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Recent Trends in Non-conventional Starches for Wastewater Treatment Applications

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Abstract. Coagulation and flocculation are essential processes in water and wastewater treatment. However, commonly used commercial coagulants pose environmental and health risks due to residual metal content and the large volumes of sludge they produce. As a sustainable alternative, starch-based biocoagulants have attracted increasing research interest due to their biodegradability, cost-effectiveness, and lower sludge generation, with some studies reporting up to 5-fold lower sludge volumes than with conventional chemical coagulants. Among these, non-conventional starches offer a promising solution because of their diversity, regional availability, and lack of competition with the food supply. This review explores extraction methods, modification strategies, and characterization techniques for structural and mechanistic validation. Reported studies revealed excellent pollutant removal performance under optimal conditions, including turbidity (98.91%), TSS (90.7%), COD (84.96%), color (100%), and selected metals (100%). Normalized removal efficiencies ranged from1.855% per mg/L for turbidity, 0.541% per mg/L for COD, and 1.7778% per mg/L for TSS, depending on the starch source and wastewater type. Mechanisms such as charge neutralization and interparticle bridging have also been identified. Despite challenges such as composition variability, high dosage requirements, and scalability issues, techno-economic assessments suggest potential industrial applicability. Overall, non-conventional starch-based biocoagulants hold considerable promise for sustainable wastewater treatment applications.

Keywords: Biocoagulants, Chemical Characterization, Functionalization, Starch Modification, Turbidity removal

INTRODUCTION

Chemical coagulants widely used in water treatment processes have been associated with environmental degradation and potential health hazards. These substances, often derived from metal salts such as aluminum and iron compounds, can alter water chemistry (Krupińska, 2020), accelerate the corrosion of piping materials (Brandt *et al.*, 2017), and lower water pH levels, potentially reducing overall plant growth (Lin *et al.*, 2017). These metal-derived coagulants are non-biodegradable, and their residues can persist in ecosystems and enter the food chain (Mortula *et al.*, 2009; Pandey, 2020). When ingested, these residues may accumulate in the human body, leading to

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harmful health effects. The use of commercial coagulants may also result in a larger volume of sludge, which increases disposal costs and the risk of hazardous waste generation (Mohamed Noor *et al.*, 2022). Several studies have linked chemical coagulant exposure to presenile dementia and a heightened risk of Alzheimer's disease (Exley, 2017; Soleimani *et al.,* 2025). Consequently, there is a pressing need to investigate safer, more sustainable alternatives.

Biocoagulants, obtained from plants, animals, or microorganisms (Amran *et al.*, 2018), are promising substitutes for chemical coagulants. Materials such as rice starch, potato starch, cassava, and Moringa oleifera seeds have been successfully utilized as biocoagulants (Kurniawan *et al.*, 2020). Being biodegradable, these materials pose fewer risks to both the environment and human health. Biocoagulants also offer multiple benefits, including easy accessibility to communities and antimicrobial properties (Chandrashekara *et al.,* 2020). Moreover, water treatment processes employing natural coagulants generate less sludge than those employing inorganic salts (Dorea, 2006). The biodegradable sludge produced is nutrient-rich, safe, and suitable for use as fertilizer (Manholer *et al.*, 2019).

One of the most widely studied plant-based biocoagulants is starch. Starch is abundant, affordable, biodegradable, and easily chemically modified to enhance its ability to target specific pollutants, improving coagulation efficiency (Asharuddin *et al.*, 2021) Starch-based coagulants are increasingly being acknowledged for their effectiveness in water treatment, owing to functional groups like carboxyl and hydroxyl attached to their polysaccharide rings—features that are further improved through chemical modification (Lau *et al.*, 2024). Modified starch has demonstrated potential to improve water quality, reduce E. coli levels, remove heavy metals, and capture microplastics (El-Naggar *et al.*, 2018; Gao *et al.*, 2023).

Common starch sources studied for biocoagulant applications include corn, potato, barley, yam, and cassava (Asharuddin *et al.,* 2021). Conventional starches—such as those from corn, potato, wheat, and various types of rice—are widely consumed and commercially available globally (Santana & Meireles, 2014). However, using these food crops for non-food purposes, such as wastewater treatment, may compete with food production, underscoring the need for alternative starch sources that do not compromise food security.

Research interest has increasingly focused on non-conventional starches, derived from non-commercial crops (Makroo *et al.,* 2021), minor grains and tubers (Bangar *et al.,* 2024), or discarded parts of conventional starch sources. These starches possess unique properties with potential for food and non-food applications, though extraction and modification technologies are still developing. Adoption depends on factors such as regional availability, cultural relevance, by-product utilization, and potential technological advantages. Despite their promise, research on non-conventional starches remains limited (Makroo *et al.,* 2021; Zhu, 2020).

Therefore, this review consolidates recent studies on the modification, characterization, and application of non-conventional starches for wastewater treatment. Unlike previous review papers that broadly discuss natural coagulants, bio-based polymers, or conventional starch sources, this study specifically focuses on non-conventional starches derived from underutilized plant sources and agricultural residues, which remain less explored despite their promising potential for sustainable wastewater treatment. This review is important in providing a comprehensive and updated synthesis of their extraction methods, modification strategies, characterization approaches, and treatment performance across different wastewater matrices. It further compares their performance and working mechanisms, discusses limitations, identifies existing research gaps, and proposes future research directions to enhance their potential as sustainable alternatives to conventional flocculants.

OVERVIEW OF NON-CONVENTIONAL STARCHES

Non-conventional starches offer several advantages over conventional sources, including reduced competition with the food supply and potential for non-food applications. Examples include mango kernels, plantain peels, jackfruit seeds, sago palm trunks, and cassava peels (Makroo *et al.,* 2021; Bangar *et al.,* 2024). Typically produced in limited quantities or significant only in local markets, these starches are often derived from agricultural residues or waste materials, supporting low-cost, waste-to-resource strategies aligned with a circular economy. Additionally, industrial processing of conventional starch sources generates non-edible parts, including seeds, roots, stems, leaves, and bracts, that may serve as untapped non-conventional starch sources.

Regional and local availability can reduce reliance on imports. Simplified extraction and modification methods enable community-based utilization, enhance local self-sufficiency, and promote livelihood opportunities through decentralized production.

Non-conventional starches also exhibit diverse physicochemical properties, enabling applications in wastewater treatment, biodegradable materials, pharmaceutical carriers, and agricultural films. Over 25 non-traditional starch sources, including Dioscorea, pea, sago palm, banana, jackfruit, jack bean, and cassava, have been investigated for nanoparticle development in drug delivery systems (Troncoso & Torres, 2020). Starch-based films from non-conventional sources have improved food packaging, extending shelf life and quality—for example, mango kernel starch for tomatoes, pea starch for cherries, and tapioca starch for chicken (Henning *et al.,* 2022). Arrowroot starch coatings have been successfully applied as edible films for plums, minimizing mass loss during storage without affecting key physicochemical properties, including respiratory rate, pH, total titratable acidity, and anthocyanin content, with results primarily influenced by storage temperature (Nogueira *et al.,* 2023).

APPLICATIONS IN WASTEWATER TREATMENT

A systematic Google Scholar search was conducted to identify peer-reviewed studies on starch-based biocoagulants for wastewater treatment using the keywords "starch AND biocoagulant AND wastewater treatment." The review focused on non-conventional starches derived from non-commercial sources (e.g., gadung Dioscorea hispida, oil palm, Polynesian arrowroot Tacca leontopetaloides) or discarded plant parts (e.g., banana pith, cassava peels, durian seeds, green plantain peels, sago trunks), excluding common commercial starches such as wheat, cassava, rice, corn, potato, arrowroot, and sago pith.

For each study, information on the type of wastewater treated, starch extraction methods, and modifications to enhance coagulation/flocculation was documented. Characterization results were analyzed to explain treatment functionality, while adsorption and coagulation mechanisms were summarized to describe pollutant interactions. In total, 18 studies were identified, indicating that both native and modified starches can serve effectively as coagulants or flocculants, with modifications improving pollutant affinity and overall treatment efficiency.

Extraction Method of Starch

Starch extraction generally involves water-based, chemical-assisted, or mechanical methods.

Water-based extraction was used in 5 of the 18 reviewed studies. It involves homogenizing the starch source with distilled water, filtering through cloth or paper, allowing the starch to settle, removing the supernatant, and drying the sediment. This method, commonly used for cassava peel starch (CPS) (Asharuddin *et al.*, 2019; Asharuddin *et al.*, 2023; Kumar *et al.*, 2020; Kumar *et al.*, 2021; Othman *et al.*, 2018), is cost-effective and avoids chemical residues, eliminating the need for neutralization.

Chemical-assisted extraction was reported in 11 studies, using agents such as ascorbic acid, sodium hydroxide, and sodium metabisulfite to disrupt cell structures or prevent enzymatic browning. The general procedure involves blending the raw material with a dilute chemical solution, filtering, repeating the process with fresh solution, allowing the extract to settle, and then oven-drying the starch. Specifically, ascorbic acid was used for starch extraction from green plantain peel (Cortes-Pérez *et al.*, 2023); sodium hydroxide was applied to durian seed and jackfruit seed starches (Choy *et al.,* 2017; Yunus and Azaha 2021; Yusoff and Mohamad Zuki, 2015; Yusoff *et al.*, 2018); and sodium metabisulfite was utilized for starches derived from banana pith (Yushananta and Ahyanti; 2022), gadung (Yusoff *et al.*, 2021), native sago trunk (NSTS) (Aziz and Sobri, 2015), and oil palm trunk (Ahmed *et al.*, 2021; Yusoff *et al.*, 2019).

Mechanical extraction was reported in 2 studies. For example, Polynesian arrowroot starch was obtained by blending, filtering, settling, and decanting—without chemical additives, making it eco-friendly (Makhtar *et al.*, 2020). Another method, applied to durian seeds, involved dry milling (cutting, drying, grinding, and sieving) and wet milling (blending with NaCl, treating with NaOH, centrifugation, and purification). Final steps included neutralization with HCl and drying at 45 °C for 24 hours (Zamri *et al.*, 2018).

Starch extraction from non-conventional sources employs various methods with differing environmental impacts. Alkaline extraction using sodium hydroxide (NaOH) requires proper neutralization to prevent elevated pH levels in receiving waters, while sodium metabisulfite, though effective, poses occupational health risks. In contrast, citric acid offers a biodegradable and safer alternative, and distilled water extraction remains the most environmentally benign, requiring no chemicals.

Mechanical methods, such as wet and dry milling, avoid chemical inputs but are typically more energy-intensive, often relying on fossil fuels that contribute to CO_2 emissions. Compared with conventional coagulants like alum and ferric chloride, which produce hazardous sludge (Mortula *et al.,* 2009; Pandey, 2020), starch-based biocoagulants—particularly those derived through green extraction—represent a more sustainable option, though comprehensive life-cycle assessments are needed to confirm their overall environmental advantage.

Starch Modification

Among the 18 studies reviewed, seven reported using starch modification to enhance performance. The primary methods applied to non-conventional starches include chemical (e.g., esterification and cross-linking), physical (e.g., gelatinization), and hybrid methods (e.g., combined cross-linking and microwave irradiation). Chemical modification remains the most widely used approach for both conventional and non-conventional starches (Zarski *et al.,* 2024).

Esterification modifies starch by introducing ester groups through reactions between organic acids (or their derivatives) and alcohols (Otache *et al.,* 2021). For example, lemongrass-modified cassava peel starch (MCPS) incorporated active groups that enhanced antimicrobial and flocculation performance (Asharuddin *et al.,* 2019). Similarly, acetylation of green plantain peel starch using acetic anhydride introduced acetyl groups that reduced water affinity and imparted hydrophobicity, confirming successful modification (Cortes-Pérez *et al.,* 2023).

Chemical cross-linking, another modification route, forms covalent bonds between starch hydroxyl (-OH) groups using cross-linking agents (Malik *et al.,* 2022). Glutaraldehyde was used to produce durian starch hydrogels (Pimpa and Pimpa, 2014), while epichlorohydrin-cross-linked durian seed starch (CDSS) and oil palm trunk starch exhibited improved structure and flocculation efficiency (Yusoff *et al.,* 2018; Yusoff *et al.,* 2019).

A documented physical modification is gelatinization, where heating starch in water disrupts its crystalline structure, increasing solubility and altering viscosity. Polynesian arrowroot starch treated by this method demonstrated high removal efficiencies for turbidity, TSS, and color (Makhtar *et al.,* 2020).

Hybrid modification combines chemical and physical approaches. For instance, microwave-assisted graft copolymerization of banana pith starch with 3-chloro-2-hydroxypropyltrimethylammonium chloride (GTA) yieldedcationic graft polymers viafree-radical formation, thereby significantly improving coagulation efficiency (Yushananta &Ahyanti, 2022).

Starch Characterization and Functional Groups

Characterizing starch is essential for understanding its properties and optimizing its performance in water treatment. Of the 18 studies reviewed, 13 employed one or more characterization techniques.

Zeta potential analysis, a key method, measures the surface charge of starch particles in suspension to assess colloidal stability and coagulation potential. Higher absolute zeta potential values indicate greater particle repulsion, thus requiring higher coagulant dosages (Al-Hamadani *et al.,* 2011; Cañizares *et al.,* 2009).

Microscopy techniques, such as Scanning Electron Microscopy (SEM), reveal the surface morphology of starch and are often paired with Energy-Dispersive X-ray Spectroscopy (EDX) for elemental analysis. For instance, Polynesian arrowroot starch was analyzed by elemental analysis and ICP spectrometry to quantify phenolic content associated with enhanced flocculation (Makhtar *et al.,* 2020).

Fourier Transform Infrared (FTIR) and Nuclear Magnetic Resonance (NMR) spectroscopy are commonly used to identify functional groups and confirm structural modifications. NMR, for example, verified the incorporation of lemongrass-derived compounds into cassava peel starch (Asharuddin *et al.,* 2019). Crystallinity and phase transitions are assessed using X-ray Diffraction (XRD), while X-ray Fluorescence (XRF) provides non-destructive elemental composition data.

Physical and thermal behaviors are typically characterized through Laser Diffraction Particle Size Analysis (LDPSA), Thermogravimetric Analysis (TGA), and Differential Scanning Calorimetry (DSC). Chromatographic and spectrophotometric methods—such as High-Performance Liquid Chromatography (HPLC) and UV–Vis spectroscopy—are employed to quantify sugar content and absorbance of active compounds. In one study, a Photometric Dispersion Analyzer (PDA) was used to monitor floc formation from durian seed starch, revealing that its combination with polyaluminum chloride (PAC) improved floc quality (Yusoff *et al.,* 2018).

Common functional groups identified in starch-based coagulants include hydroxyl (-OH), amine (-NH), carbonyl (-C=O), carboxyl (-COOH), methyl ($-CH_3$), ether (C–O–C), alkene ($C=CH_2$), and alkyl ($-CH_2-$, $-CH_3$) groups. These groups influence solubility, surface charge, and metal ion chelation, which are critical for enhancing flocculation and contaminant removal (Asharuddin *et al.,* 2019; Makhtar *et al.,* 2020).

Starch-Based Water Treatment Performance Overview

Chemical coagulants are widely used but can be costly, toxic, and environmentally harmful. Natural biocoagulants, particularly those derived from non-conventional starches, offer an eco-friendly alternative and can achieve comparable performance, especially when chemically or physically modified. Table 1 summarizes studies on their application, most (17 of 18) used jar tests to evaluate coagulation and flocculation, adjusting key variables such as dosage and pH to optimize performance.

Performance by Starch Source

Non-conventional starch biocoagulants have shown excellent wastewater treatment performance. For instance, turbidity removal rates have been reported as high as 98.91% for banana pith starch (Cortes-Pérez *et al.*, 2023), 92.75% for cassava peel starch (Asharuddin *et al.*, 2019), 95.1% for durian seed starch (Yusoff *et al.*, 2018), and 94% for gadung starch (Yusoff *et al.*, 2021). Additionally, these starch-based coagulants have shown potential for removing heavy metals from wastewater. Native sago trunk starch (NSTS), when combined with PAC, achieved high removal efficiencies for turbidity (98.9%), suspended solids (99.2%), color (94.7%), COD (35.5%), NH_3-N (2.4%), UV_{254}-absorbing organics (69.5%), and cadmium (53.8%), but was ineffective for nickel (0%). Using NSTS alone at a higher dosage of 7,000 mg/L and pH 4 improved nickel removal to 44.1% (Aziz &Sobri, 2015). Notably, oil palm trunk starch removed100% of manganese (Mn), zinc (Zn), and phosphate (PO_4^{3-}), and 95.6% of copper (Cu). Furthermore, cassava peel starch has demonstrated antimicrobial activity, as evidenced by a 100% removal of E. coli from wastewater.

Effect of pH

Some starch-based biocoagulants, including cassava peel, durian seed, gadung, green plantain peel, and oil palm trunk starch, perform best at neutral pH, often when combined with alum. At the optimum pH, hydroxoaluminum species form—monomeric and polymeric cations that enhance surface adsorption and particle binding, respectively (Cañizares *et al.,* 2009). Starch polymers, such asamylose and amylopectin, also form interparticle bridges, further improving coagulation efficiency (Kumar *et al.,* 2021). This dual mechanism enhances overall flocculation performance.

Cassava peel starch combined with alum achieved optimal removal efficiency at pH 8, where total suspended solids (TSS) removal increased up to this level before declining beyond it (Asharuddin *et al.*, 2019). Conversely, jackfruit seed starch, native sago trunk starch, and Polynesian arrowroot performed better under acidic conditions. For Polynesian arrowroot, turbidity, TSS, and color removal improved as pH decreased to 3, attributed to protonation of carboxyl and hydroxyl groups, which increases positive charge density and promotes colloidal destabilization (Makhtar *et al.,* 2020).

Similarly, jackfruit seed starch showed high dye removal at low pH, with color removal efficiency decreasing from 87.5% at pH 2 to 65.3% at pH 7, due to reduced electrostatic attraction between cationic dye molecules and hydroxyl groups on the starch surface (Yusoff & Zuki M., 2015).

Impact of Modifications

Starch modifications have also proven to enhance performance. Cassava peel starch modified with lemongrass extract, incorporating active groups such as neral and geranial, citral isomers, as identified by NMR analysis. The modified cassava peel starch, when used with alum, showed an impressive 100% removal across a pH range of 2-11, demonstrating its suitability for a wide pH range. In contrast, the unmodified cassava peel starch exhibited fluctuating performance, ranging from approximately 65% to 90% removal within the study's pH range (Asharuddin *et al.*, 2019).

Acetylation of green plantain starch introduced acetyl groups, reducing the starch's water affinity and improving flocculation. Additionally, acetylation enhances starch's affinity for both water and oil, improving its gel solubility, swelling capacity, and viscosity, while reducing its initial gelatinization temperature (Reddy *et al.*, 2015). While acetylated starch exhibited up to 46.5% removal, its combination with aluminum sulfate enhanced turbidity removal up to 98.91% (Cortes-Pérez *et al.*, 2023).

Durian seed starch, when cross-linked with epichlorohydrin, enhanced the interconnection between starch molecules, producing larger flocs and better floc behavior. This modification may help reduce the consumption of the chemical coagulant polyaluminum chloride (PAC) in leachate treatment. At the optimum dosage of 400 mg/L of durian seed starch-based flocculants, combined with 2200 mg/L of PAC, the removal percentages of color, COD, suspended solids (SS), and turbidity were determined to be 91%, 65.5%, 87.2%, and 89.7%, respectively. SS and COD levels were within the landfill discharge standard limits set by the Environmental Quality Act (EQA) (Yusoff *et al.*, 2018).

Interestingly, durian seed starch was also used in another study to treat leachate without any modifications. As a result, it achieved color and COD removal rates of 10.41% and 12.78%, respectively. The unmodified starch was outperformed by its modified counterpart. However, the modified starch was still concluded to be unsatisfactory for use as a coagulant in wastewater treatment due to its low efficiency (Zamri *et al.*, 2018).

Meanwhile, gelatinization of Polynesian arrowroot caused the separation of amylose and amylopectin from the starch, facilitating bridging flocculation. The resulting flocs were uniform, smooth, and compact, making them easier to settle. The highest removals of turbidity, TSS, and color were 75.1–79%, 90.75–91.9%, and 93.6–94.31%, respectively, with 240 mg/L of modified starch. At higher dosages, the colloidal mixture began to restabilize due to repulsion between the polymer and colloid particles, resulting in poorer performance (Makhtar *et al.*, 2020).

Banana pith starch, when cross-linked with GTA and irradiated by microwave, produced a cationized starch structure. This modification enabled bridging flocculation, resulting in a 94.4%reduction in turbidity with color and TDS removal of87.46% and 57.33%, respectively, at 300 mg/L. At higher doses, colloidal particles began to restabilize, leading to reduced performance (Cortes-Pérez *et al.*, 2023).

Limitations and Knowledge Gaps

Numerous studies on starch-based coagulants demonstrate their potential, yet methodological and reporting limitations hinder practical application and scalability. A recurring issue is reliance on single-variable optimization, where only one parameter—such as pH, dosage, or alum-starch ratio—is varied at a time. This approach, applied in cassava peel starch studies (Asharuddin *et al.*, 2019; Asharuddin *et al.*, 2023; Kumar *et al.*, 2020; Othman *et al.*, 2018) and studies on jackfruit seed starch (Yunus & Azaha, 2021), native sago trunk starch (Aziz & Sobri, 2015), oil palm trunk starch (Yusoff et al., 2019), gadung starch (Yusoff *et al.*, 2021), and Polynesian arrowroot starch (Makhtar *et al.*, 2020), limits the ability to evaluate interactions between variables. Advanced optimization techniques, such as Response Surface Methodology (RSM), are recommended for a more comprehensive and statistically robust understanding of optimal conditions.

Incomplete reporting of experimental details further reduces reproducibility. For instance, the banana pith starch study (Cortes-Pérez *et al.*, 2023) tested acetylated starch alone and in combination with alum but did not explicitly specify the dosages used. Some cassava-based studies (Kumar *et al.*, 2020; Kumar *et al.*, 2018) reported only ratios without corresponding mass or volume measurements, or presented data in the graphical formats that hindered extraction of exact values. Such omissions impede replication and comparative analysis.

Mechanistic understanding of coagulation or flocculation was also inconsistently addressed. The banana pith starch study (Yushananta & Ahyanti, 2022) lacked a discussion of the working mechanismIn contrast, the green plantain peel starch study (Cortes-Pérez *et al.*, 2023) inferred a bridging mechanism without verification using analytical techniques such as FTIR or zeta potential analysis. Durian seed starch studies (Zamri *et al.*, 2018) reported the presence of amines and carboxylic acid groups in dry-milled samples. Still, they did not explain their absence in wet-milled samples or relate their findings to performance outcomes. Similarly, one cassava starch study (Othman *et al.*, 2018) omitted any mechanistic discussion, limiting understanding of performance variability.

In some studies, performance assessment was restricted to turbidity removal, omitting critical parameters such as COD and TSS. For example, the banana pith starch study (Yushananta & Ahyanti, 2022) would have benefited from a more comprehensive set of performance metrics. Durian seed starch/PVOH composite hydrogels (Pimpa & Pimpa, 2014) demonstrated good adsorption of methylene blue but lacked regeneration studies to assess reusability. Another durian seed starch study (Zamri *et al.*, 2018) showed limited contaminant removal with mechanical extraction, suggesting utility mainly as a coagulant aid; further chemical modification could enhance floc formation and settling.

Notably, cassava peel starch (Yushananta & Ahyanti, 2022) displayed antibacterial properties after chemical modification, potentially reducing the need for separate disinfection and operational costs. However, the economic implications were not quantified, thereby missing an opportunity to connect functional properties to cost-benefits analyses.

Working Mechanism

Eight of the 18 studies reviewed explicitly discussed the coagulation mechanisms of starch-based materials, including adsorption, charge neutralization, sweep flocculation, interparticle bridging, and patch agglomeration between the starch and contaminants.

Adsorption

Adsorption occurs when starch molecules interact with suspended particles, adhering to their surface through chemical or physical forces (Manholer *et al.*, 2019). The hydrolysis of coagulants can produce complexes with a high positive charge that adsorb to the surfaces of negatively charged colloidal particles, neutralizing their charge and eventually destabilizing the colloids (Ghernaout *et al.*, 2010). This mechanism is typically confirmed upon revealing the surface morphology. In an experiment on durian seed starch, it was observed that different particles adhere to the surface, suggesting adsorption mechanisms. Jackfruit seed starch has demonstrated effective adsorption properties due to its surface functional groups and structural compatibility. The presence of a high amount of amylopectin in the starch favors enhanced adsorption capacity (Choy *et al.*, 2017). Under acidic conditions, durian seed starch exhibited coagulation behavior, attributed to surface adsorption and interparticle bridging, as confirmed by FESEM and EDX analyses (Zamri *et al.*, 2018). Cassava peel starch also exhibited adsorption and interparticle bridging mechanisms, as evidenced by floc characterization using FTIR, SEM, and EDX (Asharuddin *et al.*, 2023).

Charge Neutralization

Charge neutralization occurs when the charges of suspended particles are balanced by those of starch-based flocculants, leading to particle destabilization (Amran *et al.*, 2018). The process depends on factors such as molecular weight, charge density, and particle charge (Qudsieh *et al.*, 2008). Dry-milled durian seed starch, for instance, exhibits strong alkaline properties that enable effective neutralization under acidic conditions (Zamri *et al.*, 2018), as evidenced by zeta potential analysis. Similarly, sago starch-grafted polyacrylamide copolymers utilize charge neutralization during rapid mixing, forming macroparticles that subsequently aggregate into flocs (Qudsieh *et al.*, 2008). Although cassava peel starch also demonstrates this mechanism, its charge-neutralization capacity is generally weaker than that of alum (Asharuddin *et al.*, 2023), as evidenced by its electrokinetic profile based on zeta potential measurements.

Sweep Flocculation

Sweep flocculation involves the formation of a matrix-like structure that traps suspended particles as it settles (Okuda *et al.,* 1999). In one study, cassava peel starch with alum enhanced contaminant removal efficiency: alum initiated floc formation via charge neutralization, while the starch's negatively charged components bound bivalent cations, forminga net-like structure (Asharuddin *et al.,* 2023). This mechanism was also observed in durian seed starch, where large particle clusters accumulated within flocs and dense black particles stacked at their centers (Zamri *et al.,* 2018).

Interparticle Bridging

Inter-particle bridging involves the starch molecules forming connections between particles, linking them together into larger aggregates. The interparticle bridging mechanism involves the formation of a "particle-polymer-particle" complex (Moussa *et al.*, 2017). It has been the most identified working mechanism in this study. A study on native sago trunk starch found that an increase in floc particle size provided evidence of interparticle bridging. Additionally, its high molecular weight, weakly ionic nature, and the presence of hydroxyl (O–H) and carboxyl (C=O) groups contributed to enhanced flocculating efficiency (Aziz and Sobri, 2015). Starches with a higher amylopectin content exhibit enhanced particle-bridging capabilities, attributed to their substantial molecular weight and branched structure. This characteristic facilitates the formation of larger flocs, making such starches particularly effective as coagulants in water treatment processes (Choy *et al.*, 2017).

Electron microscopy of oil palm trunk starch confirmed floc formation via interparticle bridging, facilitated by hydroxyl, carboxylic, and amino groups that promote effective particle aggregation (Ahmed *et al.,* 2021). Similarly, cross-linked durian seed starch exhibited enhanced flocculation, as new intermolecular covalent bonds formed during cross-linking improved its capacity to attract and bind particles in leachate (Yusoff *et al.,* 2018). In cassava peel starch, hydroxyl (-OH) and amine (-NH_2) groups interact with functional groups on suspended particles, further promoting coagulation (Kumar *et al.,* 2021).

Additionally, the interparticle bridging mechanism has been reported in various starches, including jackfruit seed starch, with zeta potential analysis providing supporting evidence for the proposed mechanism (Choy *et al.,* 2017), as well as in oil palm trunk starch (Yusoff *et al.,* 2019) and cassava peel starch (Asharuddin *et al.,* 2023).

Patch Aggregation

Patch aggregation occurs when starch molecules adhere to specific regions of particles, leaving uncoated areas that promote particle attraction. Flocculants adhere to colloidal particles due to their opposite charges, partially neutralizing the particle's surface. These adsorbed flocculants then serve as anchoring sites, facilitating the aggregation of adjacent particles (Chen *et al.*, 2018). Cassava peel starch is a notable example of this mechanism, with zeta potential analysis providing supporting evidence (Asharuddin *et al.,* 2023).

Table 1. Performance of non-conventional starch-based biocoagulants

No.	Starch Source	Type of Water Treated	Test Conducted	Optimum Condition	Initial Conditions (mean values)	Optimum Performance (% removal)	References
1	Banana pith	River Water	**Jar test**	**Dosage:** 300 mg/L	**Turbidity:** 385.9 NTU	**Turbidity:** 98.91%	Yushananta and Ahyanti; 2022
2	Cassava peel	Dam reservoir water	**Jar test**	**Dosage:** Alum-MCPS 7.5–50 mg/L, **pH:** 7	**Turbidity:** 26.06 NTU, **E. coli:** 10,000 CFU/mL	**Turbidity:** 92.75%, **E. coli :**100%	Asharuddin *et al.*, 2019
3	Cassava peel	Dam reservoir water	**Jar test**	**Dosage:** alum-CPS 7.50–50.00 mg/L, **pH:** 7	**Turbidity:** 26.06 NTU, **TSS:** 26.50 mg/L, **COD:** 11.88 mg/L	**Turbidity:** 90.32%, **TSS:** 88.89%, **COD:** 27.04%	Asharuddin *et al.*, 2023
4	Cassava peel	Institutional wastewater	**Jar test**	**Dosage:** 30 mg/L-400 mg/L, alum CPS ratio 40:60, **pH:** 8	**Turbidity:** 268-502 NTU	**Turbidity Removal:** 81%	Kumar *et al.*, 2020
5	Cassava peel	Institutional wastewater	**Jar test**	**Dosage:** Alum-CPS ratio4:1 ratio, **pH:** 8	**Turbidity:** 194 NTU, **TSS:** 284 mg/L, **COD:** 296.25 mg/L	**Turbidity:** 77.48%, **TSS :** 77.34%, **COD:** 56.89%	Kumar *et al.*, 2021
6	Cassava peel	Dam reservoir water	**Jar test**	**Dosage:** Alum-CPS ratio 70:30	**Not mentioned**	**Turbidity:** 90%, **COD :** 20% (approximate values)	Othman *et al.*, 2018
7	Durian seed	Methylene blue solution and acid orange 8 solution	**Batch adsorption test**	**Dosage:** 3% DSS; **pH** 7 (MB), **pH** 2.5 (OA)	**Dye concentration:** 2 x 10^{-5} M	**Optimum adsorption capacities:** 3.411 mg/g (MB), 3.274 mg/g (OA)	Pimpa and Pimpa, 2014

8	Durian seed	Landfill leachate	**Jar test**	**Dosage:** 400 mg/L CDSS with 2200 mg/L of PAC	**Turbidity:** 243 NTU, **SS:** 750 mg/L, **COD:** 3,770 mg/L, **Color:** 7,020 PtCo	**Turbidity:** 95.1% **SS:** 85.2%, **COD:** 60.9%, **Color:** 96.1%	Yusoff *et al.*, 2018
9	Durian seed	Landfill leachate	**Jar test**	**Dosage:** Dry-milled DSS 3000 mg/L (color) and 1000 mg/L (COD), **pH:** 6	**COD:** 352 mg/L, **Color:** 1,134 PtCo	**COD:** 12.78%, **Color:** 10.41%	Zamri *et al.*, 2018
10	Gadung Starch	textile effluent	**Jar test**	**Dosage:** 2500 mg/L **pH:** 7	**Turbidity:** 21.37 NTU, **COD:** 460 mg/L, **Color:** 645 PtCo	**Turbidity:** 94%, **COD:** 28% **Color:** 64%	Yusoff *et al.*, 2021
11	Green plantain peel	River water	**Jar test**	**Dosage:** $Al_2(SO_4)_3$/ Acetylated starch hybrid at a 3:1 ratio, **pH:** 7	**Turbidity:** 385.9 NTU (average)	**Turbidity:** 98.1%	Cortes-Pérez *et al.*, 2023
12	Jackfruit seed	Synthetic kaolin water	**Jar test**	**Dosage:** 60 mg/L	**Turbidity:** 167 NTU	**Turbidity:** 43%	Choy *et al.*, 2017
13	Jackfruit seed	synthetic textile wastewater	**Jar test**	**Dosage:** 50 mg/L, **pH:** 2	**Dye Concentration:** 200 mg/L Congo Red	**Turbidity Removal:** 89.1% **Color Removal:** ~100%	Yunus and Azaha 2021
14	Jackfruit seed	Landfill leachate	**Jar test**	**Dosage:** 523.32 mg/L PAC, 400 mg/L starch **pH:** 5	**COD:** 345-902 mg/L	**COD removal:** 26.85%	Yusoff and Mohamad Zuki, 2015

15	Native sago trunk	landfill leachate	**Jar test**	**Dosage:** 6,000 mg/L NSTS, 2,000 mg/L PAC **pH:** 6	**Turbidity:** 263 NTU, **SS:** 290 mg/L, **COD:** 3,200 mg/L, **Color:** 5,206 PtCo, **NH_3-N:** 826 mg/L, **organic UV_{254}:** 12.6 cm^{-1}, **Cd:** 0.069 mg/L, **Ni:** 0.243 mg/L.	**Turbidity:** 98.9%, **SS :** 99.2%, **COD:** 35.5%, **Color :** 94.7%, **NH_3-N:** 2.4%, **Organic UV_{254} :** 69.5%, **Cd:** 53.8% mg/L, **Ni :** 0.0%	Aziz and Sobri, 2015
16	Oil palm trunk	Landfill leachate	**Jar test**	**Dosage:** 500 mg/L **pH:** 7	**Mn:** 5.83 mg/L, **Zn:** 1.15 mg/L, **PO_4^{3-}:** 53.25 mg/L, **Cu:** 4.00 mg/L	**Mn:** 100%, **Zn:** 100%, **PO_4^{3-} :** 100%, **Cu:** 100%	Yusoff *et al.*, 2019
17	Oil palm trunk	Landfill leachate with humic acid	**Jar test**	**Dosage:** 500 mg/L **pH:** 7	**COD:** 4,142 mg/L, **Color:** 5,039 PtCo	**COD:** 84.96%, **Color:** 48.84%	Ahmed *et al.*, 2021
18	Polynesian arrowroot	Landfill leachate	**Jar test**	**Dosage:** 240 mg/L **pH:** 3	**Turbidity:** 218 NTU, **TSS:** 214 mg/L, **Color:** 14,201 PtCo	**Turbidity:** 75.0-79.0%, **TSS:** 90.0%-90.7%, **Color:** 93.0%-94.0%	Makhtar *et al.*, 2020

QUANTITATIVE COMPARATIVE ANALYSIS AND NORMALIZED PERFORMANCE METRICS

A comparative evaluation of the treatment performance of non-conventional starch-based biocoagulants remains challenging due to the heterogeneity of reporting across the reviewed studies. The reported treatment objectives vary considerably depending on the type of wastewater and the focus of the individual study. Consequently, key performance indicators such as turbidity, chemical oxygen demand, and suspended solids, despite being among the most common in the studies reported, are not consistently reported across all investigations.

In this study, the performance of the different non-conventional starch-based biocoagulants across the three indicators was compared through normalization to dosage requirement using the following metric:

$$Normalized\ Efficiency = \frac{Removal\ Efficiency\ (\%)}{Dosage\ (\%)}$$

This metric expresses pollutant removal efficiency per unit dosage and provides a basis for comparing the dosage-effectiveness of different starch sources and modification strategies. It enables a more objective comparison among studies with varying dosage levels, particularly where direct comparison based solely on removal efficiencies may be misleading. Where multiple studies reported data for the same starch source, the computed normalized efficiencies were aggregated and presented as a range to facilitate cross-study synthesis.

Table 2 presents the normalized efficiencies of different non-conventional starch-based biocoagulants, expressed as percentage removal per unit dosage (mg/L). Based on turbidity removal, cassava peel starch exhibited the highest normalized efficiency, ranging from 1.806 to 1.855% per mg/L, followed by jackfruit seed starch with values ranging from 0.717 to 1.782% per mg/L. These results suggest that both starch sources can achieve high removal efficiencies at relatively lower dosages compared with other starches. In contrast, native sago trunk starch and gadung starch showed substantially lower normalized turbidity efficiencies of 0.016 and 0.038% per mg/L, respectively, indicating the need for much higher dosages to achieve comparable treatment performance.

For COD removal, cassava peel starch again demonstrated the highest normalized efficiency (0.5408% per mg/L), followed by oil palm trunk starch (0.170% per mg/L) and durian seed starch, which showed a wider range (0.0123–0.15225% per mg/L). The variation observed for durian seed starch may reflect differences in wastewater characteristics, dosage conditions, and whether the starch was used alone or in combination with commercial coagulants. Meanwhile, native sago trunk starch and gadung starch exhibited lower normalized COD efficiencies, suggesting weaker performance in reducing organic load under the reviewed conditions.

For TSS removal, cassava peel starch also yielded the highest normalized efficiency (1.7778 % per mg/L), followed by durian seed starch (0.213 % per mg/L) and oil palm trunk starch (0.098 % per mg/L). The consistently higher normalized values for cassava peel starch across multiple response variables may indicate its strong potential as a biocoagulant source.

Overall, the normalized comparison suggests that cassava peel and jackfruit seed starches show the most promising performance among the reviewed non-conventional starch sources. However, these values should be interpreted with caution, as performance is still influenced by factors such as wastewater composition, pH, coagulant combinations, and optimization methodology.

In addition to dosage normalization, future comparative analyses may benefit from incorporating multi-criteria performance indicators that account for water characteristics (e.g., pH, contaminant type and concentration, and temperature), coagulant/flocculant properties (e.g., material type, dosage, mixing speed, and particle size), as well as sustainability and applicability considerations (e.g., regeneration potential, sludge generation, cost, and health concerns), which are among the key factors affecting coagulation and flocculation performance (Badawi *et al.,* 2023). Furthermore, PCA and AHP may support more robust cross-study comparisons and of non-conventional starch sources based on technical, economic, and environmental criteria.In contrast, RSM and other DOE-based optimization tools are more suitable for identifying optimal operational conditions within experimental studies.

LIMITATIONS IN THE USE OF NON-CONVENTIONAL STARCHES

Variability in Raw Material Composition

Despite their potential, non-conventional starches face several challenges that hinder widespread adoption. They exhibit considerable variability in composition, which affects starch yield and physical, chemical, structural, thermal, and nutritional properties. This variability, influenced by botanical sources (Carvalho *et al.,* 2024), complicates standardization and selection of appropriate modification methods. Identification of functional groups is also essential, as chemical moieties provide insights into coagulation behavior (Salehizadeh & Yan, 2014).

Table 2. Normalized efficiencies of each type of non-conventional starch biocoagulants

Starch source	**Normalized efficiency (% per mg/L)**			**Reference**
	Turbidity	COD	TSS	
Banana Pith	0.3297	NR	NR	Yushananta and Ahyanti; 2022
Cassava Peel	1.806-1.855	0.5408	1.7778	Asharuddin et al., 2019; Asharuddin et al., 2023
Durian seed	0.238	0.0123-0.15225	0.213	Yusoff et al., 2018; Zamri et al., 2018
Gadung Starch	0.038	0.011	NR	Yusoff et al., 2021
Jackfruit seed	0.717-1.782	0.067	NR	Choy et al., 2017; Yunus and Azaha 2021; Yusoff and Mohamad Zuki, 2015
Native sago trunk	0.016	0.006	0.017	Aziz and Sobri, 2015
Oil palm trunk	NR	0.170	0.098	Ahmed et al., 2021

Note: NR indicates that the information was not reported in the cited study.

Such variability poses a barrier to industrial adoption because it compromises reproducibility and consistency in treatment outcomes. Fluctuations in gelatinization temperature, amylose-to-amylopectin ratios, and surface charge can lead to inconsistent coagulation efficiency (Kumar *et al.,* 2021; Cortes-Pérez *et al.,* 2023; Choy *et al.,* 2017; Makhtar *et al.,* 2020). To address this, starches should be characterized before and after modification to identify pathways yielding consistent performance. Extraction methods that minimize structural damage to starch granules can further enhance the uniformity and predictability of coagulation.

Another limitation is the inability of starch-based biocoagulants to remove certain dissolved nutrients, such as ammonia nitrogen (NH_3-N). For instance, sago starch, which contains protein, is ineffective at removing NH_3-N generated during methanogenesis (Sung & Liu, 2023). COD removal also varies widely, from 28% for gadung starch (Yusoff *et al.,* 2021) to only 1.7% for native sago trunk starch (Aziz & Sobri, 2015). These differences are explained by the starch's physical and chemical properties. Gadung starch contains functional groups that facilitate bridging with molecules, promoting floc formation and enhancing COD removal (Yusoff *et al.,* 2021). Native sago trunk starch, with a zeta potential of –22.2 mV, forms unstable particles in wastewater (–15.3 mV), limiting its standalone effectiveness. However, combined with alum at optimal dosages, COD removal can reach 35.5% (Aziz & Sobri, 2015).

Operational and Optimization Limitations

High dosage requirements remain a significant operational limitation for certain non-conventional starch-based bio-coagulants. For instance, gadung starch requires up to 2,500 mg/L (Yusoff *et al.,* 2021), native sago trunk starch 6,000 mg/L at pH 6 (Pimpa & Pimpa, 2014), and oil palm trunk starch 1,680 mg/L (Yusoff *et al.,* 2019). Such high dosages may increase material consumption, sludge generation, and long-term operational costs, hindering practical large-scale implementation. To improve treatment efficiency and reduce the required dosage, many studies have employed combinations with commercial coagulants. For example, durian seed starch (CDSS) demonstrated optimal performance at 400 mg/L when combined with 2,200 mg/L PAC (Yusoff *et al.,* 2018), while cassava peel starch has been reported to perform best when paired with alum at specific ratios (Kumar *et al.*, 2020; Kumar *et al.,* 2021).

Optimization of process conditions is therefore essential to improve the adaptability and economic feasibility of starch-based coagulation systems, particularly when long-term operational costs are considered. Several studies have applied statistical optimization methods to determine optimal operating parameters, including dosage, pH, mixing speed, and settling time. For example, oil palm trunk starch (OPTS) has been optimized using Taguchi robust design in PAC-OPTS and PAC-COPTS coagulation systems (Yusoff *et al.,* 2017). Similarly, natural oil palm trunk starch has been optimized using central composite design (CCD) coupled with response surface methodology (RSM) (Ahmed *et al.,* 2021). In another study, cassava peel starch was optimized using RSM based on CCD to evaluate the interaction effects among process variables (Kumar *et al.,* 2021).

However, several studies still rely on the traditional one-variable-at-a-time (OVAT) or one-factor method, in which only a single parameter is varied while the others are kept constant. Although this method is simple and widely used at the laboratory scale, it may fail to capture interaction effects among operational variables and may increase the number of experimental runs. It may lead to suboptimal process conditions (Bezerra *et al.,* 2008). Advanced optimization tools based on design of experiments (DOE), such as Box–Behnken design (BBD), central composite design (CCD), and Taguchi methods, offer more robust alternatives by simultaneously evaluating multiple factors and their interactions. In addition, machine learning and multivariate statistical tools may offer further opportunities to optimize coagulation performance and predict system behavior under varying wastewater conditions.

Response surface methodology (RSM) is a mathematical and statistical approach widely used to model and analyze processes in which the desired response is influenced by multiple variables, enabling optimization of the response. RSM is commonly used in optimizing output variables and process design, especially in experiments involving biocoagulants (Arulmathi *et al.,* 2019; Shahzadi *et al.,* 2024; Zaid *et al.,* 2019). Box–Behnken design (BBD) and central composite design (CCD) are among the most commonly used experimental designs within RSM (Szpisják-Gulyás *et al.,* 2023). However, optimal (custom) designs are also promising, such as D-optimal design (Madjene *et al.,* 2023; Madjene *et al.,* 2025) and I-optimal design (Khoo *et al.,* 2021) in coagulant studies.

Other DOE-based methods have likewise been reported in related biocoagulant applications. These include the Doehlert design for optimizing coagulation–flocculation using chitosan as a biocoagulant in tannery wastewater treatment plants (Yahia *et al.,* 2021), fractional factorial design in extracted proteins from oak leaves as a bio-coagulant for water and wastewater treatment (Benalia *et al.,* 2023), and Box–Behnken design for the clarification of landfill leachate using biocoagulants (Semassel *et al.,* 2025). Similarly, the removal of color and turbidity from wet coffee processing industry wastewater has also been optimized through central composite design (Getahun *et al.,* 2024).

In recent years, machine learning (ML) data-driven models have also emerged as promising tools for process optimization in water treatment applications, including decision tree (DT), artificial neural network (ANN), support vector machine (SVM), random forest (RF), and K-nearest neighbor (KNN) methods (Matovelle *et al.,* 2023). For example, Luffa cylindrica seed (LCS) extract was optimized using RSM and ANN models, and ANN was found to provide better prediction of the removal of color/total suspended particles (CTSP) and chemical oxygen demand (COD) from dye-polluted wastewater (Onukwuli *et al.,* 2025). Similarly, an ANN was used to predict the turbidity removal efficiency of PACl and Moringa oleifera in water treatment plants (Krishnan *et al.,* 2023).

Other predictive models are likewise suggested for incorporation into future studies involving non-conventional starch biocoagulants as innovative tools for process optimization, performance forecasting, and operational decision support. Future studies should prioritize the use of advanced optimization frameworks to improve process robustness, reduce dosage requirements, and strengthen the techno-economic viability of non-conventional starch-based coagulants for pilot- and industrial-scale applications.

Scale-Up and Techno-Economic Constraints

Like conventional starches, non-conventional starches face significant challenges in scaling up for biocoagulant applications. Most studies have been limited to laboratory-scale research, and industrial-scale implementation remains underexplored (Kurniawan *et al.,* 2020; Nanje Gowda *et al.,* 2024). Scaling up requires large-scale biocoagulant production, reliable and continuous raw material supply, and modifications to treatment infrastructure to maintain optimal coagulation conditions. Similar scale-up bottlenecks are commonly discussed in wastewater technology reviews and techno-economic assessments.

Starch modification methods, such as cationization and polymer grafting, are often labor-intensive and costly, limiting practicality. Some crosslinking agents, including epichlorohydrin, are effective but carry health risks; epichlorohydrin is classified as a Category 1B carcinogen under CLP Regulation (EC) No 1272/2008), indicating presumed carcinogenic potential based on animal studies.

Despite these challenges, some economic analyses highlight cost advantages. Cassava peel starch coagulant production is estimated at USD 1,295 per ton—much lower than refined cassava starch at USD 3,300 per ton (Kumar *et al.,* 2021). A techno-economic study indicated that daily coagulant costs for a PAC-CDSS system were RM 6,179.24, compared to RM 7,698.24 for PAC alone (Yusoff *et al.,* 2018), demonstrating that combining starch-based coagulants with commercial coagulants can reduce operational costs while improving treatment efficiency.

Few studies have addressed system design tailored to non-conventional coagulants. One pilot-scale design using PAC-CDSS treated up to 2,404.08 m^3 of landfill leachate, with three settling tanks of 22.68 m^3 each and a depth of 7.56 m. Compared to PAC-only systems, PAC-CDSS increased treatment capacity by ~1.6%, reduced the number of tanks needed, and improved floc formation and settling efficiency. These results suggest that starch-based coagulants can be integrated into existing wastewater treatment infrastructure with minimal modifications, offering economic and environmental benefits. Overall, while scale-up challenges persist, techno-economic analyses indicate strong potential for industrial adoption.

A practical pathway to industrial adoption may involve a location-based implementation strategy that reduces transportation, handling, and storage costs. The adoption of non-conventional starch biocoagulants may be more sustainable when aligned with areas where starch-rich waste materials are readily available. For example, starches derived from agricultural residues, market wastes, or agro-industrial by-products may be best utilized near their source of generation. This localized approach may improve the sustainability and economic feasibility of the treatment process.

A relevant example from the broader field of biocoagulants is chitosan, which possesses excellent coagulation and flocculation properties and has been shown to remove pollutants from industrial wastewater effectively. Since chitosan is commonly derived from waste materials from the fisheries sector, its use represents a sustainable approach for treating wastewater from fish-processing industries (Sibiya *et al.,* 2022). Similarly, starch-rich wastes generated by markets and agricultural industries may serve as abundant, low-cost raw materials for wastewater treatment.

Future studies should include feasibility and techno-economic analyses of locally available waste materials, particularly from the agricultural and fisheries sectors, to evaluate their potential as sustainable biocoagulants and bioflocculants. Such assessments would be valuable in identifying abundant, underutilized raw materials and supporting pathways toward industrial-scale adoption (Kurniawan et al., 2020).

Fig. 1: Proposed pathway for industrial adoption of non-conventional starch-based biocoagulants

The proposed pathway presented in Figure 1 addresses the current lack of pilot- and industrial-scale studies by outlining a stepwise framework for potential scale-up and adoption. It emphasizes a stepwise transition from laboratory findings toward practical industrial implementation. The initial stage focuses on site and feedstock suitability assessment to ensure that non-conventional starch sources are locally abundant and logistically feasible. This is followed by establishing a stable supply chain and optimizing extraction and modification protocols to maintain consistent coagulant quality. Subsequent bench-scale and pilot-scale validations are necessary to evaluate performance under real wastewater conditions and in continuous-flow systems. Finally, integration with existing wastewater treatment units, along with techno-economic and life-cycle assessments, is essential to assess the operational feasibility, environmental sustainability, and scalability of the proposed biocoagulant system. Techno-economic assessment provides critical insights into the feasibility of biocoagulants and supports the identification of viable market applications, thereby reducing costs and enhancing industrial adaptability (Bernard *et al.,* 2024).

Incomplete Reporting and Reproducibility Constraints

Several reviewed studies omit critical experimental details, including coagulant dosage, starch-to-coagulant ratios, mixing conditions, and mechanistic validation procedures. Such incomplete reporting limits reproducibility and weakens cross-study comparative analysis. In particular, the absence of standardized reporting on removal efficiency, dosage basis, and operational parameters complicates quantitative synthesis across different starch sources and wastewater types.

While it is recognized that each study has its own objectives and limitations, future studies are strongly encouraged to report the core operational parameters commonly used in coagulation–flocculation experiments, such as pH, coagulant dosage, mixing speed, mixing duration, and settling time, as these directly influence treatment performance and process scalability (Kurniawan et al., 2020). In studies employing dual biocoagulant or hybrid coagulant systems, ratios should be accompanied by the actual dosage of each component to improve clarity and comparability.

Among the reviewed studies, turbidity and COD were the most frequently reported response variables. Future studies are encouraged to report the initial, and final concentrations, and the removal efficiency (%) for these parameters. Additional water quality indicators may also be selected based on the intended wastewater application and relevant regulatory standards to improve cross-study comparison and practical relevance.

RESEARCH GAPS AND FUTURE DIRECTIONS

Comparative Performance Studies

Despite the diversity of non-conventional starches, studies on their use in wastewater treatment remain limited. This gap stems from the dominance of conventional starches, whose properties are well-established (Carvalho et al., 2024). Future research should investigate performance differences between starches from non-conventional and conventional sources. Comparative studies may use normalized efficiencies to enable fair comparison of performance across different starch types and operating conditions. In addition, a composite index may be developed considering several criteria, such as removal efficiencies, economic feasibility, environmental impacts, and social acceptability, similar to multi-criteria decision analysis (MCDA) frameworks, where weights are assigned systematically via methods such as expert judgment, AHP, PCA, and other statistical and decision-making techniques.

Process Optimization and Extraction Simplification

Extraction methods for non-conventional starches remain resource-intensive, requiring time, energy, and labor. Simplifying and optimizing these methods could lower barriers for industrial adoption while maintaining functional properties. Research should focus on protocols that maximize yield, minimize energy input, and assess the impact of extraction techniques on flocculation efficiency. The frameworks outlined in the previous sections may provide new researchers with ideas for the most promising optimization approaches, including RSM and emerging data-driven techniques such as machine learning-based optimization. This will support a more efficient, systematic process design for starch extraction and its application in wastewater treatment.

Life-Cycle and Techno-Economic Assessment

Economic feasibility is another critical aspect in the potential adoption of non-conventional starch-based biocoagulants. Comprehensive studies are needed to evaluate cost-effectiveness, identify the production steps that drive costs, and estimate potential returns at different scales. Understanding these factors is essential for translating laboratory findings into practical industrial applications. Future studies are encouraged to employ techno-economic assessment (TEA) frameworks that account for raw material sourcing, extraction, and modification costs, operational requirements, sludge handling, and potential savings from reduced use of chemical coagulant use.

In addition to economic feasibility, life-cycle assessment (LCA) remains underexplored in the current literature. Comparative studies on environmental footprints covering raw material collection, extraction, application, sludge generation, and disposal help clarify the sustainability advantages of non-conventional starches over conventional chemical coagulants. Review literature increasingly emphasizes integrated TEA–LCA frameworks for wastewater technologies, and a similar approach is recommended for future studies on starch-based biocoagulants.

A major consideration within both TEA and LCA is sludge generation and management. According to reports, a water treatment facility employing alum with a treatment capacity of 190 million liters per day is expected to generate at least 3 tonnes of solid waste per day, amounting to more than 1000 tonnes annually (Verma *et al.,* 2012; Zhao *et al.,* 2021). In contrast, many studies have reported that natural coagulants and flocculants can produce substantially lower sludge volumes, in some cases up to 5times lower than those produced by chemical coagulants/flocculants (Teh *et al.,* 2016). This reduction may translate into lower sludge handling, transportation, and disposal costs, which should be incorporated into future techno-economic analyses.

However, sludge management remains critical because coagulant sludge may release contaminants into the environment if not adequately contained. Improperly managed sludge can result in the leaching of residual pollutants into soil and groundwater and their subsequent migration into surrounding ecosystems. To mitigate these risks, sludge should undergo appropriate processing such as dewatering, stabilization, and solidification to reduce contaminant mobility and prevent environmental release (Ejimofor *et al.,* 2021; Loganathan *et al.,* 2024). Soil amendments such as lime, gypsum, and organic matter may also be employed to improve stability and reduce the risk of contaminant transport.

Beyond disposal, sludge valorization and resource recovery should be further explored. Recovery of phosphorus from sludge has been suggested, as the gradual release of nutrients into soil may benefit plants with extended growth periods (Loganathan *et al.,* 2024). Likewise, the nutrient content, organic matter, and binding properties of sludge may improve soil quality and promote plant growth when applied in appropriate quantities and in accordance with regulatory guidelines (Cai *et al.,* 2020; Loganathan *et al.,* 2024). Such approaches align with circular economy principles and may provide additional environmental and economic benefits.

In addition to sludge reuse, future studies may further explore the broader applicability of non-conventional starch-based biocoagulants and other natural flocculants across different wastewater streams. For example, the yam bio-flocculant demonstrated 80% solids removal when used in combination with a coagulant in oleochemical wastewater treatment, without altering pH, highlighting its potential to replace conventional flocculants in industrial wastewater treatment systems (Lee *et al.,* 2015). Similarly, chitosan powder from tahong (Perna viridis) shells used to treat swine biogas digester effluent showed significant reductions in BOD, phosphate, and nitrate levels (Magnaye *et al.,* 2025). These findings suggest that bio-based coagulants and flocculants may have broader applicability beyond the wastewater matrices reported for non-conventional starches. They should be considered in future LCA and TEA frameworks.

Hybrid and Advanced Material Integration

There is also potential for integrating non-conventional starches with other sustainable materials, such as biodegradable polymers or polysilicic acid, to enhance coagulation performance and pollutant removal efficiency. However, research on such synergistic combinations remains limited, and identifying optimal blend ratios could further improve performance while reducing reliance on conventional chemical coagulants (Hu et al., 2022). Such hybrid materials may be designed to enhance sustainability by enabling regeneration and reuse of the biocoagulant system, thereby extending operational lifespan while maintaining acceptable treatment efficiency thresholds.

Standardization of Characterization and Mechanistic Validation

Future studies should adopt a standardized characterization framework to improve comparability across different non-conventional starch sources. Based on the analysis of the reviewed literature, characterization approaches may be broadly classified into intrinsic and mechanism-supporting categories. Intrinsic characterization primarily focuses on the fundamental properties of the material, including physicochemical, thermal, and rheological characteristics, which define the composition, stability, and processability of the starch. In contrast, mechanism-supporting characterization refers to analyses that aid in identifying and validating the underlying coagulation and flocculation mechanisms. These include structural characterization, surface and charge analysis, and coagulation performance evaluation, which collectively provide evidence for mechanisms.

The proposed framework is presented in Figure 2, along with representative examples of each characterization category. It should be noted, however, that this framework is not exhaustive, and additional characterization techniques may be incorporated depending on the specific objectives and applications of the study.

CONCLUSION

Non-conventional starches are a promising alternative to synthetic coagulants and adsorbents in wastewater treatment. However, they often require extraction and modification, such as chemical, physical, or combined methods, to enhance their contaminant-removal properties. Techniques such as esterification, cross-linking, and gelatinization can alter starch structures, improving performance. Characterization of these starches is essential, using methods such as SEM and XRD for surface morphology and FTIR for functional group identification, which influence flocculation and adsorption efficiency.

Studies have shown that non-conventional starches can effectively remove turbidity, metals, and E. coli, demonstrating potential as alternatives to commercial coagulants. Notable examples include cassava peel, durian seed, green plantain, jackfruit seed, native sago trunk, oil palm trunk, and Polynesian arrowroot starches. Many have been modified or combined with alum or aluminum sulfate, achieving contaminant removal comparable to chemical coagulants under optimal conditions.

However, challenges remain, including variability in composition, limited removal efficiency for some pollutants, high dosage requirements, and scalability issues. Future research should explore improved extraction methods, economic feasibility, integration with other materials, and life cycle assessments. With further refinement, non-conventional starch-based coagulants offer an eco-friendly and cost-effective solution for wastewater treatment.

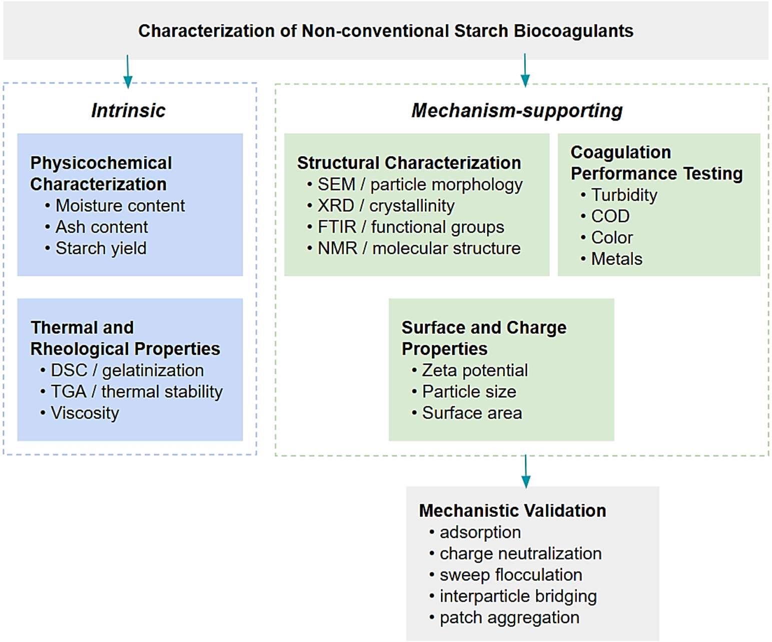

Fig. 2: Proposed framework for the characterization of non-conventional starch biocoagulant

AI-ASSISTED TOOLS DISCLOSURE

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