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RESEARCH ARTICLE

Synthesis and characterization of bauxite-derived alum and banana peel composite coagulant for water treatment

Mohd Hanafi Effandy Ahmad Bihauddin[1], Ahmad Zamani Ab Halim[1]*, Anis Nabilah Shamsul Bahrin[1], Mohd Hasbi Ab Rahim[1], Norshahidatul Akmar Mohd Shohaimi[2], Nurasmat Mohd Shukri[3], Nor Hakimin Abdullah[4]

[1]Faculty of Industrial Science and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang Malaysia
[2]Faculty of Applied Sciences, Universiti Teknologi MARA Pahang, 26400 Bandar Tun Abdul Razak Jengka, Pahang, Malaysia
[3]School of Health Sciences, Universiti Sains Malaysia, Health Campus, 16150 Kubang Kerian, Kelantan, Malaysia
[4]Advanced Materials Research Centre, Faculty of Bioengineering and Technology, Universiti Malaysia Kelantan, Locked Bag 100, 17600 Jeli, Kelantan, Malaysia

Abstract - Aluminium sulphate (alum) is an inorganic coagulant widely used in wastewater treatment due to its good performance and broad availability. However, the use of alum at high dosages can negatively impact human health and aquatic organisms, in addition to generating large quantities of sludge. Therefore, an alternative approach was explored to reduce alum usage by combining it with a natural coagulant derived from banana peel. This study aims to synthesise an inorganic–organic composite coagulant from bauxite-derived alum and banana peel for wastewater treatment, and to evaluate its physicochemical properties and treatment performance under optimum conditions. Alum, banana peel, and alum–banana peel composites at ratios of 10:90, 50:50, and 90:10 (banana peel: alum) were tested using a jar test containing 500 mL of wastewater. Final turbidity and pH values were measured for performance evaluation. Samples were characterised using Fourier Transform Infrared Spectroscopy and X-ray Diffraction. The results show that the 50:50 banana peel to alum composite achieved the best performance, with a turbidity of 12.20 NTU, a pH of 6.13, and a total turbidity removal efficiency of 82.82%.

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1. Introduction

Water plays an essential role in sustaining life, supporting ecological balance, and facilitating diverse human activities. However, rapid industrialisation, urban growth, and population expansion have intensified the discharge of untreated or inadequately treated wastewater into natural water bodies, resulting in severe degradation of freshwater resources worldwide [1,2]. Wastewater commonly contains dissolved and suspended contaminants, including organic matter, heavy metals, nutrients, pathogens, and various inorganic species. These impurities significantly alter fundamental water quality parameters, including turbidity, colour, temperature, pH, and electrical conductivity, ultimately threatening both environmental and human health [3,4]. Among the available treatment technologies, coagulation–flocculation remains one of the most widely applied and cost-effective methods for large-scale wastewater treatment [5,6]. The process destabilises colloidal particles, aggregates, and suspended solids, facilitating sedimentation, making it a preferred option for both municipal and industrial water treatment operations. Conventional coagulants such as aluminium and iron salts continue to dominate global usage due to their high efficiency, availability, and relatively low cost [7,8]. Aluminium sulphate (alum) is the most used coagulant in many countries for the removal of turbidity, natural organic matter, colour, chemical oxygen demand and biological oxygen demand. Despite its effectiveness, excessive use of alum has raised increasing concern. High alum dosages contribute to significant sludge generation, potential residual aluminium in treated water, and operational issues associated with pH sensitivity, as alum typically requires precise pH adjustment for optimum performance [9,10]. Recent studies report that residual aluminium may pose neurological risks and disrupt aquatic ecosystems, prompting the search for safer, more sustainable alternatives [11]. As global water treatment practices shift towards greener and circular-economy approaches, there is growing interest in incorporating natural or biodegradable coagulants to partially replace chemical coagulants.

Plant-based coagulants, particularly those derived from agricultural waste, have gained attention as viable, eco-friendly alternatives [12,13]. Banana peel, which accounts for approximately 30–50% of the fruit's weight, is readily available yet often discarded as waste. Previous research indicates that banana peel biomass contains pectin, cellulose, hemicellulose, lignin, and various functional groups, including hydroxyl and carboxyl groups [14,15]. These active sites readily interact with contaminants through mechanisms such as chelation, coordination, hydrogen bonding, and electrostatic attraction, making banana peel a promising natural coagulant or coagulant aid. Given the environmental concerns associated with the use of pure alum and the increasing emphasis on waste valorisation, combining inorganic and organic coagulants has emerged as a promising strategy [16,17]. Integrating alum with bio-based materials may reduce alum dosage, decrease sludge volume, and enhance pollutant removal efficiency via synergistic coagulation. Accordingly, this study aims to synthesise an inorganic–organic composite coagulant derived from bauxite-based alum and banana peel and to investigate its physicochemical properties and performance in wastewater treatment under optimal conditions.

***CORRESPONDING AUTHOR | M Hanafi** | ✉ nafy_fnd@yahoo.com

2. Materials and Methods

The chemicals used in this study include sulphuric acid (H_2SO_4), potassium sulphate (K_2SO_4), and sodium hydroxide (NaOH). The apparatus employed consists of beakers, a magnetic stirrer, a hot plate, measuring cylinders, volumetric flasks, a heating mantle, a reflux condenser, a retort stand, glass rods, a mortar and pestle, Petri dishes, round-bottom flasks, filter funnels, and filter paper.

2.1 Preparation of Alum

To prepare the alum, bauxite ore was first calcined in a furnace at 600 °C for one hour. The calcined bauxite was then cooled to room temperature and left for twenty-four hours. Subsequently, 10 g of the calcined bauxite was transferred into a round-bottom flask, followed by the addition of 6.70 mL of sulphuric acid. The mixture was gently shaken to ensure complete wetting of the bauxite. Then, 150 mL of distilled water was added, and the flask was placed on a heating mantle for reflux for 4 hours. After refluxing, the mixture was transferred into a beaker and allowed to cool overnight. The upper layer of the solution formed in the beaker was carefully pipetted out and mixed with 17.5 g of potassium sulphate. The mixture was stirred until all the potassium sulphate dissolved completely. Finally, the solution was placed in an ice bath to promote crystallisation. The resulting alum crystals were collected, dried, and ground into a fine powder for subsequent use.

2.2 Preparation of Banana Peel Extract

Fresh banana peels were washed thoroughly with distilled water to remove dirt and contaminants. The peels were then dried in an oven at 60 °C for 48 hours. The dried samples were ground into fine powder using a mortar and pestle and subsequently sieved. For extract preparation, 1 g of the powdered banana peel was added to 100 mL of distilled water and stirred at room temperature for 1 hour using a magnetic stirrer. The mixture was then filtered, and the filtrate was diluted to 1000 mL with distilled water to obtain the working banana peel extract.

2.3 Preparation of Composite Coagulants

A stock alum solution was prepared by dissolving 1 g of the alum powder in 1000 mL of distilled water. Composite coagulants were formulated by mixing banana peel extract with alum at ratios of 10%:90%, 50%:50%, and 90%:10% (banana peel extract: alum).

2.4 Sampling

Wastewater samples were collected from the Belat River, Gambang, Pahang. Belat River is a tributary of the Kuantan River, which ultimately flows into the South China Sea.

2.5 Jar Test

Jar tests were conducted using 500 mL of wastewater in each of six beakers. The initial mixing speed was set at 30 rpm. Varying volumes of alum solution (10–60 mL) were added to the beakers, and the mixing speed was increased to 100 rpm for 1 minute to promote rapid coagulation. The speed was then reduced to 30 rpm for 15 minutes for flocculation. After mixing, the solutions were allowed to settle undisturbed for 15 minutes before samples were collected for analysis. The same jar test procedure was repeated for the banana peel extract and each composite coagulant.

2.6 Characterisation of Coagulants

The synthesised coagulants were characterised using Fourier Transform Infrared (FTIR) Spectroscopy to identify functional groups and X-ray Powder Diffraction (XRD) to determine crystalline phases.

2.6.1 Fourier transform infrared

Approximately 1–2 mg of the sample was mixed thoroughly with 100 mg of spectroscopic-grade potassium bromide (KBr) and pressed into a transparent pellet using a hydraulic press. Each pellet was then placed in the FTIR instrument's sample holder. FTIR spectra were recorded using an FTIR spectrometer operating in the mid-infrared region from 4000 to 400 cm^{-1} at a resolution of 4 cm^{-1}. Each spectrum was obtained by averaging 32 scans to improve the signal-to-noise ratio. A background scan using a pure KBr pellet was performed before each sample measurement to eliminate atmospheric CO_2 and H_2O interference.

2.6.2 X-ray powder diffraction

Samples were first ground into fine powder to ensure uniform packing and reduce preferred orientation effects. A thin layer of each powdered sample was placed onto a glass sample holder and gently pressed to form a smooth surface. XRD measurements were performed using an X-ray diffractometer equipped with a Cu Kα radiation source (λ = 1.5406 Å). The instrument was operated at 40 kV and 30 mA. Diffraction patterns were recorded over the 2θ range of 10°–80°, with a scan speed of 2°/min and a step size of 0.02°. The obtained diffractograms were processed to remove background noise and identify major crystalline peaks.

3. Results and Discussion

Jar tests were conducted to evaluate how different concentrations of alum, banana peel extract, and their combinations influence the coagulation behaviour and treatment efficiency of wastewater. Coagulant dosage plays a key role in determining the degree of particle destabilisation and floc formation, and therefore optimising the dosage is essential to achieving the highest turbidity removal while maintaining acceptable water quality conditions [18]. The raw wastewater sample collected from the Belat River exhibited an initial turbidity of 71.0 NTU and a pH of 5.56, indicating significant suspended matter and mild acidity. High turbidity levels are commonly associated with organic debris, silt, microbial content, and colloidal particles, which are typical of river systems receiving domestic runoff and diffuse pollution.

3.1 Coagulation Performance of Alum

Figure 1 shows that alum effectively reduced turbidity across all concentrations tested. Optimum performance was achieved at 20 mg/L, lowering turbidity to 6.84 NTU, corresponding to a removal efficiency of 90.37%, with a final pH of 5.39. This behaviour is consistent with alum hydrolysis, in which Al^{3+} ions form amorphous $Al(OH)_3$ flocs that destabilise colloids via charge neutralisation and sweep flocculation [19]. At higher alum dosages, turbidity removal declined slightly, likely due to re-stabilisation effects or the presence of excess positive charges, which can disperse previously aggregated particles—an effect widely reported in coagulation studies. The decrease in pH with increasing alum dosage is typical, as alum releases H^+ ions during hydrolysis, shifting the equilibrium toward acidity. Despite this, the pH remained within the effective coagulation window for alum (pH 5–7), hence maintaining high treatment efficiency.

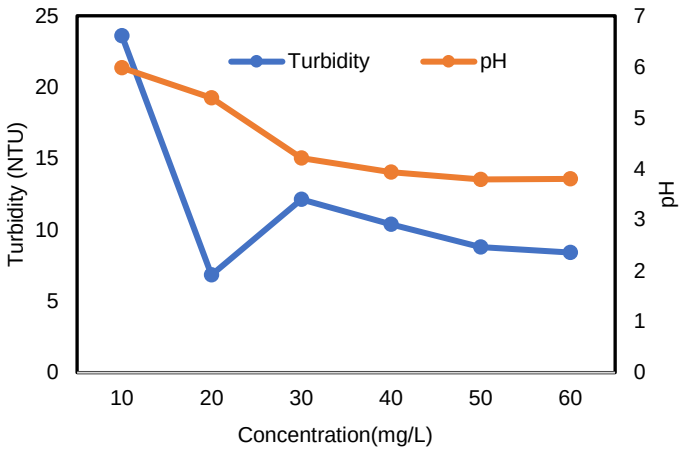

Figure 1. Turbidity and pH across different concentrations

3.2 Coagulation Performance of Banana Peel Extract

Figure 2 illustrates the coagulation behaviour of banana peel extract. Although less effective than alum, the extract demonstrated measurable turbidity removal ability, with the best performance at 50 mg/L, reducing turbidity to 41.8 NTU (41.13% removal) and yielding a final pH of 6.49. Banana peel contains substantial quantities of cellulose, hemicellulose, pectin, lignin, and polyphenolic compounds, all of which possess functional groups (–OH, –COOH, –C–O–C–) capable of interacting with suspended particles through adsorption, hydrogen bonding, and bridging flocculation [20]. Natural coagulants generally perform better in slightly acidic conditions, as protonated functional groups exhibit greater affinity for negatively charged colloids. This explains the improved performance observed around pH 6.5. Although turbidity removal was moderate relative to alum, banana peel offers advantages such as biodegradability, low toxicity, and utilisation of agricultural waste—attributes that support circular economy strategies in water treatment.

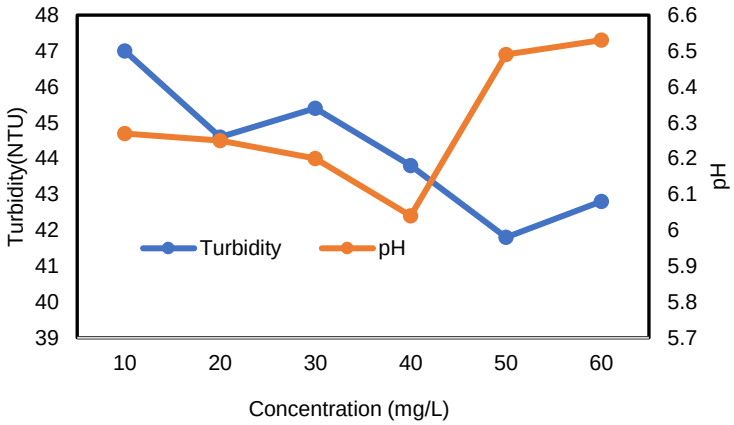

Figure 2. Coagulation behaviour of banana peel extract

3.3 Composite Coagulation Performance

The most notable outcome of this study was observed in the performance of the composite coagulants prepared by mixing banana peel extract with alum at ratios of 10%:90%, 50%:50%, and 90%:10% (banana peel: alum). Among these combinations, the 50%:50% mixture demonstrated the highest coagulation efficiency, as shown in Figure 3. This formulation reduced wastewater turbidity to 12.20 NTU and achieved a final pH of 6.13, corresponding to an impressive 82.82% turbidity removal. Although this value is slightly lower than the optimal performance of alum alone, the composite system offers several compelling advantages, highlighting its potential as an effective, more sustainable coagulant. The superior performance of the composite coagulant can be attributed to the synergistic action between the inorganic alum and the organic banana peel extract [21]. Alum contributes primarily through charge neutralisation, initiating the formation of amorphous $Al(OH)_3$ sweep flocs that effectively destabilise colloidal particles and promote their aggregation. In parallel, the banana peel extract provides a rich matrix of natural biopolymers capable of adsorption and interparticle bridging, mechanisms known to enhance floc size, density, and overall settling behaviour. These biopolymers—composed of cellulose, hemicellulose, pectin, lignin, and associated functional groups—introduce additional active sites that complement alum's coagulation pathways.

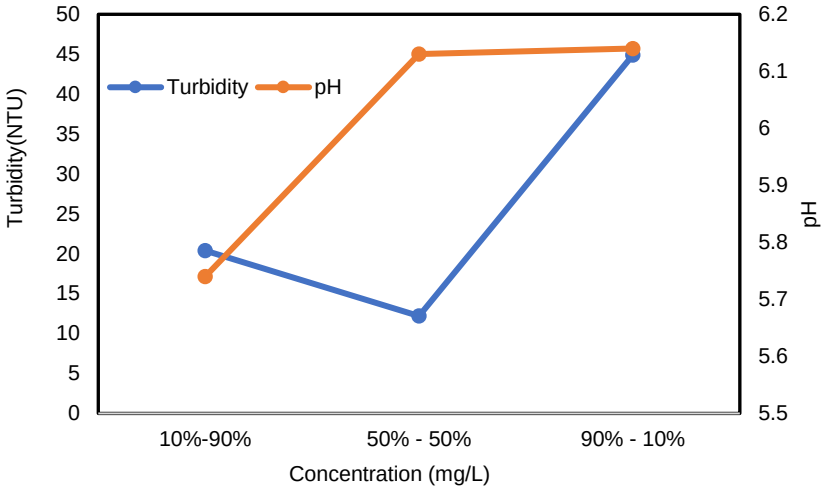

Figure 3. Coagulation performance of the composite

While alum alone achieved the highest turbidity removal of 90.37%, the composite coagulant offers several practical advantages that extend beyond removal efficiency. These include reduced alum consumption, decreased chemical sludge production, and the incorporation of a renewable, low-cost plant-based material derived from agricultural waste. Such benefits align with current trends in sustainable water treatment, which emphasise environmental compatibility, resource efficiency, and the valorisation of natural materials. Similar findings have been reported in recent studies, in which natural coagulant aids were shown to enhance floc properties, reduce chemical dosages, and contribute to more sustainable treatment processes.

3.4 Characterizations

3.4.1 Fourier transform infrared analysis

The FTIR spectra of alum, banana peel extract, and their composite coagulants (10% B:90% A, 50% B:50% A, and 90% B:10% A) reveal characteristic functional groups that explain the synergistic coagulation performance observed in this study [22] (Figure 4). A broad band at 3300–3400 cm^{-1} corresponding to O–H stretching vibrations is evident across all samples, with the highest intensity detected in the banana peel extract, consistent with the presence of lignocellulosic hydroxyl groups, polyphenols, and bound water typical of plant-derived biomaterials. Weak aliphatic C–H stretching bands at 2920–2950 cm^{-1} appear prominently in the banana peel and composite systems, confirming incorporation of organic matter, which is common for cellulose- and hemicellulose-based extracts. The banana peel spectrum also exhibits a distinct band at 1630–1650 cm^{-1} attributed to carbonyl (C=O) or carboxylate (COO^-) stretching; its reduction and slight shift in the composite coagulants suggest electrostatic interaction or complexation between carboxyl functional groups and Al^{3+} species released from alum. The fingerprint region (1500–1200 cm^{-1}), associated with aromatic C=C bending and C–O–C stretching vibrations from polysaccharides, becomes broader in the composite samples, indicating modification of the organic matrix upon contact with alum.

Meanwhile, alum-specific sulphate (SO_4^{2-}) stretching bands at 1050–1100 cm^{-1} and Al–O/Al–OH vibrations at 600–500 cm^{-1} remain visible in the composite coagulants, although with varying intensities, confirming the coexistence of inorganic and organic functional structures. Collectively, these spectral changes provide clear evidence of molecular-level interactions between banana peel biopolymers and alum species. Notably, the 50% B:50% A composite exhibits the most balanced expression of both sets of functional groups, aligning with its superior turbidity-removal efficiency and indicating optimal synergy between organic bridging and inorganic charge-neutralisation mechanisms.

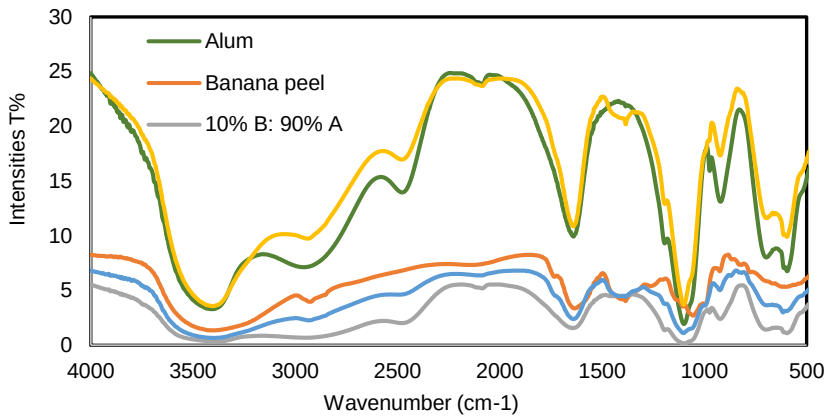

Figure 4. FTIR of alum, banana peel and the composites

Table 1. FTIR results and the corresponding functional groups

Wavenumber (cm^{-1})	Functional Group / Vibration	Assignment	Observed In
3300–3400	O–H stretching	Hydroxyl groups, hydrogen bonding	All samples
2920–2950	C–H stretching	Aliphatic $–CH_2$ / $–CH_3$ groups	Banana peel; composites
1630–1650	C=O / COO^- stretching; H–O–H bending	Carbonyl/carboxyl groups; adsorbed water	Banana peel; reduced in composites
1500–1200	C=C, C–O–C vibrations	Aromatic rings; cellulose/hemicellulose	Banana peel; broadened in composites
1100–1050	SO_4^{2-} stretching	Sulfate groups from alum	Alum; composites
600–500	Al–O, Al–OH deformation	Al–O lattice vibrations	Alum; composites

3.4.2 X-ray powder diffraction analysis

Figure 5 presents the XRD patterns of alum, banana peel powder, and the alum–banana peel composite coagulant. As shown in the lowest spectrum, banana peel exhibits no distinct diffraction peaks and instead displays a broad, featureless halo between 20° and 35° 2θ. This confirms that the banana peel powder is highly amorphous, which is typical for lignocellulosic biomass [23]. The presence of cellulose, hemicellulose, lignin, and pectin—with extensive hydrogen bonding and disordered molecular arrangements—prevents the formation of long-range crystalline domains, producing an amorphous profile in XRD. The single crystals exhibit prominent intensity peaks at 20.860, 22.180, 27.680, 31.70, 47.460, 56.820, and 64.120, corresponding to aluminium oxide (Al_2O_3). The entire pattern shows sharp, intense peaks, indicating the crystalline nature of single crystals with octahedral and cubic structures in neutral and alkaline solutions, respectively. Alum with space group P a −3 and lattice parameter 12.18 Å, the XRD peak characteristics shown can be assumed to be equivalent to JCPDF 07-0017 for $KAl(SO_4)_2 \cdot 12H_2O$ is aluminium potassium sulphate.

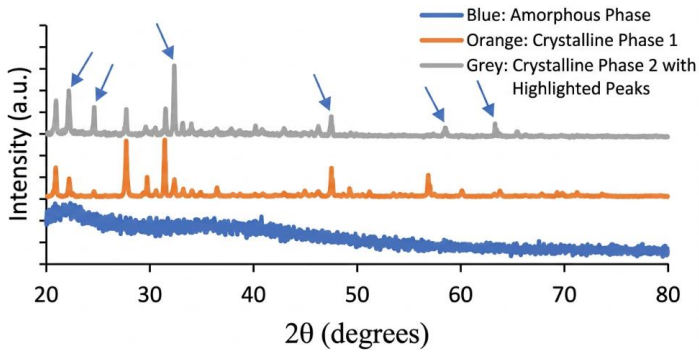

Figure 5. XRD results of alum, banana peel powder and the composite coagulant

In contrast, alum displays sharp and well-defined crystalline peaks across the 2θ range, consistent with its known hydrated sulphate crystal structure. When a banana peel is mixed with alum (grey spectrum), the resulting composite pattern retains the same set of characteristic alum peaks, indicating that the crystalline structure of alum remains unchanged. The absence of additional peaks attributable to banana peel further reinforces its amorphous nature and its minimal contribution to diffraction intensities. Similar observations have been reported where amorphous organic biomass phases do not alter or mask the diffraction signatures of crystalline inorganic components in hybrid materials, as only the crystalline fraction contributes significantly to Bragg reflections [24]. The XRD results reveal two key structural

conclusions. First, the banana peel component is completely amorphous, as shown by the absence of any crystalline peaks, indicating that it does not introduce new crystalline phases into the composite. Second, the characteristic alum peaks remain unchanged after mixing, demonstrating that the addition of banana peel does not disrupt alum's crystallinity. This shows that, while molecular-level interactions may occur between the two materials, the amorphous banana peel does not integrate into the alum lattice, and the alum's crystalline structure continues to dominate the composite's diffraction pattern.

3.5 Proposed Hybrid Synergistic Mechanism of the Alum–Banana Peel Composite

The hybrid coagulation mechanism formed by the alum–banana peel composite represents a unique combination of inorganic charge-neutralisation processes and organic polymer-like bridging, resulting in superior coagulation performance compared to either component alone [25]. This synergy arises from the complementary structural and chemical properties of the two materials, which operate simultaneously to destabilise, aggregate, and remove suspended impurities from water. Alum, as an inorganic coagulant, contributes primarily through charge neutralisation and sweep flocculation. Upon dissolution, alum undergoes hydrolysis to produce trivalent aluminium ions (Al^{3+}) and a series of aluminium hydroxide complexes. These positively charged species neutralise the surface charge of negatively charged colloids, diminishing the electrostatic repulsion that normally keeps them dispersed. As hydrolysis progresses, amorphous $Al(OH)_3$ precipitates form a voluminous gelatinous matrix capable of trapping suspended solids by enmeshment. This initial destabilisation lays the foundation for rapid floc formation, but alum-generated flocs are often brittle and may not form sufficiently large aggregates for efficient sedimentation.

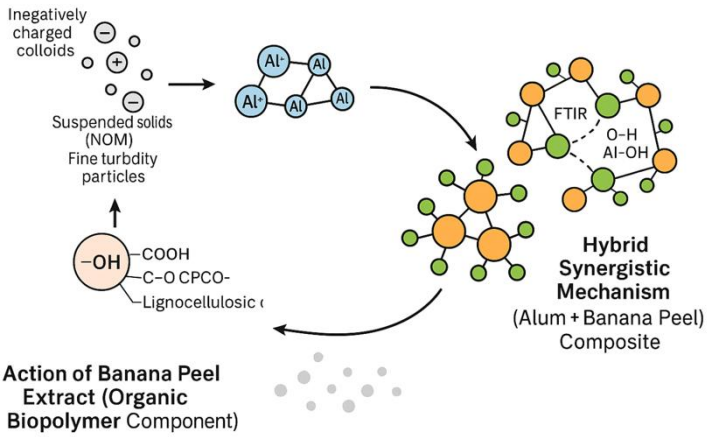

Figure 6. Proposed hybrid synergistic mechanism of the alum–banana peel composite

The introduction of banana peel extract enhances this process by providing an organic biopolymer rich in functional groups, including hydroxyl (–OH), carboxyl (–COOH), and ether (C–O–C) linkages. These groups are characteristic of lignocellulosic materials and impart strong adsorption and bridging abilities. Unlike alum, the banana peel component does not contribute crystalline phases, as confirmed by XRD, which shows an entirely amorphous structure. This amorphous nature is advantageous, as it provides a flexible polymer-like chain network capable of simultaneously binding multiple destabilised particles. Through hydrogen bonding, surface complexation, and physical adsorption, the banana peel extract strengthens floc integrity and produces larger, more stable aggregates. The hybrid alum–banana peel system functions through organic–inorganic cooperation, as evidenced by FTIR spectral shifts indicating interactions between the carboxylate groups of banana peel and the hydrolysed aluminium species. These interactions promote the formation of hybrid flocs in which inorganic $Al(OH)_3$ particles act as nucleation centres, while the organic biopolymer chains extend outward, linking multiple particles into denser aggregates. Rather than operating independently, alum and banana peel reinforce each other—alum destabilises the colloids, and banana peel binds them together into robust structures. As a result, the composite coagulant produces flocs that are larger, denser, and settle more rapidly than those formed by alum alone. The synergy is most pronounced at the 50% banana peel: 50% alum ratio, where both charge-neutralisation and bridging mechanisms are optimally balanced. This hybrid system demonstrates not only enhanced turbidity removal but also improved floc strength, reduced coagulant dosage requirements, and more sustainable performance due to the utilisation of a biodegradable, low-cost agricultural waste material.

4. Conclusions

In conclusion, an inorganic-organic composite coagulant from bauxite and banana peel was successfully synthesized for wastewater treatment. Comparison was made across all coagulants, and the results indicate that the combination of banana peel with alum at a 50%:50% ratio has the best performance, with total turbidity removal of 82.82%, a turbidity reading of 12.2 NTU, and a pH of 6.13. The characterisation by FTIR and XRD shows the coagulant to have adsorption characteristics for coagulation to take place. The results also show that the use of alum was successfully reduced by 50% compared with 100% alum for wastewater treatment, demonstrating the potential for more sustainable water treatment approaches through the valorisation of agricultural waste materials.

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Declaration of Competing Interest
The author declares no conflicts of interest.

CRediT Authorship Contribution Statement
Mohd Hanafi Effandy Bin Ahmad Bihauddin (Investigation; Data analysis)
Ahmad Zamani (Conceptualization; Supervision; Validation; Writing- review and editing.)
Anis Nabilah binti Shamsul Bahrin (Methodology; Data curation; Writing - original draft; Resources)
Mohd Hasbi Ab Rahim (Supervision; Writing – review and editing)
Norshahidatul Akmar Mohd Shohaimi (Supervision; Writing – review and editing)
Nurasmat Mohd Shukri (Supervision; Writing – review and editing)
Nor Hakimin Abdullah (Supervision; Writing – review and editing)

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

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