Environmental Quality Management

WILEY

RESEARCH ARTICLE

The Potential of *Elephantorrhiza goetzei* Seed Extract as a Coagulant for Household Drinking Water Treatment

Denzil Diver[1] | Innocent Nhapi[2] | Walter Ruziwa[3] | Hongtao Wang[4] | Fengting Li[4]

[1]Department of Environmental Engineering, School of Engineering Sciences and Technology, Chinhoyi University of Technology, Chinhoyi, Zimbabwe | [2]Centre for Urban Resilience, Water and Climate Change, Chinhoyi, Zimbabwe | [3]Department of Fuels and Energy, School of Engineering Sciences and Technology, Chinhoyi University of Technology, Chinhoyi, Zimbabwe | [4]UN Environment-Tongji Institute of Environment for Sustainable Development, College of Environmental Sciences and Engineering, State Key Laboratory of Pollution Control and Resource Reuse, Tongji University, Shanghai, People's Republic of China

Correspondence: Denzil Diver (denzildiver20@gmail.com)

Received: 21 March 2024 | **Revised:** 19 July 2024 | **Accepted:** 26 July 2024

Funding: This study was financially supported by the Chinhoyi University of Technology, Zimbabwe, and the Tongji University Institute for Environment and Sustainable Development, China.

Keywords: *Elephantorrhiza goetzei (E. goetzei)* seed extract | natural coagulants | sludge quality | treatment efficiency | turbidity removal | water treatment

ABSTRACT

Poor access to adequate, clean, and safe water is one of the greatest world problems people encounter. There has been considerable attention in recent times toward the use of natural coagulants for water treatment. This study seeks to promote this by investigating the potential of *Elephantorrhiza goetzei (E. goetzei)* seed extract as natural coagulants for water treatment. This included the determination of key ingredients responsible for the coagulation process and optimal dosages for the removal of turbidity, fluoride, manganese, and iron. The residual content of organic matter in the treated water and the quality of sludge produced were also investigated. The methodology consisted of a proximate analysis procedure to investigate the active ingredient(s) responsible for coagulation and standard jar tests. Standard methods were used for the analyses. Coagulant dosages ranging from 0 to 300 mg/L at a rapid mixing speed of 120 rpm for 1 min, a slow mixing speed of 30 rpm for 15 min, and a settling time of 15 min were used for the jar test. The analysis of variance (ANOVA) using IBM SPSS Version 20 was conducted, and regression models were developed to determine the effect of coagulant dosage on turbidity, pH, total dissolved solids, fluoride, iron, manganese, chemical oxygen demand (COD), nitrogen, and phosphorus. The results obtained from the proximate analysis of *E. goetzei* seed extract show that values of 5.25%, 21.40%, 8.23%, 32.99%, 2.20%, and 29.93% were obtained for moisture, crude protein, crude fiber, fat, ash, and carbohydrate content, respectively. Moreover, seed extract of *E. goetzei* achieved removal efficiencies up to 94.8%, 50.1%, 90.0%, and 53.9% for turbidity, fluoride, iron, and manganese in water, respectively. The coagulant has the potential to achieve the desired World Health Organization (WHO) drinking water standards for turbidity, fluoride, iron, and manganese. The COD increased from 55.3 to 419.3 mg/L as the coagulant dosage increased from 0 to 100 mg/L. This could cause an unwanted rise in microbial activities, affecting the microbiological quality of the treated water. The total nitrogen and phosphorus concentrations obtained in the sludge at 100 mg/L were 0.343 and 0.194 µg/kg, respectively, and this compromises its attractiveness for agricultural reuse purposes.

1 | Introduction

Poor access to adequate, clean, and safe water is one of the greatest world problems people encounter (Pandey et al. 2021). Water can become contaminated by either natural or anthropogenic sources of pollutants (Ojha 2020). When groundwater infiltrates through the pores of rocks and various soils, it can contaminate the water through natural processes by mixing with various natural substances, including iron and nitrate. Consequently, high concentrations or undesirable quantities of naturally occurring compounds, such as arsenic and fluoride, can contaminate the groundwater. The consumption of this contaminated water could cause health problems such as dental and skeletal fluorosis (Ali and Ahmad 2020; Sharmila et al. 2019).

"*Coagulants and flocculants come in various forms and are used in conventional water treatment processes.*"

Coagulants and flocculants come in various forms and are used in conventional water treatment processes. Coagulants can be grouped into inorganic coagulants, synthetic organic polymers, and natural coagulants (Halder 2021). Natural coagulants are polyelectrolytes, which can be anionic, cationic, or neutral polymers (Yin 2010). Natural organic polymers have been used as coagulants and coagulant aids for water with high turbidity in China, India, and Africa for over 2000 years (Asrafuzzaman, Fakhruddin, and Hossain 2011). Some of the natural coagulants that have been investigated include Nirmali seeds (Alenazi et al. 2020), *Moringa oleifera* seeds (Tong et al. 2021), *Carica papaya* seeds (Amran et al. 2021), *Aloe vera* (Benalia et al. 2021), *Tulsi (Ocimum sanctum)* (Bayu et al. 2022), *Cassia fistula* seeds (Dunoyer, Carrillo, and Cuello 2022), and Walnut seeds (Zedan et al. 2022). Natural coagulants are biodegradable, thereby making them a potentially sustainable option for water treatment (Agarwal and Saini 2022). They have a strong ability to sustain the pH of the treated water while being safe and economical. In contrast to chemical coagulants, natural coagulants do not increase the metal load during treatment and are characterized by the production of a small amount of sludge, which significantly lowers the cost of disposal (Alazaiza et al. 2022; Owodunni and Ismail 2021).

The extraction steps for plant-based coagulants are standardized and efficiently organized (Epalza, Jaramillo, and Guarín 2018). The extraction of plant-based coagulants follows a three-stage process, which consists of primary, secondary, and tertiary processing. In the primary stage, the usable parts of the plant are carefully selected and washed thoroughly to remove impurities like sand, stones, or grain wastes. The drying process is then carried out either in an oven or outdoors to evaporate the water content and reduce moisture levels. Subsequently, the dried extract undergoes crushing, mechanical grinding, and powdering using equipment such as an electric blender, followed by passing through a mill to pulverize the material (Epalza, Jaramillo, and Guarín 2018). In the secondary stage of processing, the active coagulating agents present in each plant are extracted using different solvents such as organic solvents, water, or salt solutions. Finally, in the tertiary stage, purification methods such as dialysis, lyophilization (freeze-drying), and ion exchange can be employed to ensure the purity and quality of the extracted coagulants (Ang et al. 2020).

Elephantorrhiza goetzei, an indigenous plant in Zimbabwe, exhibits similar characteristics to other natural coagulant plants like *M. oleifera*. *E. goetzei*, also commonly known as *Goetze's Elephantorrhiza*, is a small and deciduous tree or shrub that grows in countries such as Botswana, Malawi, Mozambique, Namibia, South Africa, Tanzania, Zambia, and Zimbabwe (Maroyi 2017).

Both *E. goetzei* and *M. oleifera* contain comparable phytochemicals, such as phenolic compounds, flavonoids, and tannins (Maroyi 2017; Saini 2016). Thus, exploring the potential of *E. goetzei* as a natural coagulant for water treatment is logical. The objective of this research was to assess the suitability of *E. goetzei* seed extract for household drinking water treatment. This involved identifying key coagulation ingredients, determining optimal dosages for turbidity, fluoride, manganese, and iron removal, evaluating residual organic matter in treated water, and assessing sludge quality.

2 | Materials and Methods

2.1 | Research Design

"*The research framework involved the following key areas:* E. goetzei *reconnaissance, seed extract collection and preparation, synthetic water preparation, and conducting experiments to assess the suitability of* E. goetzei *seeds for water treatment.*"

The research framework involved the following key areas: *E. goetzei* reconnaissance, seed extract collection and preparation, synthetic water preparation, and conducting experiments to assess the suitability of *E. goetzei* seeds for water treatment. These experiments include proximate analysis, coagulation–flocculation experiments, chemical oxygen demand (COD) determination, and assessing sludge quality through nitrogen and phosphorus content testing. COD, chosen over total organic carbon (TOC), provides a comprehensive assessment of water pollution caused by organic substances, detecting both biodegradable and non-biodegradable organic matter (Islam et al. 2019).

A completely randomized design was employed to investigate the impact of *E. goetzei* seed extract's coagulant dosage on various parameters, including turbidity, fluoride, iron, manganese, nitrogen, phosphorus, COD, pH, and TDS. The study included different coagulant dosage concentrations ranging from 0 to 300 mg/L, with initial turbidity varying from 12.33 to 167.67 NTU. Coagulant dosages of 0–100 mg/L were used for fluoride, iron, and manganese, with initial concentrations of 11.16, 5.50, and 5.46 mg/L, respectively. To ensure result consistency, all experiments were conducted in triplicates.

2.2 | *E. goetzei* Seeds Collection and Preparation for Proximate Analysis

"E. goetzei *seeds were collected from Walden North Farm in Chegutu District, Central Northern Zimbabwe.*"

EXHIBIT 1 | Characterization of synthetic water used for coagulation–flocculation experiments.

Parameter	Units	Mean ± SD
Turbidity	NTU	12.33 ± 0.55
	NTU	28.46 ± 0.02
	NTU	45.22 ± 0.66
	NTU	71.33 ± 1.15
	NTU	105.33 ± 1.15
	NTU	167.67 ± 3.18
pH		8.16 ± 0.06
TDS	mg/L	94.44 ± 5.09
Fluoride	mg/L	11.16 ± 0.01
Iron	mg/L	5.50 ± 0.29
Manganese	mg/L	5.46 ± 0.01

Abbreviations: NTU, nephelometric turbidity unit; TDS, total dissolved solids.

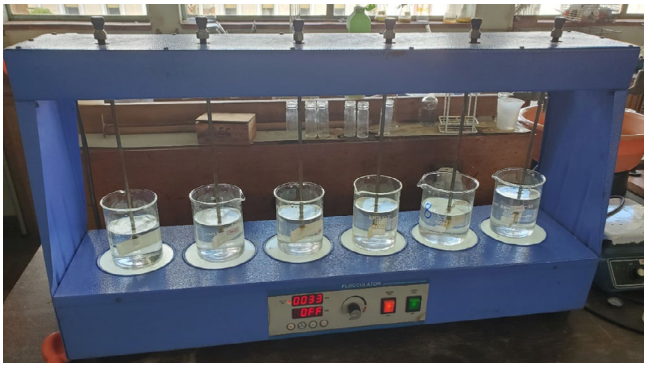


EXHIBIT 2 | Coagulation–flocculation experimental setup. [Color figures can be viewed at wileyonlinelibrary.com.]

E. goetzei seeds were collected from Walden North Farm in Chegutu District, Central Northern Zimbabwe. The seeds were manually handpicked while still in their seed coats, discarding any damaged ones. To dry the seeds, they were laid out in sunlight until a constant mass was achieved. The seed coats were then manually cracked and the seeds were ground into a fine powder using an Electro Master electric grinder, model EM-BL-1058-2 IN 1-P. Grinding the coagulant into smaller particles ensures a more reliable and consistent performance (Azamzam et al. 2022). Coagulants with a larger surface area are desirable as they enhance bridging mechanisms and provide more adsorption sites (Bahrodin et al. 2022). The ground powder was sieved through a 250-μm sieve to obtain fine particles for the coagulant solution. Utilizing a small sieve opening increases the surface area, contributing to improved water treatment performance (Desta and Bote 2021).

2.3 | Sample Collection and Preparation for Coagulation–Flocculation Experiments

The salt extraction method adapted from Okuda et al. (2001) and Ali et al. (2010) was used to prepare the *E. goetzei* seed

EXHIBIT 3 | Proximate analysis results for *E. goetzei* seeds collected from Walden North Farm in Chegutu District, Mashonaland West Province, Zimbabwe.

Parameter	Mean values (%)
Ash content	2.20 ± 0.00
Moisture content	5.25 ± 0.14
Crude fiber	8.23 ± 0.29
Crude protein	21.40 ± 0.30
Carbohydrates	29.93 ± 0.82
Fat content	32.99 ± 0.74

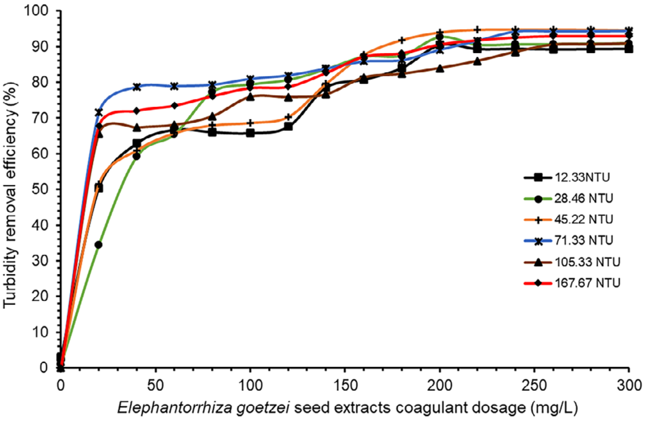


EXHIBIT 4 | Effect of *E. goetzei* seed extract coagulant dosage and initial turbidity on turbidity removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

extract coagulant solution. For every gram of the *E. goetzei* seed powder, 100 mL of 1 M sodium chloride solution was added. The mixture was stirred using a magnetic stirrer for 30 min. The suspension formed was filtered using Whatman qualitative filter paper with a pore size of 11 μm and a diameter of 125 mm on a vacuum filtration system. The filtrate was used as a coagulant for subsequent coagulation–flocculation experiments.

2.4 | Preparation of Synthetic Water Samples

Synthetic water was used to assess removal efficiencies of fluoride, iron, manganese, and turbidity. Synthetic turbid water was prepared by mixing 10 g of kaolin clay with 1.0 L of tap water, stirring for 30 min, and allowing it to settle for 24 h for complete hydration of the clay particles (Ghebremichael et al. 2005). Different turbidities were achieved through dilution. For fluoridated water, a 100 mg/L standard stock fluoride solution was made by dissolving 0.221 g of anhydrous sodium fluoride in 1 L of distilled water (Bayu et al. 2022). A 1000 mg/L standard ferrous (Fe^{2+}) stock solution was prepared by dissolving 0.70 g of ferrous ammonium sulfate hexahydrate in deionized water containing 1% concentrated sulfuric acid, while a 1000 mg/L standard manganese solution was created by dissolving 1.0 g of manganese metal in 50.0 mL of concentrated hydrochloric acid and diluting to 1.0 L (Namjan et al. 2023; Ogah et al. 2016). Other concentrations were obtained through dilution of these stock solutions. Initial parameter values for the synthetic water were

EXHIBIT 5 | ANOVA results of the effect of initial turbidity and *E. goetzei* seed extract coagulant dosage on turbidity removal efficiency.

Source	Type II sum of squares	*df*	Mean square	*F*	Sig.
Corrected model	47,617.791	20	2380.890	107.833	0.000
Intercept	557,450.244	1	557,450.244	25,247.584	0.000
Initial turbidity	618.295	5	123.659	5.601	0.000
Coagulant dosage	46,999.496	15	3133.300	141.911	0.000
Error	1655.951	75	22.079		
Total	606,723.987	96			
Corrected total	49,273.743	95			

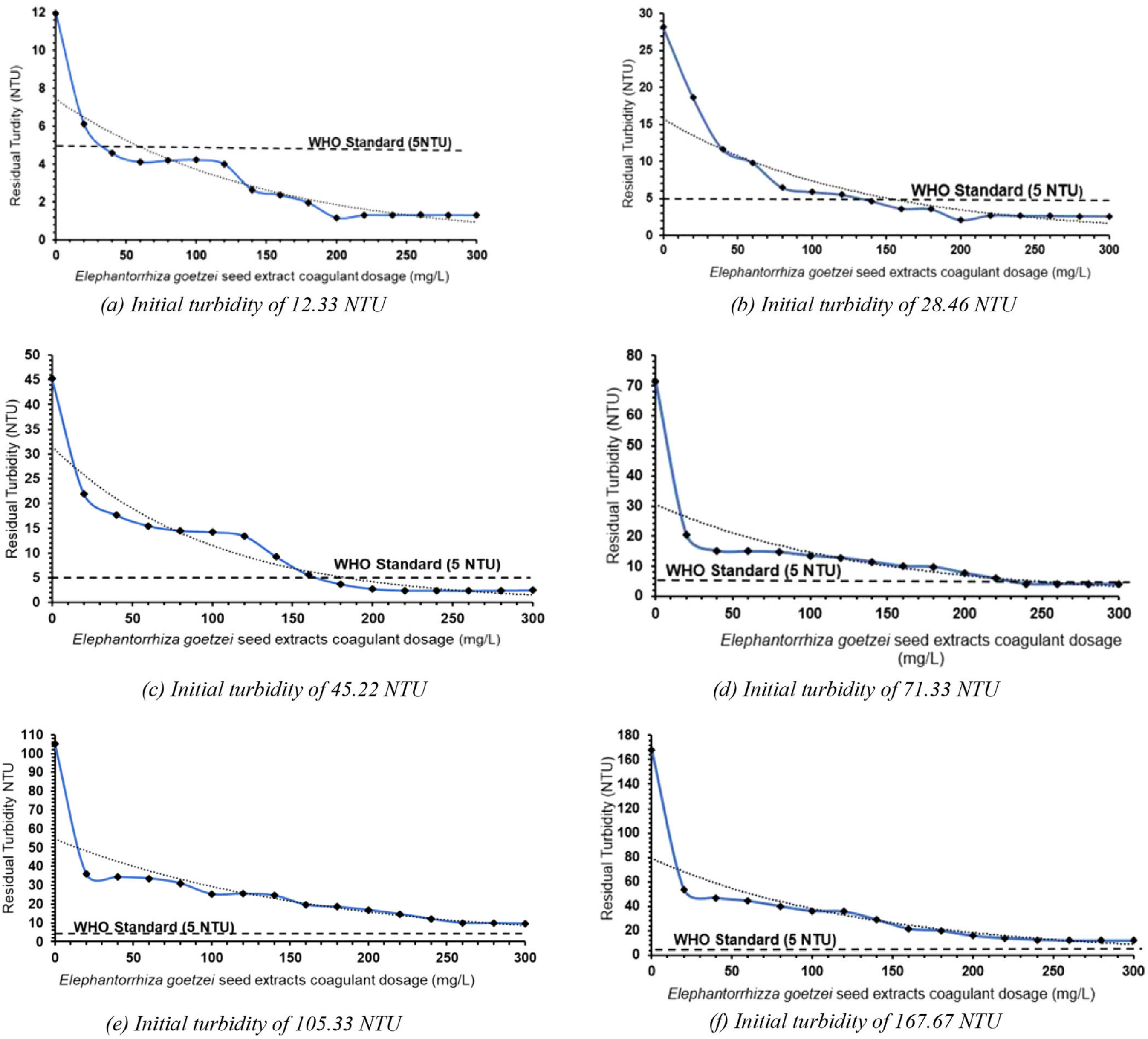


EXHIBIT 6 | Effect of *E. goetzei* seed extract coagulant dose on the water with different initial turbidity levels. [Color figures can be viewed at wileyonlinelibrary.com.]

EXHIBIT 7 | ANOVA results of the effect of initial turbidity and coagulant dosage on residual turbidity.

Source	Type II sum of squares	*df*	Mean square	*F*	Sig.
Corrected model	36,646.508	20	1832.325	11.627	0.000
Intercept	26,692.340	1	26,692.340	169.383	0.000
Initial turbidity	13,764.285	5	2752.857	17.469	0.000
Coagulant dosage	22,882.223	15	1525.482	9.680	0.000
Error	11,818.957	75	157.586		
Total	75,157.804	96			
Corrected total	48,465.465	95			

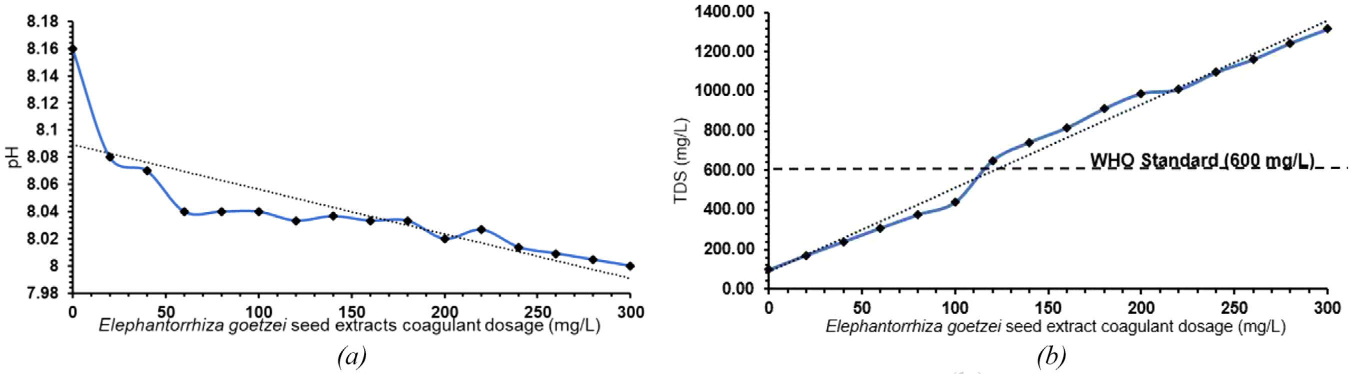


EXHIBIT 8 | Effect of *E. goetzei* seed extract coagulant dosage on *(a)* pH of the treated water and *(b)* TDS of the treated water. [Color figures can be viewed at wileyonlinelibrary.com.]

measured in triplicates, and the mean ± standard deviation (SD) values are presented in **Exhibit** 1.

2.5 | Laboratory Experiments

The jar test was conducted at room temperature to determine the optimal coagulant concentration for the effective treatment of synthetic water. Six 500 mL beakers were used in the coagulation–flocculation experiment, with synthetic water and coagulant added to each beaker. The experiment made use of a Flocculator Multiple Spindle Stirrer, Model SHI-198, with rapid mixing at 120 rpm for 1 min, followed by slow mixing at 30 rpm for 15 min, and settling for 15 min (Gidde, Bhalerao, and Malusare 2012). The supernatant from each beaker was collected to measure the turbidity, fluoride, iron, and manganese after treatment. The setup for the coagulation–flocculation experiment is shown in **Exhibit** 2.

Moisture content, crude protein content, and fat content in the seed extract of *E. goetzei* were also measured using standard methods from the Association of Official Analytical Chemists, AOAC (2000).

Standard methods from the American Public Health Association/American Water Works Association/Water Environment Federation, APHA/AWWA/WEF (2017) were used for the determination of various parameters including turbidity, iron, manganese, and fluoride in water. Turbidity was determined using the 2130 B, Nephelometric Method. The method is based on a comparison of the intensity of light that is scattered by the sample under defined conditions with the intensity of light scattered by a standard reference suspension under the same conditions. The instrument that was used to measure turbidity was a Lutron turbidity meter (TU-2016). The turbidity removal efficiency was expressed using Equation (1).

$$\text{Turbidity removal efficiency (\%)} = \frac{(T_i - T_r) \times 100}{T_i} \quad (1)$$

where T_i and T_r represent the initial and final turbidity, respectively.

The pH and total dissolved solids (TDS) were also measured before and after coagulation–flocculation using a Milwaukee MW 801 pH/EC/TDS Smart Combined Meter.

Fluoride concentration was determined using the 4500-F-D, SPANDS Method according to APHA/AWWA/WEF (2017). The SPANDS colorimetric method is based on a reaction that occurs between the fluoride ions and a zirconium-dye lake. Fluoride reacts with the dye-lake dissociating a part of it into a colorless complex anion (ZrF_6^{2-}), and the dye. As the amount of fluoride becomes greater, the color produced gradually becomes lighter. A spectrophotometer is used to read the absorbance of the sample after setting the reference point of the photometer. The fluoride removal efficiency was calculated using Equation (2).

$$\text{Fluoride removal (\%)} = \frac{C_e - C_g}{C_e} \times 100 \quad (2)$$

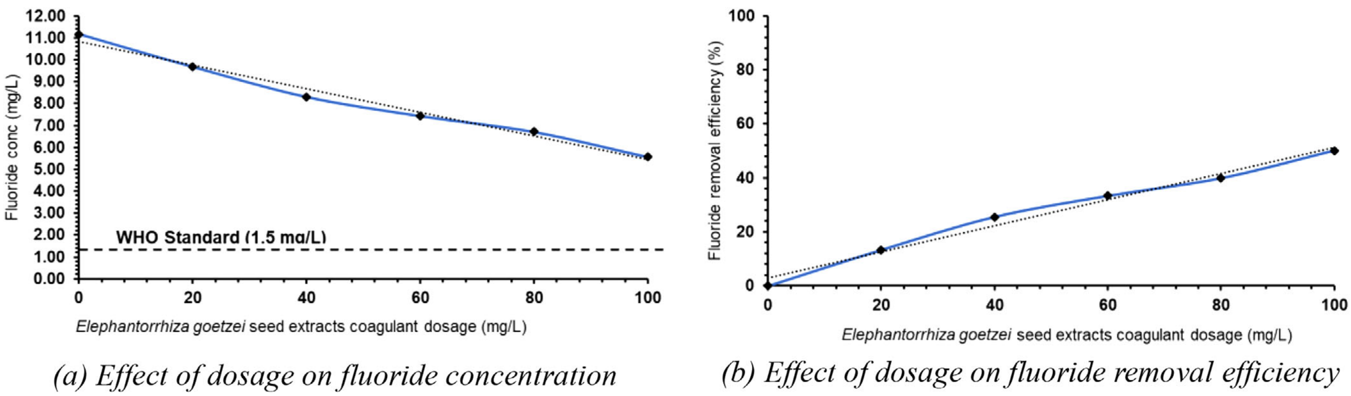


EXHIBIT 9 | Effect of *E. goetzei* seed extract coagulant dosage on fluoride concentration in treated water and fluoride removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

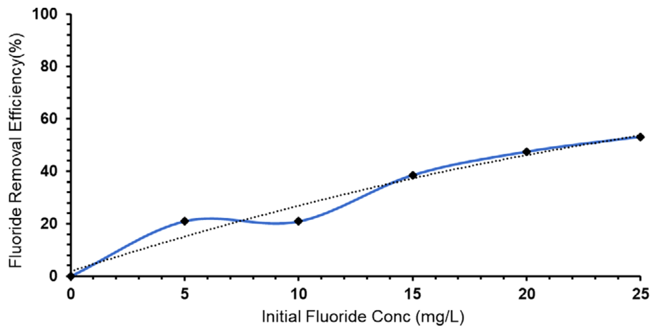


EXHIBIT 10 | Effect of initial fluoride concentration on fluoride removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

where C_e and C_g are the initial and final fluoride concentrations, respectively.

Iron was determined using the 3500-Fe B phenanthroline method according to APHA/AWWA/WEF (2017). In this method, iron is brought into solution, reduced to the ferrous state through boiling with acid and hydroxylamine, and then treated with 1,10 phenanthroline at a pH of 3.2–3.3. Three molecules of phenanthroline then chelate each atom of ferrous iron resulting in the formation of an orange–red complex. Photometric measurements are carried out and standards are read against water set at zero absorbance and a calibration curve is plotted including a blank.

Manganese was determined using 3500-Mn B persulfate method according to APHA/AWWA/WEF (2017). In this method, persulphate oxidation of soluble manganese compounds to form permanganate is done in the presence of silver nitrate. The color that is formed is stable for at least 24 h if excess persulfate is present and organic matter is absent. Photometric measurements are done against a distilled water blank. Manganese and iron removal efficiency was calculated using

$$\text{Removal efficiency (for manganese and iron)} = \frac{C_i - C_f}{C_i} \times 100\%, \tag{3}$$

where C_i is the initial concentration of manganese or iron in water and C_f is the final concentration of manganese or iron in water.

COD in water was obtained using Standard Method C (a mercury-free large scale (10 mL) flask digestion using chromium(III) potassium sulfate and silver nitrate solution), according to Westwood (2007). Samples were oxidized by a reflux process involving 5 mL potassium dichromate and 15 mL sulfuric acid silver sulfate solution. The resultant mixture was refluxed for 2 h, and any residual dichromate was then measured spectrophotometrically (Westwood 2007).

The total nitrogen was obtained using the method by the Swiss Federal Institute of Aquatic Science and Technology, EAWAG Aquatic Research (2007). Sample digestion was done using a digestion reagent which consisted of 20.1 g of potassium persulphate, $K_2S_2O_8$, and 3 g of sodium hydroxide in 1 L of reagent water. After digestion, total nitrogen was measured similarly to NO_3 with pH being neutralized with 30% sodium hydroxide, before adding 1 mL of Na-salicylate. Nitrate in a strongly acidic solution with salicylic acid forms 3- and 5-nitro salicylic acid. In alkaline solutions, their concentrations were determined colorimetrically using a spectrophotometer.

The total phosphorus concentration was determined using the 4500-P C method, which is also known as the vanadomolybdophosphoric acid colorimetric method from APHA/AWWA/WEF (2017). In a dilute orthophosphate solution, ammonium molybdate reacted under acidic conditions to form a heteropoly acid, and the acid formed was molybdophosphoric acid. The intensity of the yellow color, which was measured using a spectrophotometer, corresponded to the phosphate concentration.

3 | Results

3.1 | Key Ingredients in the *E. goetzei* Seed Extract Responsible for the Coagulation Process

Exhibit 3 shows the results that were obtained for moisture, crude protein, crude fiber, fat, ash, and carbohydrate content in the seed extract of *E. goetzei*. The results are reported as mean ± SD. The component with the lowest value was ash content, and the highest was fat content.

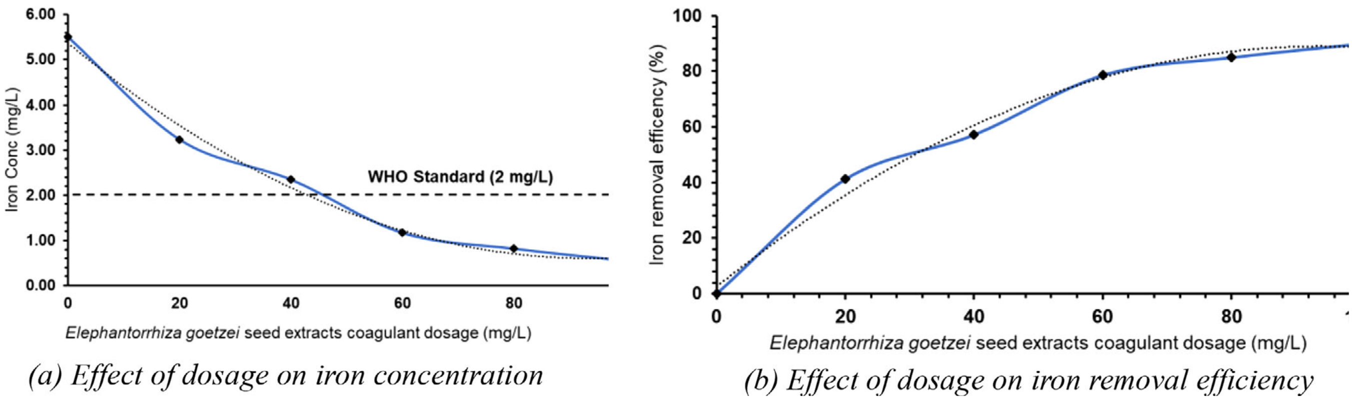


EXHIBIT 11 | Effect of *E. goetzei* seed extract coagulant dosage on iron concentration in water and iron removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

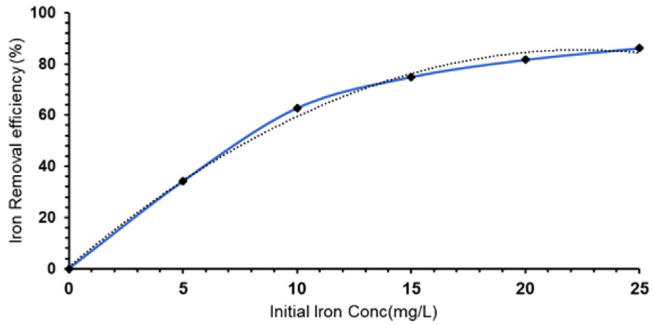


EXHIBIT 12 | Effect of initial iron concentration on iron removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

3.2 | Determination of Optimal Dosages for Efficient Removal of Turbidity and Effect on pH and TDS

3.2.1 | Removal of Turbidity

The optimum coagulant dosages were 200 and 240 mg/L for initial turbidity ranging from 12.33 to 45.22 NTU and 71.33 to 167.67 NTU, respectively. The turbidity removal efficiency of turbidity using seed extract of *E. goetzei* increased with an increase in dosage in all the turbidities, which were investigated as shown in **Exhibit 4**. **Exhibit** 5 shows that initial turbidity had a significant effect on turbidity removal efficiency ($p < 0.05$).

As illustrated in **Exhibit** 6, the residual turbidity obtained in this study at the maximum coagulant dosage of 300 mg/L was 1.30 NTU at an initial turbidity of 12.33 NTU. Generally, there was a decrease in the residual turbidity as the coagulant dosage increased from 0 to 300 mg/L. The WHO standard of 5 NTU for turbidity in drinking water was achieved in the range of 40–180 mg/L *E. goetzei* seed extract coagulant dosages.

The highest R^2 value was 0.89 at an initial turbidity of 45.22 NTU, while the lowest was 0.61 at an initial turbidity of 71.33 NTU. The ANOVA was significant for all the initial turbidities ($p <$ 0.05) as shown in **Exhibit** 7. Thus, there is significant evidence to conclude that both *E. goetzei* seed extract coagulant dosage and initial turbidity had a significant effect on the turbidity of the treated water.

3.2.2 | Effect of *E. goetzei* Seed Extract Coagulant Dosage on pH and TDS

As shown in Exhibit 1, the pH of the synthetic water was found to be 8.16 ± 0.06. There was a slight change in the pH of the water when the coagulant was introduced into the water at different doses, as demonstrated in **Exhibit** 8. It was observed that the TDS reached a maximum value of 1316.28 ± 0.00 mg/L when the *E. goetzei* seed extract coagulant dosage was 300 mg/L. The coagulant dosage had a significant influence on both the pH and TDS levels of the treated water, as indicated by a p-value below 0.05.

3.3 | Removal of Fluoride, Manganese, and Iron From Synthetic Water

3.3.1 | Fluoride Removal

Exhibit 9 shows that the fluoride concentration reached a minimum of 5.57 mg/L from an initial of 11.16 ± 0.01 mg/L when a coagulant dosage of 100 mg/L was applied. The fluoride removal efficiency improved with an increase in coagulant dosage, rising from 0% to 50.1% as the coagulant dosage increased from 0 to 100 mg/L.

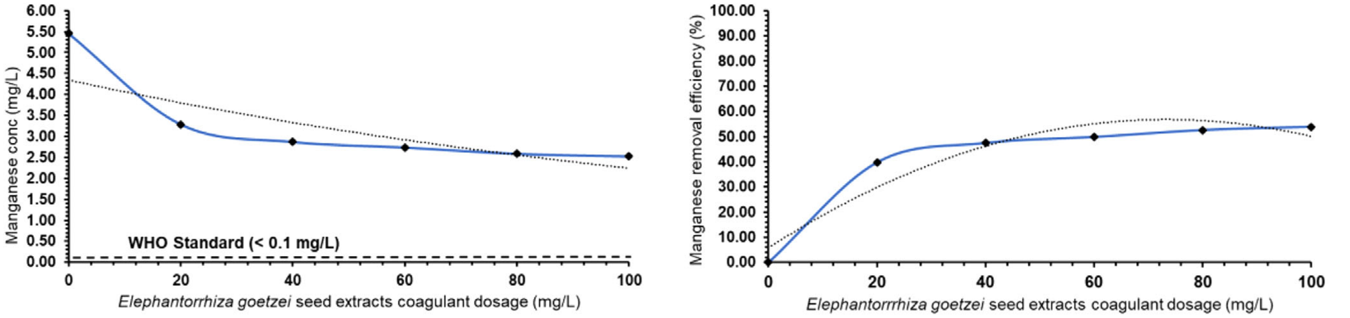
E. goetzei seed extract coagulant dosage had a significant effect on the fluoride concentration of the treated water ($p < 0.05$). There was also an increase in fluoride removal efficiency from 21.0% to 53.1%, as the initial fluoride concentration increased from 5.00 to 25.00 mg/L, as shown in **Exhibit** 10.

3.3.2 | Iron Removal

In **Exhibit** 11, a coagulant dosage of 100 mg/L resulted in a residual iron concentration of 0.55 ± 0.02 mg/L. Generally, as the initial iron concentration increased from 5 to 25 mg/L, the iron removal efficiency increased from 34.2% to 86.1% as shown in **Exhibit** 12.

3.3.3 | Manganese Removal

Exhibit 13 shows that the residual manganese concentration at a coagulant dosage of 100 was 2.52 mg/L. As shown in **Exhibit** 14, as



(a) Effect of dosage on manganese concentration *(b) Effect of dosage on manganese removal efficiency*

EXHIBIT 13 | Effect of *E. goetzei* seed extract coagulant dosage on manganese concentration in water and manganese removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

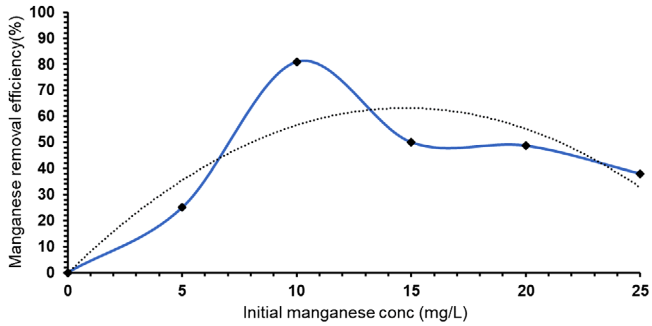


EXHIBIT 14 | Effect of initial manganese concentration on manganese removal efficiency. [Color figures can be viewed at wileyonlinelibrary.com.]

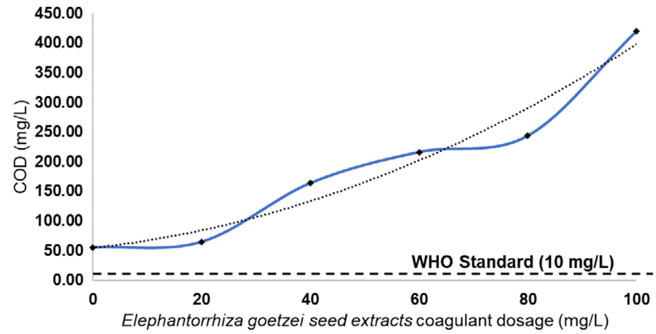


EXHIBIT 15 | Effect of *E. goetzei* seed extract coagulant dosage on COD of treated water. [Color figures can be viewed at wileyonlinelibrary.com.]

the initial manganese concentration increased from 5 to 10 mg/L, there was an increase in manganese removal efficiency from 25.0% to 81.0%. The removal efficiency then decreased from 50.1% to 38.0%, as the initial manganese concentration increased from 15 to 25 mg/L.

3.4 | Residual Content of Organic Matter in Water Treated With *E. goetzei* Seed Extract

Exhibit 15 shows that there was an increase in COD from 55.33 to 419.33 mg/L as the coagulant dosage increased from 0 to 100 mg/L. Coagulant dosage had a significant effect on the COD concentration of the treated water ($p < 0.05$).

3.5 | Quality of Sludge Produced From Treating Synthetic Water With *E. goetzei* Seed Extract

The total nitrogen fluctuated between a slight increase and a slight decrease as the coagulant dosage increased from 0 to 100 mg/L (**Exhibit** 16*a*). This could be due to a phenomenon known as nitrogen rebound whereby nitrogen is re-accumulated in the sludge after a period of nitrogen reduction (Xiujie et al. 2019). The *p*-value was less than 0.05, indicating that coagulant dosage had a significant effect on the total nitrogen in the sludge.

There was a general increase in the total phosphorus in the sludge as the coagulant dosage increased as depicted in Exhibit 16*b*. Results from the ANOVA show that *E. goetzei* seeds extracts coagulant dosage had a significant effect on the total phosphorus in sludge ($p < 0.05$).

4 | Discussion

4.1 | Key Ingredients in the *E. goetzei* Seed Extract Responsible for the Coagulation Process

E. goetzei seed extract had a moisture content of 5.25 ± 0.14%, attributed to their protective cell wall, which prevents deterioration and extends shelf life (Xiao et al. 2011). Similar values were found in other studies, including *Jatropha curcas* seeds, 5.35 ± 0.20% (Abidin, Madehi, and Yunus 2017), and *M. oleifera Lam*, 4.00% (Abdulkadir, Zawawi, and Jahan 2016). Compared to fluted pumpkin seeds (*Telfairia occidentalis*) with 12.58% moisture content (Obiora-Okafo, Onukwuli, and Eli-Chukwu 2020), *E. goetzei* seeds may have a longer shelf life. Moisture content significantly affects the shelf life of seeds, fruits, and vegetables by increasing susceptibility to microbial attacks (Thomas et al. 2018).

Moreover, *E. goetzei* seed extract contained a high crude protein content of 21.40 ± 0.30%, comparable to previous coagulation–flocculation research (Nnaji et al. 2022; Sofiavizhimalar et al. 2022). Similar protein content has been found in *Mucuna* seeds, and *Hibiscus esculentus L.* (okra) in separate studies (Menkiti, Ndaji, and Ezemagu 2017; Okolo et al. 2021). The presence of crude protein in *E. goetzei* seed extract provides active sites for coagulation to occur (Menkiti, Ndaji, and Ezemagu 2017).

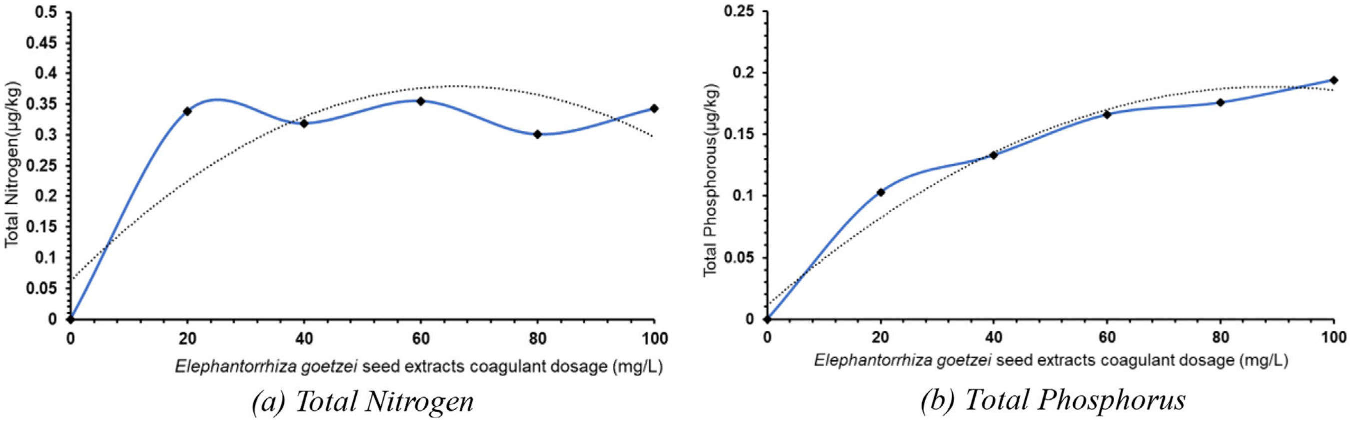


EXHIBIT 16 | Effect of *E. goetzei* seed extract coagulant dosage on *(a)* Total Nitrogen and *(b)* Total Phosphorus content in sludge. [Color figures can be viewed at wileyonlinelibrary.com.]

The carbohydrate content of *E. goetzei* seed extract was 29.93 ± 0.82%, similar to *Picralima nitida* and *Hibiscus esculentus* in other studies (Igwegbe et al. 2021; Okolo et al. 2021). Carbohydrates contain oxygen and hydrogen elements, allowing them to form hydrogen and oxygen ions (Njuguna, Mayabi, and Ndirangu 2014), which can attract metallic ions and potentially remove them from water.

The mean ash content of *E. goetzei* seed extract was 2.20%, indicating the presence of carbon compounds, salts, and oxides. Carbon, with its porous nature, plays a crucial role in adsorbing and removing contaminants from water, including metals and particles (Smith and Rodrigues 2015).

E. goetzei seed extract contain 32.99 ± 0.74% fat with potential surfactant properties for water treatment (Adetunji and Olaniran 2021). The crude fiber content (8.23 ± 0.29%) in the extracts can absorb water, act as a filter, and remove impurities and contaminants (Zheng et al. 2016). The possible active ingredients in *E. goetzei* seed extract are proteins, carbohydrates, fat, and fiber, as they all possess unique properties which enable them to remove impurities in water.

4.2 | Optimal Dosages for the Efficient Removal of Turbidity From Synthetic Water

The optimal coagulant dosages were 200 and 240 mg/L for varying initial turbidities. No significant reduction in turbidity was observed beyond these dosages. Each coagulant has a critical inflection point where further dosages disrupt particle settling (Tawakkoly, Alizadehdakhel, and Dorosti 2019). Exceeding the dosage leads to worsened water turbidity as excess coagulant no longer interacts with oppositely charged colloidal particles. The high turbidity removal (94.8%) may be attributed to soluble crude proteins in *E. goetzei* seed extract, enhancing coagulation and flocculation processes (Vargas et al. 2022).

The highest removal efficiency was 94.8% at a coagulant dosage of 260 mg/L. The maximum removal efficiency obtained in this study is higher than the 69.4%, 81.6%, and 68.2% obtained for *M. oleifera, Cicer arietinum, and Dolichos lablab* respectively at a dosage of 100 mg/L and initial turbidity of 48 NTU (Asrafuzzaman, Fakhruddin, and Hossain 2011).

The residual turbidity values obtained in this study for varying initial turbidities (12.33–71.33 NTU) comply with WHO standards for drinking water turbidity of 5 NTU (WHO 2017), except for higher initial turbidities (105.33 and 167.67 NTU). Models were developed as shown in **Exhibit** 17, to predict final turbidity with additional coagulant at those higher initial turbidities, and at a dosage of 400 mg/L, the anticipated turbidity values (4.95 and 4.81 NTU, respectively) are below the WHO standards.

The introduction of the coagulant at different doses resulted in slight pH changes in the water, with a final recorded pH of 8.00 ± 0.02 at a coagulant dosage of 300 mg/L. This pH change can be attributed to the increased concentration of dissolved substances caused by the higher coagulant dosage (Skoronski et al. 2014). The observed pH change is similar to the findings of a study by Beyene, Hailegebrial, and Dirersa (2016), which treated water with cactus powder. The pH values remained within the acceptable range of 6.5–8.5 for drinking water (WHO 2007).

The TDS increase with *E. goetzei* seed extract coagulant dosage (20–300 mg/L) was significantly higher (170.00–1316.28 mg/L) compared to the study using cactus powder where TDS increased from 354 to 686 mg/L with a dosage range of 0–3.50 g in 500 mL of water (Beyene, Hailegebrial, and Dirersa 2016). Increasing *E. goetzei* seed extract coagulant concentration in water treatment raises anion and cation levels, released from the coagulant solution, leading to higher TDS in synthetic water (Vunain et al. 2019).

4.3 | Effect of *E. goetzei* Seed Extract Coagulant Dosage on the Removal of Fluoride, Manganese, and Iron From Synthetic Water

4.3.1 | Effect of *E. goetzei* Seed Extract Coagulant Dosage on Fluoride Removal

In this study, the highest fluoride removal efficiency achieved was 50.1% at a coagulant dosage of 100 mg/L using *E. goetzei* seed extract. Higher concentrations of the coagulant may enhance fluoride removal due to increased active sites for adsorption.

EXHIBIT 17 | Regression models developed for the effect of *E. goetzei* coagulant dosages and the effect of initial concentration in water.

Equation number	Model	R^2	Description
4a	Residual turbidity = 7.4298 $e^{-0.007(\text{Coagulant dosage})}$	0.824	Effect of *E. goetzei* seed extract coagulant dose on initial turbidity of 12.33 NTU
4b	Residual turbidity = 15.706$e^{-0.008(\text{Coagulant dosage})}$	0.850	Effect of *E. goetzei* seed extract coagulant dose on initial turbidity of 28.46 NTU
4c	Residual turbidity = 31.461$e^{-0.01(\text{Coagulant dosage})}$	0.888	Effect of *E. goetzei* seed extract coagulant dose on initial turbidity of 45.22 NTU
4d	Residual turbidity = 30.568$e^{-0.007(\text{Coagulant dosage})}$	0.609	Effect of *E. goetzei* seed extract coagulant dose on initial turbidity of 71.33 NTU
4e	Residual turbidity = 54.572$e^{-0.006(\text{Coagulant dosage})}$	0.679	Effect of *E. goetzei* seed extract coagulant dosage on initial turbidity of 105.33 NTU
4f	Residual turbidity = 79.177$e^{-0.007(\text{Coagulant dosage})}$	0.685	Effect of *E. goetzei* seed extract coagulant dosage on initial turbidity of 167.67 NTU
5a	pH = 8.089$e^{-4\text{E-}05(\text{Coagulant dosage})}$	0.669	Effect of *E. goetzei* seed extract coagulant dosage on the pH of the treated water
5b	TDS = 4.232(Coagulant dosage) + 88.549	0.998	Effect of *E. goetzei* seed extract coagulant dosage on TDS of the treated water
6a	Fluoride conc = −0.053(Coagulant dosage) + 10.836	0.984	Effect of *E. goetzei* seed extract coagulant dosage on fluoride concentration in water
6b	Fluoride removal efficiency = 0.482(Coagulant dosage) + 2.901	0.984	Effect of *E. goetzei* seed extract coagulant dosage on fluoride removal efficiency
7	Fluoride removal efficiency = −0.029(Initial Fluoride Conc)^2 + 2.795(Initial Fluoride Conc) + 1.861	0.961	Effect of initial fluoride concentration on fluoride removal efficiency
8a	Iron Conc = 0.0005(Coagulant dosage)^2 − 0.102(Coagulant dosage) + 5.361	0.990	Effect of *E. goetzei* seed extract coagulant dosage on iron concentration in water
8b	Iron removal efficiency = −0.0098(Coagulant dosage)^2 + 1.845(Coagulant dosage) + 2.544	0.990	Effect of *E. goetzei* seed extract coagulant dosage on iron removal efficiency
9	Iron removal efficiency = −0.168(Initial Iron Conc)^2 + 7.553(Initial Iron Conc) + 0.778	0.996	Effect of initial iron concentration on iron removal efficiency
10a	Manganese conc = 4.341$e^{-0.007(\text{Coagulant dosage})}$	0.731	Effect of *E. goetzei* seed extract coagulant dosage on manganese concentration in water
10b	Manganese removal efficiency = −0.0095(Coagulant dosage)^2 + 1.390(Coagulant dosage) + 5.795	0.909	Effect of *E. goetzei* seed extract dosage on manganese removal efficiency
11	Manganese removal efficiency = −0.292(Initial manganese conc)^2 + 8.6024(Initial manganese conc) − 0.269	0.743	Effect of initial manganese concentration on manganese removal efficiency

(Continues)

EXHIBIT 17 | (Continued)

Equation number	Model	R^2	Description
12	COD = 0.024(Coagulant dosage)^2 + (Coagulant dosage) + 54.238	0.954	Effect of *E. goetzei* seed extract coagulant dosage on COD of treated water
13a	Total nitrogen = −7E-05(Coagulant dosage)^2 + 0.0096(Coagulant dosage) + 0.062	0.747	Effect of *E. goetzei* seed extract coagulant dosage on total nitrogen in sludge
13b	Total phosphorous = −2E-05(Coagulant dosage)^2 + 0.004(Coagulant dosage) + 0.011	0.969	Effect of *E. goetzei* seed extract coagulant dosage on total phosphorus in sludge

Compared to other coagulants like *Azadirachta indica*, *E. goetzei* seed extract demonstrated better fluoride removal efficiency at the same dosage. However, when *A. indica* and *M. oleifera* leaves were combined, a higher removal efficiency of 64.3% was achieved (Pandey et al. 2020).

E. goetzei seed extract may remove fluoride from water by utilizing positively charged proteins that interact with fluoride ions, forming soluble and slightly soluble compounds through electrostatic interactions. This ion exchange process can aid in the formation of settleable flocs, as observed in a study using *M. oleifera* for groundwater defluoridation (Masquetti and Ueda 2021). Predictions based on the model in Exhibit 17 suggest that at a coagulant dosage of 180 mg/L, the fluoride concentration in synthetic water would be approximately 1.15 mg/L, meeting the WHO standard.

4.3.2 | Effect of Initial Fluoride Concentration on Fluoride Removal Efficiency in Synthetic Water

The study found that increasing the initial fluoride concentration from 5 to 25 mg/L led to a rise in fluoride removal efficiency from 21.0% to 53.1%. Masquetti et al. (2015) reported increased removal efficiency from 68.7% to 72.0% and 60.0% to 71.4% for *M. oleifera* treatment at coagulant dosages of 5 g/L and pH levels of 3 and 7, respectively, as the initial fluoride concentration rose from 3 to 10 mg/L. Conversely, Bayu et al. (2022) revealed a decrease in fluoride removal efficiency from 79.8% to 59.5%, as the initial fluoride concentration increased from 5.5 to 10 mg/L when using *Tulsi* leaves for treating artificially fluoridated water. The higher removal efficiency at lower initial fluoride concentrations is attributed to the availability of positively charged sites on the coagulant for bonding with negatively charged fluoride ions (Agnihotri et al. 2013).

4.3.3 | Effect of *E. goetzei* Seed Extract Coagulant Dosage on Iron and Manganese Removal

The study achieved a maximum iron removal efficiency of 90.0% at 100 mg/L, with a residual iron concentration of 0.55 ± 0.02 mg/L. This iron removal efficiency is comparable to the 90.0% achieved in a study by Sajidu et al. (2005), where *M. oleifera* seeds at a dosage of 2500 mg/L were used to treat synthetic heavy metal contaminated water with an initial iron concentration of 5.00 ppm.

Pinecones powder achieved a higher iron removal efficiency of 94.0% at a coagulant dosage of 3000 mg/L when treating industrial wastewater with an initial iron concentration of 5.30 mg/L (Shadi et al. 2022). These results are comparable to the iron removal efficiency obtained in the present study using *E. goetzei* seed extract as the coagulant. To achieve a manganese concentration of at least 0.1 mg/L, a coagulant dosage of 540 mg/L of *E. goetzei* seed extract is predicted based on the model 8a in Exhibit 17.

The research did not investigate the specific process of iron and manganese removal, but it is likely that precipitation occurs after oxidation. *E. goetzei* seed extract might contain oxidizing chemicals that cause iron and manganese to precipitate as oxides (Nkurunziza et al. 2009). The higher removal efficiency of iron and manganese at increasing coagulant dosages can be attributed to the higher dose, which destabilizes colloidal suspensions and promotes floc development (Pramanik, Pramanik, and Suja 2016).

4.3.4 | Effect of Initial Manganese and Iron Concentration on Manganese and Iron Removal Efficiency

Increasing the initial metal concentration led to higher removal efficiency, but beyond the threshold, further increases resulted in lower efficiency. This could be due to the saturation of binding sites on the coagulant as more metal ions are added. The number of metal ions competing for binding sites increases with higher metal ion concentrations, leading to site saturation (Rahman and Islam 2009). The increase in electrostatic contacts, rather than covalent interactions, with a lower affinity for metal ions, contributes to improved metal absorption (Obuseng, Nareetsile, and Kwaambwa 2012).

4.4 | Residual Content of Organic Matter in Water Treated With *E. goetzei* Seed Extract

The initial COD concentration in the synthetic water sample was 44.67 mg/L. The elevated level of COD in the synthetic water could be due to organic impurities in the kaolin clay

(Aroke, Abdulkarim, and Ogubunka 2013). There was an increase in COD from 44.67 to 419.33 mg/L of the water, as the coagulant dosage increased from 20 to 100 mg/L. Similarly, in a study by Shan et al. (2017), as the dosage of *M. oleifera* seed increased from 10,000 to 30,000 mg/L, the COD increased from 99.50 to 164.00 mg/L in river water.

Increasing the coagulant dosage of *E. goetzei* seed extract raised the COD levels due to the oil present in the extracts (Shan et al. 2017). The aqueous extract contained organic matter like lipids and carbohydrates, increasing the organic load in treated water. The maximum COD obtained in this study exceeded the WHO standard for drinking water (10 mg/L). To prevent the rise of organic content, a purification step can be added during coagulant preparation to remove elements contributing to the organic load (Vega et al. 2021).

4.5 | Quality of Sludge Produced From Treating Synthetic Water With *E. goetzei* Seed Extract

The total nitrogen in the sludge varied slightly with increasing coagulant dosage, reaching 0.343 μg/kg at 100 mg/L. This value is lower than the total nitrogen obtained in a separate study by Feria-Díaz, Polo-corrales, and Hernandez-ramos (2016), using *M. oleifera* seed as a coagulant. The total phosphorus in the sludge increased from 0.073 to 0.194 μg/kg as the coagulant dosage increased from 0 to 100 mg/L. The total phosphorus value at 100 mg/L is lower than the value obtained with *M. oleifera* seed in the study by Feria-Díaz, Polo-corrales, and Hernandez-ramos (2016).

The total nitrogen and phosphorus content in this study were lower than those reported for compost samples (22.00 g/kg of nitrogen and 1.40 g/kg of phosphorus) and organic fertilizer (1.32 g/kg of nitrogen and 0.21 g/kg of phosphorus) from a previous study (Olivares-campos and Jáquez-balderrama 2012). They were also lower than the values found in municipal sewage sludge (13.70 g/kg of nitrogen and 2.80 g/kg of phosphorus) (Antonkiewicz et al. 2020).

4.6 | Limitations and Scope for Further Work

The study faced limitations owing to insufficient financial resources, resulting in restrictions on the coagulant dosage used. Models were developed to predict outcomes with higher dosages; however, further experimental validation is needed. Additionally, there was a lack of field validation to apply the research to real-world water sources. Scaling up the use of *E. goetzei* seed extract coagulant would allow for better understanding its response to water quality variations and operational conditions in larger treatment plants.

5 | Conclusion and Recommendations

5.1 | Conclusion

E. goetzei seed extract contain proteins, carbohydrates, fat, and fiber, which contribute to their ability to remove impurities in water. The research demonstrates that these extracts can effectively treat water with an initial turbidity of up to 71.33 NTU, meeting the WHO standard of 5 NTU for drinking water. Increasing the coagulant dosage improves turbidity, fluoride, iron, and manganese removal efficiency. However, at the highest dosage, residual fluoride and manganese levels still exceed WHO drinking water standards. Models suggest that further dosing can help meet the standards. The pH of the treated water remained within the WHO range (6.5–8.5); however, the TDS value exceeded the WHO guideline of 600 mg/L at the highest coagulant dosage.

It was observed that there is a general trend of increasing COD in the treated water as the coagulant dosage increases. This suggests that higher dosages of the coagulant may introduce or contribute to the presence of organic compounds or substances that contribute to the COD value. It was also concluded that the content of nitrogen and phosphorus in the sludge after water treatment is not viable for reuse applications in agriculture. Overall, this research demonstrates good potential for the use of *E. goetzei* seed extract as a coagulant for water treatment.

5.2 | Recommendations

Based on the respective objectives, the following recommendations were derived from the findings of this research:

1. More studies need to be done on the proteins, which are part of the active ingredients in the seed extract of *E. goetzei*. The proteins can be characterized to determine their molecular weight and amino acid sequences.
2. Additional research is needed to investigate a wider range of coagulant dosages using *E. goetzei* seed extract for removing turbidity, iron, manganese, and fluoride. Furthermore, the impact of operational parameters, such as pH, mixing speed, settling time, and coagulant extraction method, on the removal efficiency should be explored.
3. There is a need to investigate ways of dealing with the issue of an increase in COD in treated water with increasing coagulant dosage to improve the overall quality of the water.
4. Further studies must be done on the sludge produced from water treatment using *E. goetzei* seed extract to determine other parameters of the sludge such as water retention to come up with a beneficial use for the sludge.

Acknowledgments

The authors would like to express their gratitude for the financial support received from the Vice Chancellor Scholarship Fund of the Chinhoyi University of Technology, Zimbabwe, and complementary experiments and funding by the Tongji University Institute for Environment and Sustainable Development, China.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available owing to privacy or ethical restrictions.

References

Abdulkadir, A. R., D. D. Zawawi, and M. S. Jahan. 2016. "Proximate and Phytochemical Screening of Different Parts of *Moringa oleifera*." *Russian Agricultural Sciences* 42, no. 1: 34–36. https://doi.org/10.3103/s106836741601002x.

Abidin, Z. Z., N. Madehi, and R. Yunus. 2017. "Coagulative Behaviour of *Jatropha curcas* and Its Performance in Wastewater Treatment." *Environmental Progress & Sustainable Energy* 36, no. 6: 1709–1718. https://doi.org/10.1002/ep.

Adetunji, A. I., and A. O. Olaniran. 2021. "Treatment of Industrial Oily Wastewater by Advanced Technologies: A Review." *Applied Water Science* 11, no. 6: 1–19. https://doi.org/10.1007/s13201-021-01430-4.

Agarwal, P., and G. Saini. 2022. "Use of Natural Coagulants (*Moringa oleifera* and *Benincasa hispida*) for Volume Reduction of Waste Drilling Slurries." *Materials Today: Proceedings* 49: 3274–3278. https://doi.org/10.1016/j.matpr.2020.12.924.

Agnihotri, N., V. K. Pathak, N. Khatoon, and M. Rahman. 2013. "Removal of Fluoride From Water by *Moringa oleifera* Seed Residue After Oil Extraction." *International Journal of Scientific & Engineering Research* 4, no. 10: 106–110.

Alazaiza, M. Y. D., A. Albahnasawi, G. A. M. Ali, et al. 2022. "Application of Natural Coagulants for Pharmaceutical Removal From Water and Wastewater: A Review." *Water* 14, no. 2: 140.

Alenazi, M., K. S. Hashim, A. A. Hassan, M. Muradov, P. Kot, and B. Abdulhadi. 2020. "Turbidity Removal Using Natural Coagulants Derived From the Seeds of *Strychnos potatorum*: Statistical and Experimental Approach." *IOP Conference Series: Materials Science and Engineering* 888, no. 1. https://doi.org/10.1088/1757-899X/888/1/012064.

Ali, E. N., S. A. Muyibi, H. M. Salleh, M. Z. Alam, and M. R. M. Salleh. 2010. "Production of Natural Coagulant From *Moringa Oleifera* Seed for Application in Treatment of Low Turbidity Water." *Journal of Water Resource and Protection* 02, no. 03: 259–266. https://doi.org/10.4236/jwarp.2010.23030.

Ali, S. A., and A. Ahmad. 2020. "Analysing Water-Borne Diseases Susceptibility in Kolkata Municipal Corporation Using WQI and GIS Based Kriging Interpolation." *GeoJournal* 85, no. 4: 1151–1174. https://doi.org/10.1007/s10708-019-10015-3.

Amran, A. H., N. S. Zaidi, K. Muda, M. B. Bahrodin, and W. Loan. 2021. "Deshelled *Carica papaya* Seeds as Natural Coagulant for Improvement Quality of River Water." *Sains Malaysiana* 50, no. 6: 1521–1529. https://doi.org/10.17576/jsm-2021-5006-02.

Ang, T.-H., W. K. Kunlanan Kiatkittipong, S.-C. Chua, J. W. Lim, M. J. K. B. Pau-Loke Show, and H. Yeek-Chia. 2020. "Insight on Extraction and Characterisation of Biopolymers as the Green Coagulants for Microalgae Harvesting." *Water* 12, no. 5: 1388.

Antonkiewicz, J., A. Pop, B. Ko, et al. 2020. "Application of Ash and Municipal Sewage Sludge as Macronutrient Sources in Sustainable Plant Biomass Production." *Journal of Environmental Management* 264: 110450. https://doi.org/10.1016/j.jenvman.2020.110450.

AOAC. 2000. "AOAC Official Methods of Analysis." *Toxicology and Industrial Health* 15, no. 8. https://doi.org/10.1177/074823379901500807.

APHA/AWWA/WEF. 2017. *Standard Methods for the Examination of Water and Wastewater* (23rd ed.). Washington DC: American Public Health Association.

Aroke, U., A. Abdulkarim, and R. Ogubunka. 2013. "Fourier-Transform Infrared Characterization of Kaolin, Granite, Bentonite and Barite." *Journal of Environmental Technology* 6, no. 1: 1–14.

Asrafuzzaman, M., A. N. M. Fakhruddin, and M. A. Hossain. 2011. "Reduction of Turbidity of Water Using Locally Available Natural Coagulants." *ISRN Microbiology* 1: 632189. https://doi.org/10.5402/2011/632189.

Azamzam, A. A., M. Rafatullah, E. B. Yahya, et al. 2022. "Enhancing the Efficiency of Banana Peel Bio-Coagulant in Turbid and River Water Treatment Applications." *Water* 14, no. 16: 2473.

Bahrodin, M. B., N. S. Zaidi, A. Kadier, N. Hussein, A. Syafiuddin, and R. Boopathy. 2022. "A Novel Natural Active Coagulant Agent Extracted From the Sugarcane Bagasse for Wastewater Treatment." *Applied Sciences (Switzerland)* 12, no. 16: 7972. https://doi.org/10.3390/app12167972.

Bayu, K., A. Geremew, W. Deriba, Y. Mulugeta, S. Wagari, and G. Dirirsa. 2022. "Fluoride Removal Efficiency of Tulsi (*Ocimum sanctum*) From Water." *Water Supply* 22, no. 1: 496–509. https://doi.org/10.2166/ws.2021.257.

Benalia, A., K. Derbal, A. Khalfaoui, et al. 2021. "Use of Aloe vera as an Organic Coagulant for Improving Drinking Water Quality." *Journal of Renewable Materials* 10, no. 3.

Beyene, H. D., T. D. Hailegebrial, and W. B. Dirersa. 2016. "Investigation of Coagulation Activity of Cactus Powder in Water Treatment." *Journal of Applied Chemistry* 2016: 8–9. http://doi.org/10.1080/23311916.2017.1365676%0Ahttps://doi.org/10.15171/EHEM.2016.24%0Afile:///C:/Users/Asus/Downloads/1.pdf.

Desta, W. M., and M. E. Bote. 2021. "Wastewater Treatment Using a Natural Coagulant (Moringa Oleifera Seeds): Optimization Through Response Surface Methodology." *Heliyon* 7: e08451. https://doi.org/10.1016/j.heliyon.2021.e08451.

Dunoyer, A. A. T., L. E. G. Carrillo, and R. E. G. Cuello. 2022. "Removal of Turbidity and Color in Domestic Wastewater Using Aqueous Seed Extract of *Cassia fistula*." *Ambiente & Água—An Interdisciplinary Journal of Applied Science* 9, no. 3: 445–458. https://doi.org/10.4136/1980-993X.

Eawag Aquatic Research. 2007. *Determination of TN 13.7.2007*.

Epalza, J., J. Jaramillo, and O. Guarín. 2018. "Extraction and Use of Plant Biopolymers for Water Treatment." *Desalination and Water Treatment* 369–384.

Feria-Díaz, J. J., L. Polo-corrales, and E. J. Hernandez-ramos. 2016. "Evaluation of Coagulation Sludge From Raw Water Treated With *Moringa oleifera* for Agricultural Use." *Ingeniería e Investigación* 36, no. 2: 14–20. https://doi.org/10.15446/ing.investig.v36n2.56986.Chemical.

Ghebremichael, K. A., K. R. Gunaratna, H. Henriksson, H. Brumer, and G. Dalhammar. 2005. "A Simple Purification and Activity Assay of the Coagulant Protein From *Moringa oleifera* Seed." *Water Research* 39, no. 11: 2338–2344. https://doi.org/10.1016/j.watres.2005.04.012.

Gidde, M. R., A. R. Bhalerao, and C. N. Malusare. 2012. "Comparative Study of Different Forms of *Moringa oleifera* Extracts for Turbidity Removal." *International Journal of Engineering Research and Development* 2, no. 1: 14–21. https://www.idc-online.com/technical_references/pdfs/civil_engineering/ComparativeStudyof.pdf.

Halder, A. 2021. "Bio-Coagulants, a Substitute of Chemical Coagulants." *Journal of Advanced Scientific Research* 12, no. 4: 58–67.

Igwegbe, C. A., O. D. Onukwuli, J. O. Ighalo, and M. C. Menkiti. 2021. "Bio-Coagulation-Flocculation (BCF) of Municipal Solid Waste Leachate Using *Picralima nitida* Extract: RSM and ANN Modelling." *Current Research in Green and Sustainable Chemistry* 4: 100078.

Islam, M. M. M., S. Shafi, S. A. Bandh, and N. Shameem. 2019. "Impact of Environmental Changes and human Activities on Bacterial Diversity of Lakes." In *Freshwater Microbiology*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-817495-1.00003-7.

Maroyi, A. 2017. "Phytochemical and Ethnopharmacological Review of *Elephantorrhiza goetzei* (Harms) Harms." *Asian Pacific Journal of Tropical Medicine* 10, no. 2: 107–113. https://doi.org/10.1016/j.apjtm.2017.01.014.

Masquetti, V., M. Carla, B. Ambrosio, et al. 2015. "Removal of Excess Fluoride From Groundwater Using Natural Coagulant *Moringa oleifera* Lam and Microfiltration." *The Canadian Journal of Chemical Engineering* 93: 37–45. https://doi.org/10.1002/cjce.22101.

Masquetti, V., and N. Ueda. 2021. "Process Performance Combining Natural Coagulant *Moringa oleifera* Lam and Ultrafiltration for Groundwater Defluoridation." *Water, Air, & Soil Pollution* 232, no. 6: 222.

Menkiti, M. C., C. R. Ndaji, and I. G. Ezemagu. 2017. "Deturbidization of Petroleum-Produced Water by Novel Mucuna Seed: Characterization, Kinetics, and Statistical Analyses." *Water Conservation Science and Engineering* 2, no. 3: 67–83. https://doi.org/10.1007/s41101-017-0027-1.

Namjan, M., N. Kaewwonglom, C. Dechakiatkrai Theerakarunwong, J. Jakmunee, and W. Khongpet. 2023. "An Environmentally Friendly Compact Microfluidic Hydrodynamic Sequential Injection System Using *Curcuma putii* Maknoi & Jenjitt. Extract as a Natural Reagent for Colorimetric Determination of Total Iron in Water Samples." *Journal of Analytical Methods in Chemistry* 2023, no. 1: 3400863. https://doi.org/10.1155/2023/3400863.

Njuguna, A., A. Mayabi, and W. Ndirangu. 2014. "Removal of Organic Pollutants From Pharmaceutical Industry Wastewater by Chemical Coagulation and Bentonite Clay Pretreatment." *Proceedings of Sustainable Research and Innovation Conference*, 205–208.

Nkurunziza, T., J. B. Nduwayezu, E. N. Banadda, and I. Nhapi. 2009. "The Effect of Turbidity Levels and *Moringa oleifera* Concentration on the Effectiveness of Coagulation in Water Treatment." *Water Science and Technology* 59, no. 8: 1551–1558. https://doi.org/10.2166/wst.2009.155.

Nnaji, P. C., V. C. Anadebe, I. G. Ezemagu, and O. D. Onukwuli. 2022. "Potential of *Luffa cylindrica* Seed as Coagulation-Flocculation (CF) Agent for the Treatment of Dye Wastewater: Kinetic, Mass Transfer, Optimization and CF Adsorption Studies." *Arabian Journal of Chemistry* 15, no. 2: 103629. https://doi.org/10.1016/j.arabjc.2021.103629.

Obiora-Okafo, I. A., O. D. Onukwuli, and N. C. Eli-Chukwu. 2020. "Evaluation of Bio-Coagulants For Colour Removal From Dye Synthetic Wastewater: Characterization, Adsorption Kinetics, and Modelling Approach." *Water SA* 46, no. 2: 300–312. https://doi.org/10.17159/wsa.2020.v46i2.8246.

Obuseng, V., F. Nareetsile, and H. M. Kwaambwa. 2012. "A Study of the Removal of Heavy Metals From Aqueous Solutions by *Moringa oleifera* Seeds and Amine-Based Ligand 1,4-bis[N,N-bis(2-picoyl)amino]butane." *Analytica Chimica Acta* 730: 87–92. https://doi.org/10.1016/j.aca.2012.01.054.

Ogah, E., S. P. Malu, O. A. Ushie, B. D. Longbap, and C. V. Abiaziem. 2016. "Heavy Metal Levels in *Tilapia zilli* Samples From North Central Nigerian Rivers." *Research Journal of Food Science and Nutrition* 1, no. 3: 42–48. https://doi.org/10.31248/rjfsn2016.019.

Ojha, A. 2020. "Materials in Electrochemical Detection of Water Pollutants." In *Advanced Functional Materials and Sensors*, 161–185. Switzerland: Springer Nature. https://doi.org/10.1007/978-981-15-0671-0_10.

Okolo, B. I., O. Adeyi, E. O. Oke, et al. 2021. "Coagulation Kinetic Study and Optimization Using Response Surface Methodology for Effective Removal of Turbidity From Paint Wastewater Using Natural Coagulants." *Scientific African* 14: e00959. https://doi.org/10.1016/j.sciaf.2021.e00959.

Okuda, T., A. U. Baes, W. Nishijima, and M. Okada. 2001. "Coagulation Mechanism of Salt Solution-Extracted Active Component in *Moringa oleifera* Seeds." *Water Research* 35, no. 3: 830–834. https://doi.org/10.1016/S0043-1354(00)00296-7.

Olivares-campos, M. A., and J. L. Jáquez-balderrama. 2012. "Worm Compost and Dairy Cattle Manure Compost as Fertilisers and in Soil Improvement." *Universidad y Ciencia* 28, no. 1: 27–37.

Owodunni, A. A., and S. Ismail. 2021. "Revolutionary Technique for Sustainable Plant-Based Green Coagulants in Industrial Wastewater Treatment—A Review." *Journal of Water Process Engineering* 42: 102096.

Pandey, D., S. Verma, P. Verma, et al. 2021. "SARS-CoV-2 in Wastewater: Challenges for Developing Countries." *International Journal of Hygiene and Environmental Health* 231: 113634.

Pandey, P., F. Khan, V. Ahmad, A. Singh, T. Shamshad, and R. Mishra. 2020. "Combined Efficacy of *Azadirachta indica* and *Moringa oleifera* Leaves Extract as a Potential Coagulant in Ground Water Treatment." *SN Applied Sciences* 2, no. 7: 1–8. https://doi.org/10.1007/s42452-020-3124-2.

Pramanik, B. K., S. K. Pramanik, and F. Suja. 2016. "Removal of Arsenic and Iron Removal From Drinking Water Using Coagulation and Biological Treatment." *IWA Publishing* 14: 90–96. https://doi.org/10.2166/wh.2015.159.

Rahman, M. S., and M. R. Islam. 2009. "Effects of pH on Isotherms Modeling for Cu (II) Ions Adsorption Using Maple Wood Sawdust." *Chemical Engineering Journal* 149: 273–280. https://doi.org/10.1016/j.cej.2008.11.029.

Saini, R. K. 2016. "Phytochemicals of *Moringa oleifera*: A Review of Their Nutritional, Therapeutic and Industrial Significance." *3 Biotech* 6, no. 2: 1–14. https://doi.org/10.1007/s13205-016-0526-3.

Sajidu, S., E. Henry, G. Kwamdera, and L. Mataka. 2005. "Removal of Lead, Iron and Cadmium Ions by Means of Polyelectrolytes of the *Moringa oleifera* Whole Seed Kernel." *WIT Transactions on Ecology and the Environment* 80: 251–258.

Shadi, M., S. Abujazar, S. Ugurlu, H. Ramadan, S. S. Abu, and M. Y. D. Alazaiza. 2022. "Application of Pinecones Powder as a Natural Coagulants for Sustainable Treatment of Industrial Wastewater." *Desalination and Water Treatment* 269: 57–64. https://doi.org/10.5004/dwt.2022.28749.

Shan, T. C., M. A. Matar, E. A. Makky, and E. N. Ali. 2017. "The Use of *Moringa oleifera* Seed as a Natural Coagulant for Wastewater Treatment and Heavy Metals Removal." *Applied Water Science* 7, no. 3: 1369–1376. https://doi.org/10.1007/s13201-016-0499-8.

Sharmila, A., V. Amruthavarshini, K. R. Chandana, and H. M. Shreenidhi. 2019. "*Trichoderma harzianum*: An Effective Biosorbent for Defluoridation." *Water and Energy International* 62, no. 6: 56–60.

Skoronski, E., B. Niero, M. Fernandes, M. V. Alves, and V. Trevisan. 2014. "Turbidity Removal and pH of Raw Water Treated With Natural Coagulants." *Revista Ambiente & Água* 9: 679–687.

Smith, S. C., and D. F. Rodrigues. 2015. "Carbon-Based Nanomaterials for Removal of Chemical and Biological Contaminants From Water: A Review of Mechanisms and Applications." *Carbon* 91: 122–143. https://doi.org/10.1016/j.carbon.2015.04.043.

Sofiavizhimalar, A., B. Sunithajasmine, B. S. Rajalakshmi, et al. 2022. "Utilization of Natural Polysaccharide From *Tamarindus indica* L. Seeds for the Effective Reduction of Pollutants in Cheese Processed Wastewater." *Chemosphere* 305, no. May: 135241. https://doi.org/10.1016/j.chemosphere.2022.135241.

Tawakkoly, B., A. Alizadehdakhel, and F. Dorosti. 2019. "Evaluation of COD and Turbidity Removal From Compost Leachate Wastewater Using *Salvia hispanica* as a Natural Coagulant." *Industrial Crops and Products* 137, no. March: 323–331. https://doi.org/10.1016/j.indcrop.2019.05.038.

Thomas, O. M., L. Hitler, N. I. Nelson, et al. 2018. "Proximate Analysis and Mineral Composition of *Jatropha curcas* Seeds Obtained From Pankshin Local Government Area of Plateau State of Nigeria." *Journal of Physical Chemistry & Biophysics* 08, no. 01: 1–6. https://doi.org/10.4172/2161-0398.1000265.

Tong, C. Y., F. Huda, B. Che, and C. J. C. Derek. 2021. "Fish Farm Wastewater Treatment Using *Moringa oleifera* Seed Powder as Natural Coagulant." *IOP Conference Series: Earth and Environmental Science*. https://doi.org/10.1088/1755-1315/945/1/012070.

Vargas, A., A. S. Armas, Z. L. Valencia, and E. Benites. 2022. "Safety in Wastewater Treatment Plants and the Use of Natural Coagulants as an Alternative for Turbidity." *Chemical Engineering Transactions* 91: 301–306. https://doi.org/10.3303/CET2291051.

Vega, A. P., C. F. Palanca, M. A. C. de Oliveira, C. Y. K. Ito, and A. G. dos Reis. 2021. "Use of *Moringa oleifera* Seed as a Natural Coagulant in Domestic Wastewater Tertiary Treatment: Physicochemical, Cytotoxicity and Bacterial Load Evaluation." *Journal of Water Process Engineering* 40: 101859. https://doi.org/10.1016/j.jwpe.2020.101859.

Vunain, E., P. Mike, G. Mpeketula, M. Monjerezi, and A. Etale. 2019. "Evaluation of Coagulating Efficiency and Water Borne Pathogens

Reduction Capacity of *Moringa oleifera* Seed Powder for Treatment of Domestic Wastewater From Zomba, Malawi." *Journal of Environmental Chemical Engineering* 7, no. 3: 103118. https://doi.org/10.1016/j.jece.2019.103118.

Westwood, D. 2007. *The Determination of Chemical Oxygen Demand in Waters and Effluents*. UK: Environment Agency, National Laboratory Service.

WHO. 2007. "pH in Drinking-Water." *Guidelines for Drinking Water Quality* 2, no. 2: 1–7. http://www.who.int/water_sanitation_health/dwq/chemicals/ph_revised_2007_clean_version.pdf.

WHO. 2017. Water Quality and Health—Review of Turbidity: Information for Regulators and Water Suppliers. *Who/Fwc/Wsh/17.01*, 10. https://www.who.int/water_sanitation_health/publications/turbidity-information-200217.pdf%0Ahttp://www.who.int/water_sanitation_health/publications/turbidity-information-200217.pdf.

Xiao, J., H. Zhang, L. Niu, X. Wang, and X. Lu. 2011. "Evaluation of Detoxification Methods on Toxic and Antinutritional Composition and Nutritional Quality of Proteins in *Jatropha curcas* Meal." *Journal of Agricultural and Food Chemistry* 59, no. 8: 4040–4044. https://doi.org/10.1021/jf200104b.

Xiujie, W., W. Weiqi, Z. Jing, W. Siyu, and L. Jun. 2019. "Dominance of *Candidatus saccharibacteria* in SBRs Achieving Partial Denitrification: Effects of Sludge Acclimating Methods on Microbial Communities and Nitrite Accumulation." *RSC Advances* 9, no. 20: 11263–11271. https://doi.org/10.1039/C8RA09518C.

Yin, C.-Y. 2010. "Emerging Usage of Plant-Based Coagulants for Water and Wastewater Treatment." *Process Biochemistry* 45, no. 9: 1437–1444. https://doi.org/10.1016/j.jhazmat.2010.12.075.

Zedan, T., M. Mossad, M. Fouad, and H. Mahanna. 2022. "Potential Application of Natural Coagulant Extraction From Walnut Seeds for Water Turbidity Removal." *Water Practice and Technology* 17, no. 3: 684–698. https://doi.org/10.2166/wpt.2022.019.

Zheng, Y., Y. Zhu, A. Wang, and H. Hu. 2016. "Potential of *Calotropis gigantea* Fiber as an Absorbent for Removal of Oil From Water." *Industrial Crops and Products* 83: 387–390. https://doi.org/10.1016/j.indcrop.2016.01.009.