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Application of *Cassia fistula* Seed Extract as a Natural Coagulant for Small-Scale Gold Mining Effluent Treatment

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Abstract

Recently, the application of plant-based coagulants in wastewater/effluent treatment has drawn much attention due to their many advantages over chemical agents in terms of biodegradability, toxicity, residual sludge production, and cost. In this study, plant-based extract from *Cassia fistula* seed (CFSE) was experimentally evaluated for its efficiency in treating wastewater from small-scale gold mining operation (SSGM) as a coagulant. The coagulation tests were conducted in 1 L graduated cylinders following manual homogenisation, with interface height measurements at 0, 5, 10, 15, 20, 25, and 30 min. Particularly, the efficiency of reducing the levels of physicochemical parameters (pH, Turbidity, Total Suspended Solids-TSS, Total Dissolved Solid-TDS, and Electrical conductivity-EC) and the heavy metal ions (Arsenic-As, Cadmium-Cd, Chromium-Cr, Copper-Cu, Iron-Fe, Mercury-Hg) concentrations in the SSGM wastewater was explored in relation to coagulant dosage, settling behaviour and kinetics. The physicochemical parameters were analysed using a Crison pH meter, HACH DR/2000 spectrophotometer, Hydro Test HT 1000, Hanna RODI EC/TDS meter and Crison Conductometer Basic C30 whilst the heavy metal ions concentrations were measured using A Varian AA240FS Fast Sequential Atomic Absorption Spectrometer. The settling behaviour results showed a three-phase settling patterns that aligned with charge neutralisation mechanisms dominant in plant-based coagulants. For physicochemical parameters and heavy metals, a drastic removal/reduction was observed: turbidity (93.4% - 97.7% reduction), TDS (80.4% - 90% reduction), EC (80.3% - 93% reduction), TSS (95.9% - 97.5% reduction), As (45% - 75% removal), Cd (25% - 75% removal), Cr (6.98% - 65.12% removal), Cu (59.35% - 95.65% removal), Fe (19.06% - 53.24%) and Hg (11.54% - 23.08%). The pH of the wastewater also experienced an alkaline shift which influenced the cationic activity of the

CFSE. Generally, CFSE demonstrated optimal performance for treating SSGM wastewater at 10 g/L dosage, where peak initial settling rate (3.03 cm/min) and the most compact sludge was obtained. Overall, the findings have demonstrated that CFSE offers a sustainable alternative to chemical coagulants for SSGM effluent treatment, though the results represent preliminary or screening-level efficiency under simulated field conditions.

Keywords

Cassia fistula, Coagulants, Small-Scale Gold Mining (SSGM), Mine Wastewater

1. Introduction

The African continent continues to enjoy significant socio-economic benefits from the mining sector through foreign direct investments (FDI), foreign exchange earnings, and employment (for both skilled and unskilled) workforce (Hentschel et al., 2003; Hilson, 2003; Owusu et al., 2019; Quaicoe et al., 2023). Typically, these mining operations occur broadly as large-scale mining (LSM) [characterised by heavy mechanisation/technology] or small-scale mining (SSM) [characterised by low mechanisation and the use of rudimentary hand tools] (Bansah et al., 2016; Boadi et al., 2016; Bansah et al., 2018a; Quaicoe et al., 2023). Relatively, the small-scale mining sector provides more avenues for locals within extractive communities to participate in the mining sector than the LSM. The SSM sector contributes ~30% of total gold production and (directly/indirectly) employs ~70% of the total workforce (translating to ~1,000,000 people) in the mining industry in Ghana (Kamlongera, 2011; Boadi et al., 2016; Bansah et al., 2018b; Quaicoe et al., 2023). As reported by several researchers, the small-scale mining sector has evolved, especially in Ghana, into the use of heavy-duty and earthmoving equipment (such as excavators and dump trucks), Chinese-made diesel-powered rock crushers, dredge, gravity concentrators, and alluvial washing plant methods (Yamoah, 2002; Tepkor, 2005; Quaicoe et al., 2023).

Despite the socio-economic importance of the small-scale mining sector to many African countries, including Ghana, the industry is still plagued with several challenges that can be broadly classified into technical, environmental, health and safety, financial, legal, etc. (Opoku-Antwi, 2010; Hilson, 2020). Generally, some of the grave ecological issues that continue to affect extractive communities include siltation of rivers, disposal of untreated effluent/wastewater directly into river bodies, burning of mercury-amalgam in public places, deforestation and abandoned pits (Hilson, 2002; Mensah et al., 2015). It is worth mentioning that disposal of untreated effluent/wastewater from the sector is gaining global attention due to its deleterious constituents (e.g., heavy metals (such as mercury [Hg], lead [Pb], and iron [Fe]), colloidal particles, organic and inorganic materials) and associated health implication on human and the entire ecosystem. Technically, several effluent treatment methods exist for treating mining wastewater/effluent regardless of its constituents, however, their adoption in small-scale mining operations is limited due to their cost prohibitiveness and lack of adequate knowledge of the operations and availability of those methods (Ndiweni & Seif, 2024).

Coagulation-flocculation is considered one of the most crucial water/wastewater treatment techniques due to its cost-effectiveness, ease of use, and effectiveness in removing water pollutants (Bagwell et al., 2001; Ahmed et al., 2023). Generally, the method involves destabilising colloidal particles by adding a coagulant, which then forms aggregates that can be effectively separated by sedimentation or filtration methods (Maddela, Garcia, & Chakraborty, 2021; Sun et al., 2019). The coagulation method is underpinned by four different mechanisms: charge neutralisation, double-layer compression, sweep flocculation, and inter-particle bridging (Saleem & Bachmann, 2019; Nimesha et al., 2022). The coagulation process's efficiency and effectiveness depend largely on the coagulant type (Ibrahim et al., 2021). Typically, there are different types of coagulants which are broadly categorised into organic or inorganic. The most widely used inorganic coagulants are iron and aluminum salts, due to their high pollutant removal efficiency, ease of use, and low cost (Ibrahim et al., 2021). Contrarily, the use of inorganic coagulants presents several disadvantages, such as the production of a high volume of sludge, the need to adjust alkalinity and pH, and the high concentration of residual metals in the water (Ibrahim et al., 2021; Benalia & Derba, 2015). Additionally, the presence of residual aluminum in the resulting water can cause human diseases such as Alzheimer's (Exley, 2016; Rondeau et al., 2000; Wang et al., 2016). These challenges associated with inorganic/chemical coagulants have warranted several studies into the development of natural, environmentally friendly coagulants.

Studies have shown that the application of natural/plant-based coagulants for water and wastewater treatment has several advantages over chemical/inorganic-based (Benalia et al., 2024). Thus, using a natural coagulant produces a smaller quantity of biodegradable sludge, which can be used as fertilizer. Again, pH and alkalinity adjustments are often not required (Benalia & Derbal, 2015, Benalia & Derbal, 2023), hence making its application much simpler and easier relative to the chemical/inorganic coagulant. Although several studies have proven the efficiency of using the gums extracted from different types of seed (e.g., peas, *Cassia fistula*, *Moringa oleifera*) for treating wastewater produced from industrial activities, there still no known wastewater or drinking water treatment system at large scale using the natural gum as the coagulants or auxiliary coagulants (Ngan et al., 2017). Additionally, there are limited studies that demonstrate the potential of these natural coagulants in treating wastewater from small-scale gold mining (SSGM) operations, especially in Ghana.

This study, therefore, sought to determine the effectiveness of *Cassia fistula* seed extract (CFSE) in SSGM wastewater treatment. Particularly, the work sought to explore the removal/reduction efficiency of CFSE in reducing levels of selected physicochemical parameters (pH, Turbidity, Total Suspended Solids (TSS), Total

Dissolved Solid (TDS) and Electrical conductivity (EC)) and the heavy metal ions (Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe) and Mercury (Hg)) concentrations in the small-scale gold mining (SSGM) wastewater as well as the settling behaviour of flocs/sludge formed at different coagulant dosage rates.

Although several studies have been done using other plant-based coagulants in the treatment of wastewater, this work serves as the first study that has demonstrated the potential application of *CFSE* as a plant-based coagulant for reducing/removing selected contaminants from SSGM wastewater.

2. Materials and Methods

2.1. Materials

The wastewater used for the study was obtained as raw wastewater before entering the nearby sedimentation pond from a typical SSGM site in Tarkwa, Ghana. The physicochemical properties (**Table 1**): pH, Turbidity, TSS, TDS, and EC were measured using a Crison pH meter, HACH DR/2000 spectrophotometer, Hydro Test HT 1000, Hanna RODI EC/TDS meter and Crison Conductometer Basic C30, respectively. The metal ions (As, Cd, Cr, Cu, Fe, Hg) concentration of the wastewater, as highlighted in **Table 2**, was analysed using a Varian AA240FS Fast Sequential Atomic Absorption Spectrometer. Notably, the same analytical methods were used to obtain effluent results before and after coagulation.

Table 1. Physico-chemical properties of the SSGM wastewater.

Physico-chemical properties	pH	Turbidity (NTU)	TDS (mg/L)	TSS (mg/L)	EC (μS/cm)
Levels	6.35	3500	2400	6780	4790

Table 2. Metal ion concentration of the SSGM wastewater.

Metal ions	As	Cd	Cr	Cu	Fe	Hg
Concentration (mg/L)	0.020	0.004	0.043	1.749	22.24	0.026

2.2. Preparation of *Cassia fistula* Extract Stock Solution

Dry *Cassia fistula* seeds (**Figure 1(a)**) used in this study were collected from the University of Mines and Technology (UMaT), Tarkwa campus. The seeds were washed and air-dried for two days. The dried seeds were milled and then sieved using a 500 μm aperture size screen (undersize of < 500 μm) (**Figure 1(b)**). The ground powder was mixed with distilled water to make a 1% suspension, which was then vigorously shaken for 45 min using a magnetic stirrer to promote water extraction of the coagulant proteins and to achieve solubilization of active ingredients in the seed. The solution was then passed through a 0.45 μm filter paper (Whatman no. 42, 125 mm dia.). The filtrate portions were used for the required dose of natural coagulants. Fresh solutions were prepared daily and kept refrigerated to prevent any aging effects (such as changes in pH, viscosity, and coagulation activity). Solutions were shaken vigorously before use. Notably, the methodology used in this study is similar to that presented by Gandiwa et al. (2020).

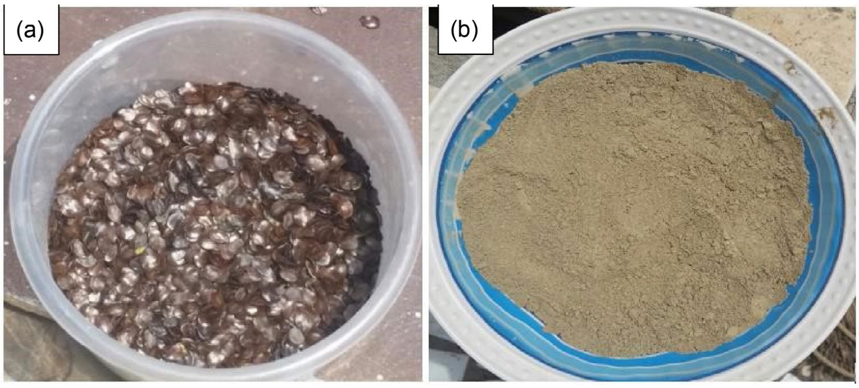

Figure 1. (a) Dried *Cassia fistula* seeds and (b) Ground *Cassia fistula* seeds powder.

2.3. Batch Treatment Tests

For the batch coagulation test, a graduated cylinder (1 L) was employed (as shown in **Figure 2**), filled with the wastewater sample, and dosed with the prepared CFSE coagulant at varying dosages of 5, 10, and 15 g/L. The mixture of wastewater and the coagulant was vigorously shaken to ensure homogenisation. The shaking intensity was calibrated to 180 rpm (rapid) and 20 rpm (slow) using a digital tachometer. This approach aligns with screening protocols for natural coagulants in field conditions with limited resources, although it is less precise than mechanical stirring (Saritha et al., 2017; Getahun et al., 2024).

A timer was started to keep track of the duration of the experiment. The colloidal particles were allowed to settle, and the position of the suspension-liquid interface was measured at different time intervals. This methodology is illustrated in **Figure 2**, where the position of the suspension-liquid interface is indicated by the red arrow. The measurement times for a batch settling curve were 0, 5, 10, 15, 20, 25, and 30 min, respectively. Notably, at the start of the test, the suspension-liquid interface was typically measured more frequently, as the colloidal particles were settling at a relatively fast pace. Later in the test, the frequency of the measurements was decreased because the interface was moving more slowly. After 30 min of settling, the levels of physicochemical parameters and heavy metals of the supernatants formed were measured and compared with the initial parameters (**Table 1** and **Table 2**). Notably, the results presented are the mean/average (the accuracy was ± 5%) of triplicate experiments conducted for each condition to ensure reproducibility. This methodology is similar to that reported in Najm et al. (1998) and Ndabigengesere et al. (1995). To ensure the reliability of the results, a comparative study between jar test (mechanical stirring at 150 rpm rapid/30 rpm slow) and the method used for this work was conducted. The result showed a

<10% deviation (especially in turbidity removal efficiency). Again, all the tests in this work were performed by a single trained operator, hence reducing the inter-operator variability.

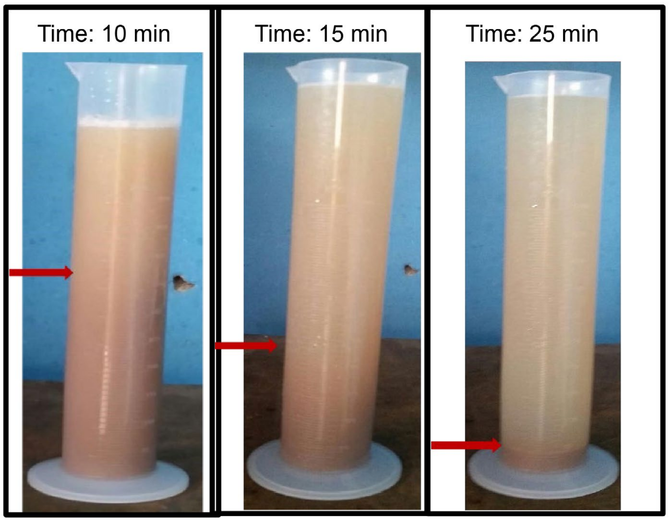

Figure 2. Photomicrograph of the batch settling column at different settling times, indicating the suspension-liquid interface.

3. Results and Discussion

3.1. Settling Behaviour and Kinetics

The settling behaviour and kinetics of suspensions coagulated with CFSE at varying dosages (5, 10, 15 g/L) were analysed from the height-time relationships shown in **Figure 3**. Tests were conducted in 1 L graduated cylinders following manual homogenisation (vigorous shaking for 2 min) at 25 ± 2˚C, with interface height measurements at 0, 5, 10, 15, 20, 25, and 30 min. The blue-line plot in **Figure 3** is the settling behaviour of the suspension without CFSE.

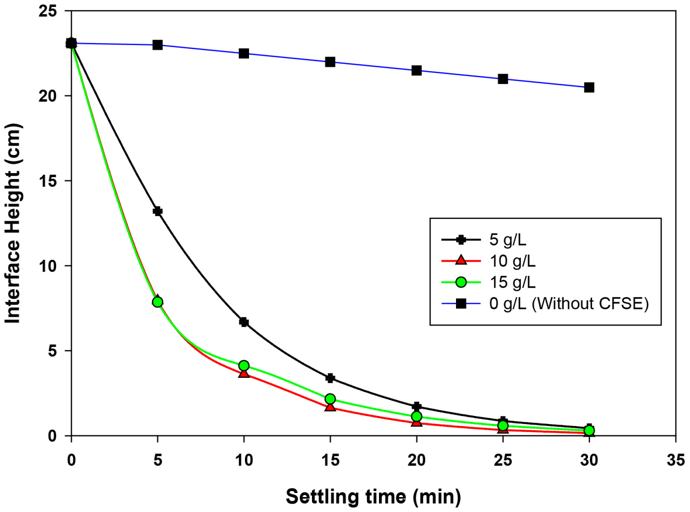

Figure 3. Settling behaviour of flocs formed during treatment.

Figure 3 shows the height-time relationship for suspensions coagulated with CFSE at varying dosages. The settling behaviour for all dosages exhibited a characteristic three-phase settling pattern similar to those described by Zodi et al. (2009), Bernard et al. (2019), Font et al. (1999), and Fitch (1979). The first phase (initial linear settling zone) is characterised by the regular height reduction of the solid/liquid interface (0 - 10 min) with a constant settling velocity (Font et al., 1999), followed by the transition-settling period (10 - 20 min), with decreasing settling velocity (Bernard et al., 2019) and third phase (the compression settling zone) (>20 min), which is characterised by a very low variation of the interface (minimal interface movement). The three-phase settling pattern aligns with charge-neutralisation mechanisms typical of plant-based coagulants (Benalia et al., 2024). The rapid initial settling (0 - 10 min) corresponds to microfloc formation through cationic protein adsorption (Ndabigengesere et al., 1995), while the velocity decline in the transition phase (10 - 20 min) reflects hindered settling due to increased solid concentration (Guibai & Gregory, 1991). The compression phase (>20 min) indicates sludge network formation where further settling requires structural rearrangement. In terms of dosage-dependent performance, the 10 g/L curve (curve below 5/15 g/L) showed the lowest interface position at 10 - 20 min, indicating optimal floc formation and/or optimal charge neutralisation. Contrarily, the lower dosage (5 g/L) provides insufficient active sites, while overdosing (15 g/L) causes colloidal re-stabilisation through steric effects/hinderance (Saxena & Brighu, 2023).

The initial settling rates, calculated from the slope of the linear portion (0 - 10 min) of the settling curves (Bernard et al., 2019), were 1.98, 3.03, and 3.05 cm/min for 5, 10, and 15 g/L dosages, respectively. The highest initial settling rate at 10 g/L (3.03 cm/min) indicates optimal coagulation performance, exceeding values reported for Moringa oleifera (1.8 cm/min at 20 g/L) by Gandiwa et al. 2020 and aligning with optimized tannin-based coagulants (2.5 - 3.1 cm/min) reported by Ibrahim et al. (2021). Additionally, the overall average settling rates (calculated as total height change over 30 min) were 0.136, 0.157, and 0.129 cm/min for 5, 10, and 15 g/L, respectively. The peak at 10 g/L further confirms its efficiency in forming dense, rapidly settling flocs. The inverse relationship between initial and overall rates reflects compression phase dominance at higher dosages.

3.2. Physico-Chemical Parameters

The effect of the CFSE as a coagulant on reducing the levels of selected physicochemical parameters (pH, turbidity, TDS, EC, TSS) was also examined.

3.2.1. pH of Wastewater

Figure 4 shows the effect of the CFSE coagulant on the pH of the wastewater at varying dosages. The initial pH of the wastewater received was 6.35 (as indicated by the brown line in **Figure 4**). Generally, the addition of the CFSE to the wastewater increased the pH of the wastewater regardless of the dosage rates. Thus, the pH increased: from 6.35 to 6.44 for 5 g/L, 6.35 to 6.57 for 10 g/L, and from 6.35 to 6.89 for 15 g/L. The pH increase, though seemingly modest in absolute terms, was statistically significant ($p < 0.05$) and represents a 1.2 to 3.5-fold reduction in H^+ ion concentration due to the logarithmic nature of pH. This alkaline shift is important as it enhances cationic protein activity in CFSE for charge neutralisation (Ndabigengesere et al., 1995), and promotes hydrolysis of metal ions that improve floc nucleation (Font et al., 1999; Amagloh & Benang, 2009). Comparatively, similar pH changes ($\Delta pH = 0.3 - 0.8$) in other plant coagulants like Moringa oleifera have been shown to significantly improve turbidity removal (Gandiwa et al., 2020), confirming the operational relevance of even numerically small pH changes.

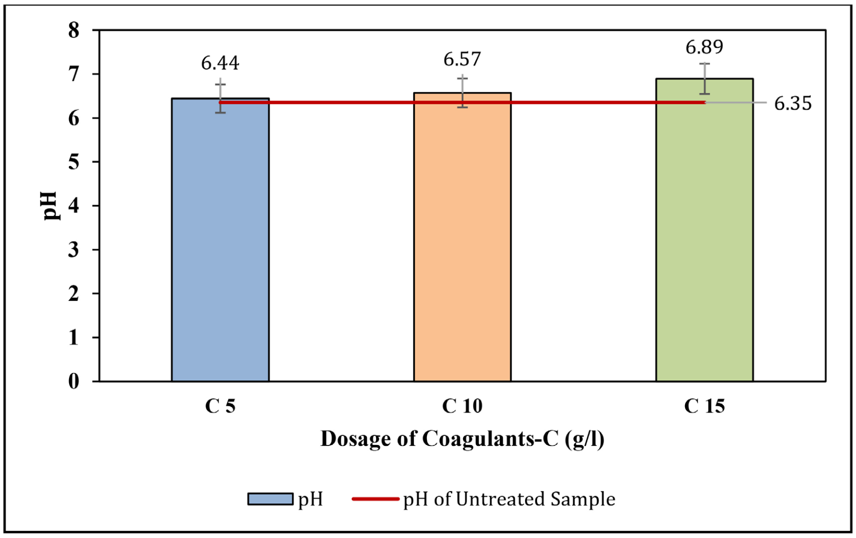

Figure 4. Resultant pH at varying doses of coagulants (pH 6.35).

3.2.2. Turbidity Reducing/Removal Efficiency (TRE)

Figure 5 shows the turbidity level reducing efficiency (TRE) of the CFSE at various dosage rates. The initial turbidity of the wastewater as received was 3500 (as indicated with the red bar in **Figure 5**). The results show that the addition of the CFSE significantly reduced the turbidity at various dosages. Particularly, the 5 g/L dosage rate reduced the turbidity from 3500 NTU to 237 NTU (93.2% TRE) whilst the 10 g/L dosage rate reduced the turbidity levels from 3500 NTU to 237 NTU (96.4% TRE). Additionally, a dosage rate of 15 g/L led to a reduction of turbidity level from 3500 NTU to 89 NTU (97.4% TRE). The turbidity-reducing efficiency of the CFSE observed can be linked to the coagulating proteins and/or polysaccharides present in the seed as reported by Oladoja et al. (2017) and Ribeiro et al. (2019). These proteins and/or polysaccharides are noted to have charged ions. Hence when released in water, the charged ions cause neutralisation and settling of oppositely charged colloids, which are responsible for turbidity in water/wastewater (Crapper et al., 1973). Moreover, the direct relations observed between the TRE and the dosage rates, thus where TRE increased with a higher dosage rate, could be linked to the amount of active charged ions present in coagulants added.

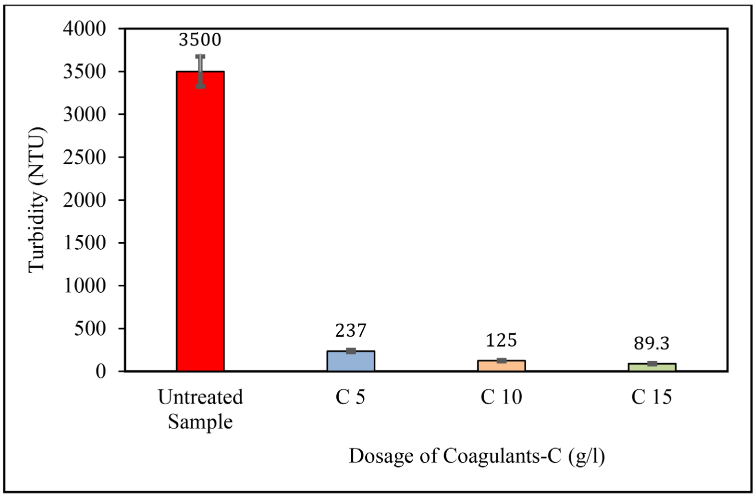

Figure 5. Effect of *Cassia fistula* seeds on turbidity.

3.2.3. Total Dissolved Solids (TDS)

Figure 6 highlights the effect of using CFSE as a plant-based coagulant on treating the levels of TDS of typical SSGM wastewater. The initial TSD level of the wastewater as received was 2400 mg/L (as indicated with the red bar in **Figure 6**). Generally, the results showed that the TDS level of the wastewater reduced drastically when contacted with the CFSE, regardless of the dosage. Particularly, it was observed that at 5, 10, and 15 g/L dosages, the TDS level decreased from 2400 mg/L to 168 mg/L (representing 93% reduction of TDS level), 236 (representing 90.2% reduction) and 471 mg/L (representing 80.4%. reduction), respectively. Notably, it was also observed that the reduction efficiency decreased with increasing dosage rate.

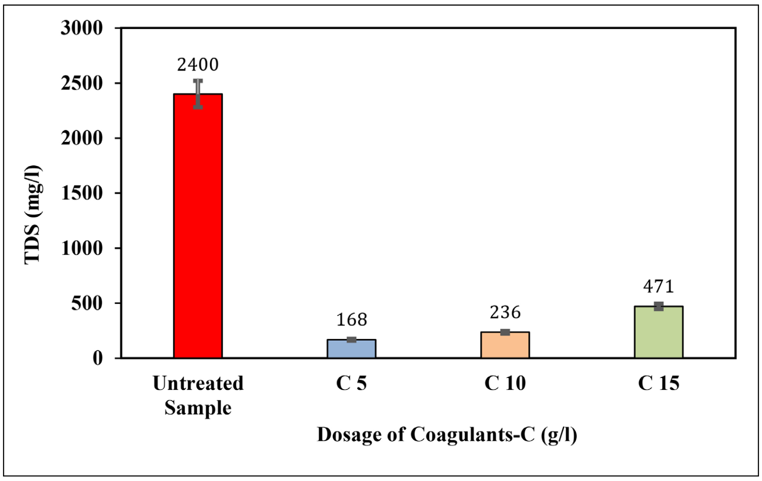

Figure 6. Effect of *Cassia fistula* seeds on total dissolved solids.

The TDS reduction observed can be attributed primarily to multiple mechanisms facilitated by bioactive compounds (proteins and polysaccharides) present in plant-based coagulants such as CFSE. Three of these probable mechanisms are: (i) Charge neutralisation (Cationic proteins adsorb onto negatively charged colloidal particles, reducing electrostatic repulsion and enabling aggregation) (Ndabigengesere et al., 1995; Benalia et al., 2024), (ii) adsorption complexation (functional groups (e.g.., Polysaccharide hydroxyl/carboxyl) form complexes with dissolved metal ions through ligand exchange) (Alazaiza et al., 2022; Wagh et al., 2022) and (iii) enmeshment (precipitated metal hydroxides incorporate dissolved ions during sweep flocculation) (Saxena & Brighu, 2023). Notably, the significant removal of heavy metals (**Table 3**) supports the role of adsorption and enmeshment, while turbidity reduction (**Figure 5**) indicates charge neutralisation. The relative contribution of these mechanisms varies with contaminant type.

Moreover, the observed inverse relationship between TDS and CFSE dosage, may be attributed to over-coagulation. According to Benalia et al. (2024) and Saxena & Brighu (2023), at higher coagulant doses, re-stabilisation of colloidal particles occurs due to charge reversal (where particles become positively charged) or steric hindrance from excess polymeric chains. Additionally, high ionic strength from the excess plant extract can compress electrical double layers, reducing electrostatic interactions necessary for aggregation (Igwegbe & Onukwuli, 2019). This phenomenon has been similarly reported for other natural coagulants like *Moringa oleifera* (Gandiwa et al., 2020).

3.2.4. Total Suspended Solids (TSS)

Figure 7 highlights the impact of using CFSE as a plant-based coagulant in treating TSS of SSGM wastewater. Notably, the initial TSS level of the wastewater was 6780 mg/L (as indicated with the red bar in **Figure 7**). In general, the results indicated that the TSS level of the wastewater reduced drastically when contacted with the CFSE, regardless of the dosage rate. Particularly, the level of TSS in the wastewater was reduced from 6780 mg/L to 276 mg/L (95% reduction efficiency) at a 5 g/L CFSE dosage rate. The dosage rates of 10 and 15 g/L CFSE yielded reduction efficiencies of 97.5% (reduced the level from 6780 mg/L to 199 mg/L) and

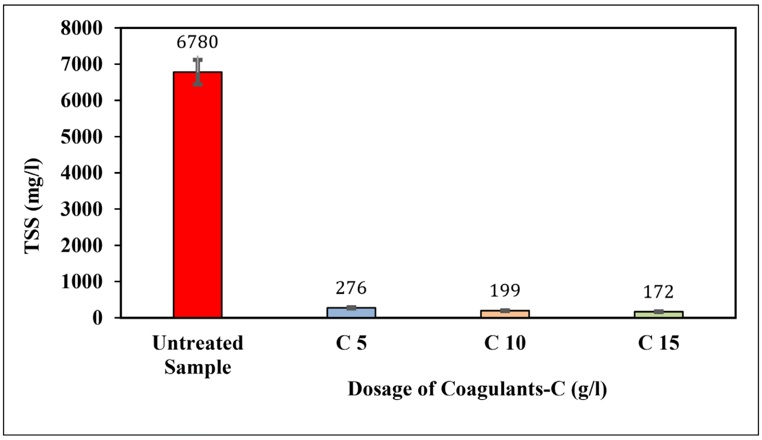

Figure 7. Effect of *Cassia fistula* seeds on total suspended solids.

99.2% (reduced the level from 6780 mg/L to 172 mg/L), respectively. Notably, this behaviour is similar to that observed for the TDS removal, hence it is expected that the same coagulation mechanism underpins this phenomenon as discussed in section 3.2.3.

3.2.5. Electrical Conductivity (EC)

Figure 8 shows the effect of CFSE on the EC of wastewater. The results show that the EC of the wastewater initially at 4790 µS/cm was reduced to 335 µS/cm (93% decrease) at a CFSE dosage rate of 5g/L. However, the results further showed that the reduction efficiencies decreased with increasing CFSE dosage rate. Particularly, CFSE dosage rates of 10 and 15 g/L yielded reduction efficiencies of 90.15% (i.e., a decrease from the initial EC of 4790 µS/cm to 472 µS/cm) and 80.33% (i.e., a decrease from the initial EC of 4790 µS/cm to 942 µS/cm), respectively. Notably, this trend is like the behaviour observed in the work published by Gandiwa et al. (2020), where plant-based (*moringa oleifera* and *cactus opuntia*) was used for the treatment of water. The observed behaviour may be due to the dissociation of the coagulant-producing ions that raise the EC of the wastewater (Marobhe et al., 2007; Gandiwa et al., 2020). Additionally, the observed inverse relationship between EC reduction and dosage mirrors observations for Sesamum indicum coagulants (Igwegbe & Onukwuli, 2019), attributed to ion leaching from plant extracts at high concentrations.

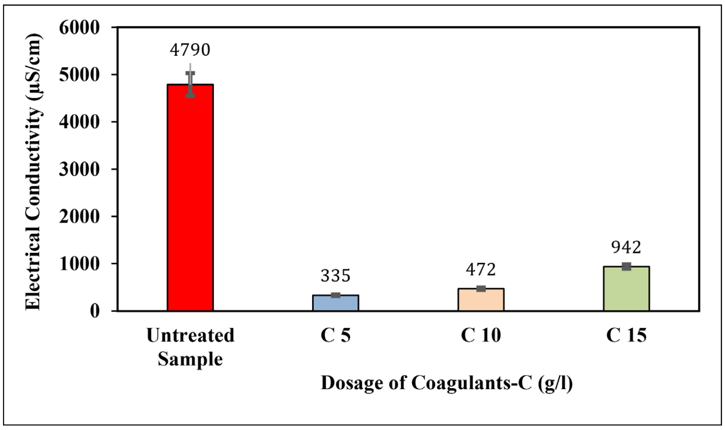

Figure 8. Effect of *Cassia fistula* seeds on electrical conductivity.

3.3. Heavy Metals Removal Capacity

Heavy metals are often difficult to remove from wastewater/water due to their low concentration and susceptibility to biodegradation (Priya et al., 2022; Renu et al., 2017), hence heavy metal removal efficiency of the *CFSE* was also explored. Table 3 shows the heavy metal removal efficiency of the CFSE at 5, 10, and 15 g/L dosage. Generally, it was observed that the CFSE drastically reduced the heavy metals concentrations from 0.02 ppm to 0.005 ppm for As, 0.004 ppm to 0.001 ppm for Cd, 0.004 ppm to 0.001 for Cr, 1.749 to 0.076 ppm for Cu, 22.24 to 10.4 ppm for Fe, and 0.026 to 0.020 ppm for Hg. The corresponding reducing efficiencies for the heavy metals from 0 to 15 g/l dosages were 45 - 75% for As, 25%- 75% for Cd, 6.98% - 65.12% for Cr, 59.35% - 95.65% for Cu, 19.06% - 53.24% for Fe, and 11.54% - 23.08% for Hg.

The mechanisms reported to underpin the efficiency of removing heavy metals by plant-based coagulants are primarily driven by mechanisms such as adsorption and polymer bridging (Alazaiza et al., 2022). However, the adsorption mechanism predominates the heavy metal removal efficiency of plant-based coagulants such as *CFSE* due to the presence of functional groups (Aziz et al., 2021). FTIR analyses of *Cassia fistula* seeds revealed key functional groups (Carboxyl (-COOH) and hydroxyl (-OH) groups, Amine groups ($-NH_2$), Sulfhydryl groups (-SH)) involved in metal adsorption (Ngan et al., 2017; Wagh et al., 2022). Whilst the Carboxyl and hydroxyl groups of the CFSE participate in ion exchange and complexation with metal cations (such as Cu^{2+}, Cd^{2+}) through electrostatic attraction and sharing of electron pairs (Alazaiza et al., 2022), the Sulfhydryl groups exhibit high affinity for soft metals like Hg^{2+} (Wagh et al., 2022). Contrarily, the Amine groups get protonated at wastewater pH (6.35 - 6.89) to form $-NH_3^+$, enabling anion exchange for oxyanions like arsenate ($HAsO_4^{2-}$) (Nimesha et al., 2022). This implies that polymer bridging plays a secondary role in this study, primarily enhancing floc aggregation post-adsorption (Saxena & Brighu, 2023).

Table 3. Summary of Metal Ion Concentration before and after Treatment.

Heavy metals	Initial Concentration (ppm)	5 g/l dosage rate (C5)		10 g/l dosage rate (C10)		15 g/l dosage rate (C15)		*Standard (ppm)
		Concentration (ppm)	Reduction efficiency (%)	Concentration (ppm)	Reduction efficiency (%)	Concentration (ppm)	Reduction efficiency (%)	
Arsenic (As)	**0.02**	0.011	45.00	0.009	55.00	0.005	75.00	**0.05**
Cadmium (Cd)	**0.004**	0.003	25.00	0.001	75.00	0.001	75.00	**0.003**
Chromium (Cr)	**0.043**	0.04	6.98	0.035	18.60	0.015	65.12	**0.05**
Copper (Cu)	**1.749**	0.711	59.35	0.159	90.91	0.076	95.65	**1**
Iron (Fe)	**22.24**	19.06	14.30	17.48	21.40	10.4	53.24	**0.3**
Mercury (Hg)	**0.026**	0.023	11.54	0.021	19.23	0.02	23.08	**0.001**

*WHO and Parsons, 2004.

4. Conclusion

This study demonstrates that *Cassia fistula* seed extract (CFSE) is an effective natural coagulant for treating small-scale gold mining (SSGM) wastewater. The key findings are:

- CFSE demonstrated optimal performance for treating SSGM wastewater at 10 g/L dosage, where peak initial settling rate (3.03 cm/min) and the most compact sludge (interface curve below other dosages) was achieved.
- Significant removal/reduction of contaminants was observed; Turbidity (93.4% - 97.7% reduction), TSS (95.9% - 97.5% reduction), Cu (59.35% -

95.65% removal), As (45% - 75% removal), Cd (25% - 75% removal), Cr (6.98% - 65.12% removal), Fe (19.06% - 53.24% removal) and Hg (11.54% - 23.08%)

- A unique settling behavior characterised by a three-phase settling pattern (regular height reduction of solid/liquid interface, transition, and compression settling) was observed regardless of the dosage rate.
- The pH of the SSGM wastewater experienced a significant alkaline shift, which potentially improved cationic protein activity in CFSE for charge neutralisation and facilitated hydrolysis of metal ions that enhanced floc nucleation.
- The EC/TDS levels of the wastewater reduced significantly at given CFSE dosages. However, an inverse relationship between EC/TDS reduction and dosage was observed, attributing the phenomenon to ion leaching from plant extracts at high concentrations.

Overall, the results demonstrate that CFSE offers a sustainable alternative to chemical coagulants for SSGM wastewater treatment. However, it is worth mentioning that the results of this study represent preliminary or screening-level efficiency under simulated field conditions. Therefore, for process-scale implementation, a jar testing method with controlled mixing (e.g., 100 - 300 rpm rapid/20 - 40 rpm slow) is highly recommended.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

Ahmed, M. J., Danish, M., Anastopoulos, I., & Iwuozor, K. O. (2023). Recent Progress on Corn (*Zea mays* L.)-Based Materials as Raw, Chemically Modified, Carbonaceous, and Composite Adsorbents for Aquatic Pollutants: A Review. *Journal of Analytical and Applied Pyrolysis, 172,* Article ID: 106004. https://doi.org/10.1016/j.jaap.2023.106004

Alazaiza, M. Y., Albahnasawi, A., Almaskari, O., Almaskari, T., Abujazar, M. S. S., Abu, Amr, S., & Nassani, D. E. (2022). Role of Natural Coagulants in the Removal of Heavy Metals from Different Wastewaters: Principal Mechanisms, Applications, Challenges, and Prospects. *Global NEST Journal, 24,* 594-606. https://doi.org/10.30955/gnj.004478

Amagloh, F. K., & Benang, A. (2009). Effectiveness of *Moringa oleifera* Seed as Coagulant for Water Purification. *African Journal of Agricultural Research, 4,* 119-123.

Aziz, N. A., Jayasuriya, N., Fan, L., & Al-Gheethi, A. (2021). A Low-Cost Treatment System for Underground Water Using *Moringa oleifera* Seeds and *Musa cavendish* Peels for Remote Communities. *Journal of Chemical Technology & Biotechnology, 96,* 680-696. https://doi.org/10.1002/jctb.6581

Bagwell, T., Barrett, K. M., Benjes, J. H. H., & Burris, B. (2001). *Handbook of Public Water Systems* (2nd ed.). Wiley and Sons.

Bansah, K. J., Dumakor-Dupey, N. K., Kansake, B. A., Assan, E., & Bekui, P. (2018b). Socioeconomic and Environmental Assessment of Informal Artisanal and Small-Scale Mining in Ghana. *Journal of Cleaner Production, 202,* 465-475. https://doi.org/10.1016/j.jclepro.2018.08.150

Bansah, K. J., Dumakor-Dupey, N. K., Stemn, E., & Galecki, G. (2018a). Mutualism, Commensalism or Parasitism? Perspectives on Tailings Trade between Large-Scale and Artisanal and Small-Scale Gold Mining in Ghana. *Resources Policy, 57,* 246-254. https://doi.org/10.1016/j.resourpol.2018.03.010

Bansah, K. J., Yalley, A. B., & Dumakor-Dupey, N. (2016). The Hazardous Nature of Small Scale Underground Mining in Ghana. *Journal of Sustainable Mining, 15,* 8-25. https://doi.org/10.1016/j.jsm.2016.04.004

Benalia, A., & Derbal K. (2015). Comparative Study between Aluminium Sulphate and Ferric Chloride in Water Treatment: Turbidity Removal. *Journal des Doctoriales, 1,* 4-9.

Benalia, A., & Derbal, K. (2023). *Extraction and Valorization of Active Products of Natural Plants as Biocoagulants Useful in the Improvement of Water Quality.* Master's Thesis, Constantine 3 Salah Boubnider University.

Benalia, A., Derbal, K., Amrouci, Z., Baatache, O., Khalfaoui, A., & Pizzi, A. (2024). Application of Plant-Based Coagulants and Their Mechanisms in Water Treatment: A Review. *Journal of Renewable Materials, 12,* 667-698. https://doi.org/10.32604/jrm.2024.048306

Bernard, K. N. M., Sylvere, N. K., Patrice, K. G., & Joseph, K. G. (2019). Erratum to "Coagulation and Sedimentation of Concentrated Laterite Suspensions: Comparison of Hydrolyzing Salts in Presence of *Grewia* spp. Biopolymer". *Journal of Chemistry, 2019,* Article ID: 2481975. https://doi.org/10.1155/2019/2481975

Boadi, S., Nsor, C. A., Antobre, O. O., & Acquah, E. (2016). An Analysis of Illegal Mining on the Offin Shelterbelt Forest Reserve, Ghana: Implications on Community Livelihood. *Journal of Sustainable Mining, 15,* 115-119. https://doi.org/10.1016/j.jsm.2016.12.001

Crapper, D. R., Krishnan, S. S., & Dalton, A. J. (1973). Brain Aluminum Distribution in Alzheimer's Disease and Experimental Neurofibrillary Degeneration. *Science, 180,* 511-513. https://doi.org/10.1126/science.180.4085.511

Exley, C. (2016). The Toxicity of Aluminium in Humans. *Morphologie, 100,* 51-55. https://doi.org/10.1016/j.morpho.2015.12.003

Fitch, B. (1979). Sedimentation of Flocculent Suspensions: State of the Art. *AIChE Journal, 25,* 913-930. https://doi.org/10.1002/aic.690250602

Font, R., García, P., & Rodriguez, M. (1999). Sedimentation Test of Metal Hydroxides: Hydrodynamics and Influence of Ph. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 157,* 73-84. https://doi.org/10.1016/s0927-7757(99)00091-6

Gandiwa, B. I., Moyo, L. B., Ncube, S., Mamvura, T. A., Mguni, L. L., & Hlabangana, N. (2020). Optimisation of Using a Blend of Plant Based Natural and Synthetic Coagulants for Water Treatment: (*Moringa oleifera-Cactus opuntia-Alum blend*). *South African Journal of Chemical Engineering, 34,* 158-164. https://doi.org/10.1016/j.sajce.2020.07.005

Getahun, M., Befekadu, A., & Alemayehu, E. (2024). Coagulation Process for the Removal of Color and Turbidity from Wet Coffee Processing Industry Wastewater Using Bio-Coagulant: Optimization through Central Composite Design. *Heliyon, 10,* e27584. https://doi.org/10.1016/j.heliyon.2024.e27584

Guibai, L., & Gregory, J. (1991). Flocculation and Sedimentation of High-Turbidity Waters. *Water Research, 25,* 1137-1143. https://doi.org/10.1016/0043-1354(91)90207-7

Hentschel, T., Hruschka, F., & Priester, M. (2003). *Artisanal and Small-Scale Mining: Challenges and Opportunities.* International Institute for Environment and Development and the World Business Council for Sustainable Development.

Hilson, G. (2002). The Environmental Impact of Small-scale Gold Mining in Ghana: Identifying Problems and Possible Solutions. *The Geographical Journal, 168,* 57-72. https://doi.org/10.1111/1475-4959.00038

Hilson, G. (2020). 'Formalization Bubbles': A Blueprint for Sustainable Artisanal and Small-Scale Mining (ASM) in Sub-Saharan Africa. *The Extractive Industries and Society, 7,* 1624-1638. https://doi.org/10.1016/j.exis.2020.11.001

Hilson, G. M. (2003). *The socio-Economic Impacts of Artisanal and Small-Scale Mining in Developing Countries.* CRC Press. https://doi.org/10.1201/9780203971284

Ibrahim, A., Yaser, A. Z., & Lamaming, J. (2021). Synthesising Tannin-Based Coagulants for Water and Wastewater Application: A Review. *Journal of Environmental Chemical Engineering, 9,* Article ID: 105007. https://doi.org/10.1016/j.jece.2020.105007

Igwegbe, C. A., & Onukwuli, O. D. (2019). Removal of Total Dissolved Solids (TDS) from Aquaculture Wastewater by Coagulation-Flocculation Process Using Sesamum Indicum Extract: Effect of Operating Parameters and coagulation-Flocculation Kinetics. *Pharmaceutical and Chemical Journal, 6,* 32-45.

Kamlongera, P. J. (2011). Making the Poor 'Poorer' or Alleviating Poverty? Artisanal Mining Livelihoods in Rural Malawi. *Journal of International Development, 23,* 1128-1139. https://doi.org/10.1002/jid.1836

Maddela, N. R., Garcia, L. C., & Chakraborty, S. (2021). Advances in the Domain of Environmental Biotechnology. In R. Prasad (Ed.), *Environmental and Microbial Biotechnology* (p. 479). Springer.

Marobhe, N., Renman, G., & Jackson, M. (2007). Investigation on the Performance of Local Plant Materials for Coagulation of Turbid River Water. *Journal of the Institution of Engineers Tanzania, 8,* 50-62.

Mensah, A. K., Mahiri, I. O., Owusu, O., Mireku, O. D., Wireko, I., & Kissi, E. A. (2015). Environmental Impacts of Mining: A Study of Mining Communities in Ghana. *Applied Ecology and Environmental Sciences, 3,* 81-94.

Najm, I., Tate, C., & Selby, D. (1998). Optimizing Enhanced Coagulation with PAC: A Case Study. *Journal A WWA, 90,* 88-95. https://doi.org/10.1002/j.1551-8833.1998.tb08521.x

Ndabigengesere, A., Narasiah, K. S., & Talbot, B. G. (1995). Active Agents and Mechanism of Coagulation of Turbid Waters Using Moringa Oleifera. *Water Research, 29,* 703-710. https://doi.org/10.1016/0043-1354(94)00161-y

Ndiweni, K., & Seif, S. K. (2024). Assessing Challenges of Enforcing Water Pollution Control Regulations on "Small Business Enterprises and, Artisanal and Small-Scale Mining Activities" in the Developing Countries: Zimbabwe Perspective. *European Journal of Theoretical and Applied Sciences, 2,* 35-46. https://doi.org/10.59324/ejtas.2024.2(4).04

Ngan, N. V. C., Thuy, L. T. D., & Trung, D. M. (2017). Apply *Cassia fistula* Seed Gum as Auxiliary Bio-Coagulant for Fish Processing Wastewater Treatment. *International Journal of Advanced Scientific Research and Management, 2,* 46-51.

Nimesha, S., Hewawasam, C., Jayasanka, D. J., Murakami, Y., Araki, N., & Maharjan, N. (2022). Effectiveness of Natural Coagulants in Water and Wastewater Treatment. *Global Journal of Environmental Science and Management, 8,* 101-116.

Oladoja, N. A., Unuabonah, E. I., Amuda, O. S., & Kolawole, O. M. (2017). Mechanistic Insight into the Coagulation Efficiency of Polysaccharide-Based Coagulants. In N. A. Oladoja, E. I. Unuabonah, O. S. Amuda & O. M. Kolawole, (Eds.), *Polysaccharides as a Green and Sustainable Resources for Water and Wastewater Treatment* (pp. 13-35). Springer International Publishing. https://doi.org/10.1007/978-3-319-56599-6_2

Opoku-Antwi, G. L. (2010). *Three Essays on Small-Scale Gold Mining Operations in Ghana: An Integrated Approach to Benefit-Cost Analysis.* Master's Thesis, KNUST.

Owusu, O., Bansah, K. J., & Mensah, A. K. (2019). "Small in Size, but Big in Impact": Socio-Environmental Reforms for Sustainable Artisanal and Small-Scale Mining. *Journal of Sustainable Mining, 18,* 38-44. https://doi.org/10.1016/j.jsm.2019.02.001

Priya, A. K., Gnanasekaran, L., Dutta, K., Rajendran, S., Balakrishnan, D., & Soto-Moscoso, M. (2022). Biosorption of Heavy Metals by Microorganisms: Evaluation of Different Underlying Mechanisms. *Chemosphere, 307,* Article ID: 135957. https://doi.org/10.1016/j.chemosphere.2022.135957

Quaicoe, I., Beyuo, M., Quaicoe, S., & Lasidzi, N. A. (2023). Diagnostic Gold Deportment Studies and Leaching Behaviour of Small-Scale Gold Mining Tailings from Eastern Region, Ghana. *Journal of Sustainable Mining, 22,* 81-88. https://doi.org/10.46873/2300-3960.1375

Renu, Agarwal, M., & Singh, K. (2017). Heavy Metal Removal from Wastewater Using Various Adsorbents: A Review. *Journal of Water Reuse and Desalination, 7,* 387-419. https://doi.org/10.2166/wrd.2016.104

Ribeiro, J. V. M., Andrade, P. V., & Reis, A. G. D. (2019). Moringa Oleifera Seed as a Natural Coagulant to Treat Low-Turbidity Water by In-Line Filtration. *Ambiente e Agua—An Interdisciplinary Journal of Applied Science, 14,* e2442. https://doi.org/10.4136/ambi-agua.2442

Rondeau, V., Commenges, D., Jacqmin-Gadda, H., & Dartigues, J. (2000). Relation between Aluminum Concentrations in Drinking Water and Alzheimer's Disease: An 8-Year Follow-Up Study. *American Journal of Epidemiology, 152,* 59-66. https://doi.org/10.1093/aje/152.1.59

Saleem, M., & Bachmann, R. T. (2019). A Contemporary Review on Plant-Based Coagulants for Applications in Water Treatment. *Journal of Industrial and Engineering Chemistry, 72,* 281-297. https://doi.org/10.1016/j.jiec.2018.12.029

Saritha, V., Srinivas, N., & Srikanth Vuppala, N. V. (2017). Analysis and Optimization of Coagulation and Flocculation Process. *Applied Water Science, 7,* 451-460. https://doi.org/10.1007/s13201-014-0262-y

Saxena, K., & Brighu, U. (2023). A Comprehensive Methodology for Analysis of Coagulation Performance: Dosing Approach, Isotherm Modelling, FTIR Spectroscopy and Floc Characterization. *Journal of Water Process Engineering, 52,* Article ID: 103509. https://doi.org/10.1016/j.jwpe.2023.103509

Sun, Y., Zhou, S., Chiang, P., & Shah, K. J. (2019). Evaluation and Optimization of Enhanced Coagulation Process: Water and Energy Nexus. *Water-Energy Nexus, 2,* 25-36. https://doi.org/10.1016/j.wen.2020.01.001

Tepkor, A. (2005). *Transforming Small-Scale Mining into a Form of Sustainable Livelihood for the Communities.* Master's Thesis, University of Mines and Technology.

Wagh, M. P., Aher, Y., & Mandalik, A. (2022). Potential of Moringa Oleifera Seed as a Natural Adsorbent for Wastewater Treatment. *Trends in Sciences, 19,* Article 2019. https://doi.org/10.48048/tis.2022.2019

Wang, Z., Wei, X., Yang, J., Suo, J., Chen, J., Liu, X. et al. (2016). Chronic Exposure to Aluminum and Risk of Alzheimer's Disease: A Meta-Analysis. *Neuroscience Letters, 610,* 200-206. https://doi.org/10.1016/j.neulet.2015.11.014

World Health Organization (WHO), & Parsons, E. (2004). *Review of Assessing Microbial Safety of Drinking Water: Improving Approaches and Methods.* North-West University.

Yamoah, S. (2002). *Socio-Economic Impact of Small-Scale Mining in the Tarkwa Area of Ghana.* Master's Thesis, University of Mines and Technology.

Zodi, S., Potier, O., Lapicque, F., & Leclerc, J. (2009). Treatment of the Textile Wastewaters by Electrocoagulation: Effect of Operating Parameters on the Sludge Settling Characteristics. *Separation and Purification Technology, 69,* 29-36. https://doi.org/10.1016/j.seppur.2009.06.028