World development*, *66*, 49-68.

[6] Ahiaba, U. V. (2019). *The Role of Grain Storage Systems in Food Safety, Food Security and Rural Development in Northcentral Nigeria* (Doctoral dissertation, University of Gloucestershire).

[7] Ajayi, A. B., Afolabi, O., Folarin, T. E., Mustapha, H., & Popoola, A. (2020). Development of a low-cost polyurethane (foam) waste shredding machine. *ABUAD*

*Journal of Engineering Research and Development*, *3*(2), 105-14.

[8] Ajayi, A. B., Popoola, A. F., Mustapha, H. A., Folarin, T. E., & Afolabi, S. O. (2020). Development of a mixer for polyurethane (foam) waste recycling machine. *ABUAD Journal of Engineering Research and Development. Accepted (13/11/2020) in-Press. http://ajerd. abuad. edu. ng/papers*.

[9] Ajibola, K. A., & Olanipekun, B. A. (2019). Effect of access to finance on entrepreneurial growth and development in Nigeria among "YOU WIN" beneficiaries in SouthWest, Nigeria. *Ife Journal of Entrepreneurship and Business Management*, 3(1), 134-149.

[10] Akande, B., & Diei-Ouadi, Y. (2010). *Post-harvest losses in small-scale fisheries*. Food and Agriculture Organization of the United Nations.

[11] Akang, V. I., Afolayan, M. O., Iorpenda, M. J., & Akang, J. V. (2019, October). INDUSTRIALIZATION OF THE NIGERIAN ECONOMY: THE IMPERATIVES OF IMBIBING ARTIFICIAL INTELLIGENCE AND ROBOTICS FOR NATIONAL GROWTH AND DEVELOPMENT. In Proceedings of: 2nd International Conference of the IEEE Nigeria (p. 265).

[12] Alam, M. A., Ahad, A., Zafar, S., & Tripathi, G. (2020). A neoteric smart and sustainable farming environment incorporating blockchain-based artificial intelligence approach. *Cryptocurrencies and Blockchain Technology Applications*, 197-213.

[13] An, H., Wilhelm, W. E., & Searcy, S. W. (2011). Biofuel and petroleum-based fuel supply chain research: a literature review. *Biomass and Bioenergy*, *35*(9), 3763-3774.

[14] Androutsopoulou, A., Karacapilidis, N., Loukis, E., & Charalabidis, Y. (2019). Transforming the communication between citizens and government through AI-guided chatbots. *Government information quarterly*, *36*(2), 358-367.

[15] Arimieari, L. and Ademiluyi, J. (2018). Modelling the relationship between sludge filtration resistance and capillary suction time. Journal of Environmental Protection, 09(02), 91-99. https://doi.org/10.4236/jep.2018.92007

[16] Babatunde, A. I. (2019). Impact of supply chain in reducing fruit post-harvest waste in agric value chain in Nigeria. *Electronic Research Journal of Social Sciences and Humanities*, *1*, 150-163.

[17] Badza, T., Tesfamariam, E., & Cogger, C. (2020). Sludge stabilization process, drying depth and polymeric material addition: implication on nitrogen content, selected chemical properties and land requirement in sand drying beds. Energies, 13(24), 6753. https://doi.org/10.3390/en13246753

[18] Belot, S. T. (2020). The state and impact of the Fourth Industrial Revolution on economic development.

[19] Bicudo, J., Parker, W., Higgins, M., Morris, S., Gerber, J., Crowley, B., … & Celmer-Repin, D. (2019). Impact of anaerobically digested biosolids characteristics and handling conditions on dewatering performance at multiple facilities. Water Environment Research, 92(3), 347-358. https://doi.org/10.1002/wer.1169

[20] Chaudhuri, A., Dukovska-Popovska, I., Subramanian, N., Chan, H. K., & Bai, R. (2018). Decision-making in cold chain logistics using data analytics: a literature review. *The International Journal of Logistics Management*, *29*(3), 839-861.

[21] Chen, Z., Zhang, W., Wang, D., Ma, T., & Bai, R. (2015). Enhancement of activated sludge dewatering performance by combined composite enzymatic lysis and chemical re-flocculation with inorganic coagulants: kinetics of enzymatic reaction and re-flocculation morphology. Water Research, 83, 367-376. https://doi.org/10.1016/j.watres.2015.06.026

[22] Collivignarelli, M., Abbà, A., Frattarola, A., Miino, M., Padovani, S., Katsoyiannis, I., … & Torretta, V. (2019). Legislation for the reuse of biosolids on agricultural land in europe: overview. Sustainability, 11(21), 6015. https://doi.org/10.3390/su11216015

[23] Cydzik-Kwiatkowska, A., Nosek, D., Wojnowska-Baryła, I., & Mikulski, A. (2019). Efficient dewatering of polymer-rich aerobic granular sludge with cationic polymer containing hydrocarbons. International Journal of Environmental Science and Technology, 17(1), 361-370. https://doi.org/10.1007/s13762-019-02505-1

[24] Danese, P., Romano, P., & Formentini, M. (2013). The impact of supply chain integration on responsiveness: The moderating effect of using an international supplier network. Transportation Research Part E: Logistics and Transportation Review, 49(1), 125-140.

[25] Das Nair, R., & Landani, N. (2020). *Making agricultural value chains more inclusive through technology and innovation* (No. 2020/38). WIDER working paper.

[26] Ding, A., Qu, F., Liang, H., Guo, S., Ren, Y., Xu, G., & Li, G. (2014). Effect of adding wood chips on sewage sludge dewatering in a pilot-scale plate-and-frame filter press process. RSC Advances, 4(47), 24762-24768.

[27] Dong, Y., Hou, J., Zhang, N., & Zhang, M. (2020). Research on how human intelligence, consciousness, and cognitive computing affect the development of artificial intelligence. Complexity, 2020(1), 1680845.

[28] Duan, Y., Edwards, J. S., & Dwivedi, Y. K. (2019). Artificial intelligence for decision making in the era of Big Data–evolution, challenges and research agenda. International journal of information management, 48, 63-71.

[29] Edwards, Q., Mallhi, A. K., & Zhang, J. (2018). The association between advanced maternal age at delivery and childhood obesity. *J Hum Biol*, *30*(6), e23143.

[30] Erden, G. and Filibeli, A. (2018). Comparison of dewatering characteristics of chemically conditioned sludge and freeze/ thawed sludge. Pamukkale University Journal of Engineering Sciences, 24(6), 1157-1160. https://doi.org/10.5505/pajes.2017.62443

[31] Ezenwa, A. E. (2019). Smart logistics diffusion strategies amongst supply chain networks in emerging markets: a case of Nigeria's micro/SMEs 3PLs (Doctoral dissertation, University of Leeds).

[32] Górecki, T., Jakubus, M., Krzyśko, M., & Wołyński, W. (2019). Application of distance covariance in selection of nutrients during dynamic process of sewage sludge conditioning with bio-preparation. Waste and Biomass Valorization, 11(8), 4157-4166. https://doi.org/10.1007/s12649-019-00747-1

[33] Górka, J., Cimochowicz-Rybicka, M., & Kryłów, M. (2018). Use of a water treatment sludge in a sewage sludge dewatering process. E3s Web of Conferences, 30, 02006. https://doi.org/10.1051/e3sconf/20183002006

[34] Guo, J., Chen, C., Jiang, S., & Zhou, Y. (2018). Feasibility and mechanism of combined conditioning with coagulant and flocculant to enhance sludge dewatering. Acs Sustainable Chemistry & Engineering, 6(8), 10758-10765. https://doi.org/10.1021/acssuschemeng.8b02086

[35] Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. *The Journal of Agricultural Science*, *149*(S1), 37-45.

[36] Ijeomah, S. (2020). Challenges of supply chain management in the oil & gas production in Nigeria (Shell Petroleum Development Company of Nigeria) (Doctoral dissertation, Dublin, National College of Ireland).

[37] Ikeh, T. C., & Ndiwe, C. U. (2019). Solar photovoltaic as an option (alternative) for electrification of health care service in Anambra West, Nigeria. *Asian Journal of Science and Technology*, 10(6), 9720-9724. Asian Science & Technology.

[38] Ilori, M. O., & Olanipekun, S. A. (2020). Effects of government policies and extent of its implementations on the foundry industry in Nigeria. *IOSR Journal of Business Management*, 12(11), 52-59

[39] Imran, S., Patel, R. S., Onyeaka, H. K., Tahir, M., Madireddy, S., Mainali, P., ... & Ahmad, N. (2019). Comorbid depression and psychosis in Parkinson’s disease: a report of 62,783

hospitalizations in the United States. *Cureus*, *11*(7).

[40] Jafari, M. and Botte, G. (2020). Electrochemical treatment of sewage sludge and pathogen inactivation. Journal of Applied Electrochemistry, 51(1), 119-130. https://doi.org/10.1007/s10800-020-01481-6

[41] Jagtap, S., Bader, F., Garcia-Garcia, G., Trollman, H., Fadiji, T., & Salonitis, K. (2020). Food logistics 4.0: Opportunities and challenges. *Logistics*, *5*(1), 2.

[42] Jarrahi, M. H. (2018). Artificial intelligence and the future of work: Human-AI symbiosis in organizational decision making. Business horizons, 61(4), 577-586.

[43] Kandziora, C. (2019, April). Applying artificial intelligence to optimize oil and gas production. In *Offshore Technology Conference* (p. D021S016R002). OTC.

[44] Kankanhalli, A., Charalabidis, Y., & Mellouli, S. (2019). IoT and AI for smart government: A research agenda. *Government Information Quarterly*, *36*(2), 304-309.

[45] Krishnan, A., Banga, K., & Mendez-Parra, M. (2020). Disruptive technologies in agricultural value chains. *Insights from East Africa. Working paper*, *576*.

[46] Lee, S., Park, S., Alam, T., Jeong, Y., Seo, Y., & Choi, H. (2020). Studies on the gasification performance of sludge cake pre-treated by hydrothermal carbonization. Energies, 13(6), 1442. https://doi.org/10.3390/en13061442

[47] Li, X., Zhang, F., Guan, B., Sun, J., & Liao, G. (2020). Review on oily sludge treatment technology. Iop Conference Series Earth and Environmental Science, 467(1), 012173. https://doi.org/10.1088/1755-1315/467/1/012173

[48] Lin, Q., Peng, H., Zhong, S., & Xiang, J. (2015). Synthesis, characterization, and secondary sludge dewatering performance of a novel combined silicon–aluminum–iron–starch flocculant. Journal of Hazardous Materials, 285, 199-206. https://doi.org/10.1016/j.jhazmat.2014.12.005

[49] Lu, Y. (2019). Artificial intelligence: a survey on evolution, models, applications and future trends. Journal of Management Analytics, 6(1), 1-29.

[50] Maćczak, P., Kaczmarek, H., & Ziegler-Borowska, M. (2020). Recent achievements in polymer bio-based flocculants for water treatment. Materials, 13(18), 3951. https://doi.org/10.3390/ma13183951

[51] Misra, N. N., Dixit, Y., Al-Mallahi, A., Bhullar, M. S., Upadhyay, R., & Martynenko, A. (2020). IoT, big data, and artificial intelligence in agriculture and food industry. *IEEE Internet of things Journal*, *9*(9), 6305-6324.

[52] Morris, K. J., Kamarulzaman, N. H., & Morris, K. I. (2019). Small-scale postharvest practices among plantain farmers and traders: A potential for reducing losses in rivers state, Nigeria. *Scientific African*, *4*, e00086.

[53] Mwangi, N. W. (2019). Influence of supply chain optimization on the performance of manufacturing firms in Kenya (Doctoral dissertation, JKUAT-COHRED).

[54] Niu, M., Zhang, W., Wang, D., Chen, Y., & Chen, R. (2013). Correlation of physicochemical properties and sludge dewaterability under chemical conditioning using inorganic coagulants. Bioresource Technology, 144, 337-343. https://doi.org/10.1016/j.biortech.2013.06.126

[55] Ochinanwata, N. H. (2019). Integrated business modelling for developing digital internationalising firms in Nigeria (Doctoral dissertation, Sheffield Hallam University).

[56] Ofori-Asenso, R., Ogundipe, O., Agyeman, A. A., Chin, K. L., Mazidi, M., Ademi, Z., ... & Liew, D. (2020). Cancer is associated with severe disease in COVID-19 patients: a systematic review and meta-analysis. *Ecancermedicalscience*, *14*, 1047.

[57] Ofori-Asenso, R., Ogundipe, O., Agyeman, A. A., Chin, K. L., Mazidi, M., Ademi, Z., ... & Liew, D. (2020). Cancer is associated with severe disease in COVID-19 patients: a systematic review and meta-analysis. *Ecancermedicalscience*, *14*, 1047.

[58] Ojo, P. and Ifelebuegu, A. (2019). The effects of aluminium- and ferric-based chemical phosphorus removal on activated sludge digestibility and dewaterability. Processes, 7(4), 228. https://doi.org/10.3390/pr7040228

[59] Olanipekun, K. A. (2020). Assessment of Factors Influencing the Development and Sustainability of Small Scale Foundry Enterprises in Nigeria: A Case Study of Lagos State. *Asian Journal of Social Sciences and Management Studies*, *7*(4), 288-294.

[60] Olanipekun, K. A., & Ayotola, A. (2019). *Introduction to marketing*. GES 301, Centre for General Studies (CGS), University of Ibadan.

[61] Olanipekun, K. A., Ilori, M. O., & Ibitoye, S. A. (2020): Effect of Government Policies and Extent of Its Implementation on the Foundry Industry in Nigeria.

[62] Olukunle, O. T. (2013). Challenges and prospects of agriculture in Nigeria: the way forward. *Journal of Economics and sustainable development*, *4*(16), 37-45.

[63] Omisola, J. O., Etukudoh, E. A., Okenwa, O. K., & Tokunbo, G. I. (2020). Innovating Project Delivery and Piping Design for Sustainability in the Oil and Gas Industry: A Conceptual Framework. *perception*, *24*, 28-35.

[64] Omisola, J. O., Etukudoh, E. A., Okenwa, O. K., & Tokunbo, G. I. (2020). Innovating Project Delivery and Piping Design for Sustainability in the Oil and Gas Industry: A Conceptual Framework. *perception*, *24*, 28-35.

[65] Oyedokun, O. O. (2019). Green human resource management practices and its effect on the sustainable competitive edge in the Nigerian manufacturing industry (Dangote) (Doctoral dissertation, Dublin Business School).

[66] Pyo, S., Kim, M., Lee, S., & Yoo, C. (2014). Evaluation of environmental and economic impacts of advanced wastewater treatment plants with life cycle assessment. Korean Chemical Engineering Research, 52(4), 503-515. https://doi.org/10.9713/kcer.2014.52.4.503

[67] Qi, L., Cheng, J., Liang, X., & Hu, Y. (2015). Synthesis and characterization of a novel terpolymer and the effect of its amphoteric property on the sludge flocculation. Polymer Engineering & Science, 56(2), 158-169. https://doi.org/10.1002/pen.24238

[68] Qi, Y., Huo, B., Wang, Z., & Yeung, H. Y. J. (2017). The impact of operations and supply chain strategies on integration and performance. International Journal of Production Economics, 185, 162-174.

[69] Qrunfleh, S., & Tarafdar, M. (2014). Supply chain information systems strategy: Impacts on supply chain performance and firm performance. International journal of production economics, 147, 340-350.

[70] Raynaud, M., Heritier, P., Baudez, J., & Vaxelaire, J. (2010). Experimental characterisation of activated sludge behaviour during mechanical expression. Process Safety and Environmental Protection, 88(3), 200-206. https://doi.org/10.1016/j.psep.2010.02.004

[71] Ren, B., Lyczko, N., Zhao, Y., & Nzihou, A. (2020). Integrating alum sludge with waste-activated sludge in co-conditioning and dewatering: a case study of a city in south france. Environmental Science and Pollution Research, 27(13), 14863-14871. https://doi.org/10.1007/s11356-020-08056-0

[72] Sawalha, O. and Scholz, M. (2012). Impact of temperature on sludge dewatering properties assessed by the capillary suction time. Industrial & Engineering Chemistry Research, 51(6), 2782-2788. https://doi.org/10.1021/ie202381r

[73] Serajuddin, M. and Sreenivas, T. (2015). Application of response surface method of optimization in flocculant assisted filtration of uranium bearing alkaline leach slurry of limestone origin. Mineral Processing and Extractive Metallurgy, 124(4), 199-207. https://doi.org/10.1179/1743285515y.0000000003

[74] Shah, N. K., Li, Z., & Ierapetritou, M. G. (2011). Petroleum refining operations: key issues, advances, and opportunities. *Industrial & Engineering Chemistry Research*, *50*(3), 1161-1170.

[75] Shukor, M. (2019). Applications, pollution, toxicity and bioremediation of acrylamide. Journal of Environmental Microbiology and Toxicology, 7(2), 1-6. https://doi.org/10.54987/jemat.v7i2.489

[76] Sibanda, S., & Workneh, T. S. (2020). Potential causes of postharvest losses, low-cost cooling technology for fresh produce farmers in Sub-Sahara Africa. *African Journal of Agricultural Research*, *16*(5), 553-566.

[77] Simchi-Levi, D., Wang, H., & Wei, Y. (2018). Increasing supply chain robustness through process flexibility and inventory. Production and Operations Management, 27(8), 1476-1491.

[78] Stathers, T., & Mvumi, B. (2020). Challenges and initiatives in reducing postharvest food losses and food waste: sub-Saharan Africa. In *Preventing food losses and waste to achieve food security and sustainability* (pp. 729-786). Burleigh Dodds Science Publishing.

[79] Taş, D., Yangin-Gomec, C., Ölmez-Hancı, T., Arikan, O., Çifçi, D., Gencsoy, E., … & Çokgör, E. (2017). Comparative assessment of sludge pre-treatment techniques to enhance sludge dewaterability and biogas production. Clean - Soil Air Water, 46(1). https://doi.org/10.1002/clen.201700569

[80] Terziyan, V., Gryshko, S., & Golovianko, M. (2018). Patented intelligence: Cloning human decision models for Industry 4.0. Journal of manufacturing systems, 48, 204-217.

[81] Tien, J. M. (2017). Internet of things, real-time decision making, and artificial intelligence. Annals of Data Science, 4, 149-178.

[82] Tien, N. H., Anh, D. B. H., & Thuc, T. D. (2019). Global supply chain and logistics management.

[83] To, V., Nguyễn, T., Bustamante, H., & Vigneswaran, S. (2019). Deleterious effects of soluble extracellular polymeric substances on polyacrylamide demand for conditioning of anaerobically digested sludge. Journal of Environmental Chemical Engineering, 7(2), 102941. https://doi.org/10.1016/j.jece.2019.102941

[84] To, V., Nguyễn, T., Vigneswaran, S., & Ngo, H. (2016). A review on sludge dewatering indices. Water Science & Technology, 74(1), 1-16. https://doi.org/10.2166/wst.2016.102

[85] To, V., Nguyễn, T., Vigneswaran, S., Bustamante, H., Higgins, M., & Rys, D. (2018). Novel methodologies for determining a suitable polymer for effective sludge dewatering. Journal of Environmental Chemical Engineering, 6(4), 4206-4214. https://doi.org/10.1016/j.jece.2018.06.012

[86] To, V., Nguyễn, T., Vigneswaran, S., Nghiem, L., Murthy, S., Bustamante, H., … & Higgins, M. (2016). Modified centrifugal technique for determining polymer demand and achievable dry solids content in the dewatering of anaerobically digested sludge. Desalination and Water Treatment, 57(53), 25509-25519. https://doi.org/10.1080/19443994.2016.1157524

[87] Truby, J. (2020). Governing artificial intelligence to benefit the UN sustainable development goals. *Sustainable Development*, *28*(4), 946-959.

[88] Tula, O. A., Adekoya, O. O., Isong, D., Daudu, C. D., Adefemi, A., & Okoli, C. E. (2004). Corporate advising strategies: A comprehensive review for aligning petroleum engineering with climate goals and CSR commitments in the United States and Africa. *Corporate Sustainable Management Journal, 2*(1), 32-38.

[89] Urciuoli, L., Mohanty, S., Hintsa, J., & Gerine Boekesteijn, E. (2014). The resilience of energy supply chains: a multiple case study approach on oil and gas supply chains to Europe. *Supply Chain Management: An International Journal*, *19*(1), 46-63.

[90] Vajihinejad, V., Gumfekar, S., Bazoubandi, B., Najafabadi, Z., & Soares, J. (2018). Water soluble polymer flocculants: synthesis, characterization, and performance assessment. Macromolecular Materials and Engineering, 304(2). https://doi.org/10.1002/mame.201800526

[91] Wang, G., Gunasekaran, A., Ngai, E. W., & Papadopoulos, T. (2016). Big data analytics in

logistics and supply chain management: Certain investigations for research and applications. International journal of production economics, 176, 98-110.

[92] Wang, H., Liu, C., Wu, Z., Yang, W., & Chen, C. (2017). Improved dewaterability of sewage sludge by fe(ii)-activated persulfate oxidation combined with polymers. Water and Environment Journal, 31(4), 603-608. https://doi.org/10.1111/wej.12266

[93] Wang, L. and Li, A. (2015). Hydrothermal treatment coupled with mechanical expression at increased temperature for excess sludge dewatering: the dewatering performance and the characteristics of products. Water Research, 68, 291-303. https://doi.org/10.1016/j.watres.2014.10.016

[94] Wang, S., Cheng, S., Xiao, X., & Lai, F. (2020). Impact of persulphate mixed with paper sludge on activated sludge dewaterability. Water and Environment Journal, 34(S1), 884-892. https://doi.org/10.1111/wej.12597

[95] Werker, A., Bengtsson, S., Korving, L., Hjort, M., Anterrieu, S., Alexandersson, T., … & Uijterlinde, C. (2018). Consistent production of high quality pha using activated sludge harvested from full scale municipal wastewater treatment – phario. Water Science & Technology, 78(11), 2256-2269. https://doi.org/10.2166/wst.2018.502

[96] West, M., Kraut, R., & Ei Chew, H. (2019). I'd blush if I could: closing gender divides in digital skills through education.

[97] Wójcik, M. (2018). Examinations of the effect of ashes from coal and biomass co-combustion on the effectiveness of sewage sludge dewatering. Engineering and Protection of Environment, 21(3), 273-288. https://doi.org/10.17512/ios.2018.3.6

[98] Xu, D., Hong, Y., Qiao-Feng, Y., Pei-Pei, C., Ling-Ling, Z., & Zhang, M. (2018). Optimizing heavy metals removal of excess sludge by biodegradable chelants glda using a response surface methodological approach. Polish Journal of Environmental Studies, 27(4), 1841-1850. https://doi.org/10.15244/pjoes/78048

[99] Yeneneh, A., Hong, E., Sen, T., Kayaalp, A., & Ang, H. (2016). Effects of temperature, polymer dose, and solid concentration on the rheological characteristics and dewaterability of digested sludge of wastewater treatment plant (wwtp). Water Air & Soil Pollution, 227(4). https://doi.org/10.1007/s11270-016-2820-4

[100] Yue, D., You, F., & Snyder, S. W. (2014). Biomass-to-bioenergy and biofuel supply chain optimization: Overview, key issues and challenges. *Computers & chemical engineering*, *66*, 36-56.

[101] Zhang, D., Angelotti, B., Schlosser, E., Novak, J., & Wang, Z. (2019). Using cerium chloride to control soluble orthophosphate concentration and improve the dewaterability of sludge: part i. mechanistic understanding. Water Environment Research, 92(3), 320-330. https://doi.org/10.1002/wer.1142

[102] Zhang, X., Li, X., Li, R., & Wu, Y. (2020). Hydrothermal carbonization and liquefaction of sludge for harmless and resource purposes: a review. Energy & Fuels, 34(11), 13268-13290. https://doi.org/10.1021/acs.energyfuels.0c02467

[103] Zhao, Y. Q. (2006). Involvement of gypsum (CaSO4· 2H2O) in water treatment sludge dewatering: a potential benefit in disposal and reuse. Separation science and technology, 41(12), 2785-2794.

[104] Zhen, Z., Jinxiang, Y., & Dai, R. (2020). A review on the physical dewatering methods of sludge pretreatment in recent ten years. Iop Conference Series Earth and Environmental Science, 455(1), 012189. https://doi.org/10.1088/1755-1315/455/1/012189

[105] Zhou, K., Stüber, J., Schubert, R. L., Kabbe, C., & Barjenbruch, M. (2018). Full-scale performance of selected starch-based biodegradable polymers in sludge dewatering and recommendation for applications. Water Science and Technology, 77(1), 7-16.

[106] Zhu, C., Wang, H., Mahmood, Z., Wang, Q., & Ma, H. (2018). Biocompatibility and

biodegradability of polyacrylate/zno nanocomposite during the activated sludge treatment process. Plos One, 13(11), e0205990. https://doi.org/10.1371/journal.pone.0205990

[107] Zhu, Y., Tan, X., & Liu, Q. (2016). Dual polymer flocculants for mature fine tailings dewatering. The Canadian Journal of Chemical Engineering, 95(1), 3-10. https://doi.org/10.1002/cjce.22628

[108] Zohuri, B., & Moghaddam, M. (2020). From business intelligence to artificial intelligence. Journal of Material Sciences & Manufacturing Research, 1(1), 1-10.