The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Partial Replacement of Alum Coagulant by Green Coagulant: A Novel Approach for Removing Turbidity from Kaolin Synthetic Water

Mukheled Al-Sameraiy✉

Environmental Research Center, University of Technology- Iraq

Article Info

Article type:
Research Article

Article history:
Received: 25 December 2023
Revised: 11 April 2024
Accepted: 25 May 2024

Keywords:
Novel Approach
Conventional Approach
Turbidity Removal
Palm Bark
Watermelon

ABSTRACT

Turbidity is of great concern in drinking water treatment. Coagulation-flocculation (CF) process is widely applied for removing turbidity, which depends on coagulant type. Alum-chemical coagulant is commonly used due to its superiority in removing it. However, alum has been associated with several adverse impacts on human health and the environment. Natural coagulants (eco-friendly materials) cannot be a feasible alternative to alum due to their limited coagulating performance in turbidity removal. In our previous research, novel approach to reduce alum impact by partially replacing it with natural coagulant was developed based on two consecutive treatments of CF process. Its concept was that a natural coagulant was used in primary treatment to significantly reduce turbidity and alum was used in secondary treatment at a minimum dose. This approach was successfully applied for treating bentonite turbid water. To verify if its concept is feasible for treating kaolin turbid water, this research was carried out. Experimental results showed that the novel approach achieved superior performance in reducing turbidity of treated water from 950 NTU to less than 5 NTU (i.e., satisfying the WHO drinking water standards) and decreasing alum dose required by 33 and 50% using palm bark and watermelon coagulants, respectively when compared with alum control treatment (i.e., replacing partially alum). The novel approach findings in current research are consistent with our previous research. Concluding its concept is validated with two types of bentonite and kaolin turbid waters. Further work needs to verify if its concept is feasible for treating river surface water.

Cite this article: Al-Sameraiy, M. (2024). Partial Replacement of Alum Coagulant by Green Coagulant: A Novel Approach for Removing Turbidity from Kaolin Synthetic Water. *Pollution*, 10 (3), 899-914.
https://doi.org/10.22059/poll.2024.369833.2192

DOI: https://doi.org/10.22059/poll.2024.369833.2192

INTRODUCTION

Turbidity is a physical characteristic of colloidal solids that cannot be naturally settled or removed from surface waters due to their fine diameter size and high stability (Davarpanah and Sharghi, 2019; Birhanu and Leta, 2021; Benalia et al., 2022). These solids are natural pollutants that make the surface waters unhealthy, and thus these waters need to be treated to meet the WHO guidelines for drinking-water quality (Jamshidi et al., 2020; Beyene et al., 2016; Skaf et al., 2021). Therefore, in real applications, the removal of turbidity has received a great deal of interest. To get an acceptable quality of drinking water, several physical processes in combination with chemical processes are developed and used to remove turbidity. Among these processes, coagulation and flocculation followed by sedimentation are a popular and simple technique used in the purification of surface water (Benalia et al., 2021; Dayarathne et al., 2022). The type of coagulant plays a significant role in evaluating their performance for removing turbidity (Mahanna et al., 2024).

On one side, inorganic-chemical coagulants such as alum are traditionally used in these

*Corresponding Author Email: *mukheled.a.hussien@uotechnology.edu.iq*

processes due to their high removal efficiency, availability and cost-effectiveness (Katrivesis et al., 2019; Cui et al., 2020). However, several inevitable disadvantages are associated with the use of alum because of the accumulation of residual aluminium ions in treated waters. The presence of this accumulation is responsible for several adverse effects on human health such as Alzheimer problems and the environment (producing high volumes of non-biodegradable sludge that require a high cost of treatment and effecting significantly the pH of treated waters (Megersa et al., 2019; Alazaiza et al., 2022).

On the other side, organic-natural coagulants such as natural polymers are derived from natural and renewable sources (plant, animals and microorganisms). These natural coagulants are safe for human health, eco-friendly and biodegradable. Furthermore, when comparing with alum coagulant, they produce low volumes of sludge and have an insignificant effect on the pH of treated waters (Jamshidi et al., 2020; Alazaiza et al., 2022; Ramavandi, 2014). These advantages make them an interesting alternative to alum and other inorganic coagulants. However, in terms of turbidity removal, the performance of these natural coagulants is generally still less than that of inorganic coagulants except in some cases (Cui et al., 2020; Ramavandi, 2014; Zemmouri et al., 2012; Mohd-Salleh et al., 2019). So, limiting their real applications in the field of water treatment.

In literature, to overcome the problems associated with alum and other inorganic coagulants when using them as a single coagulant in conventional approach using coagulation-flocculation (CF) process, several attempts have been carried out to combine these coagulants with natural coagulants. The best performance of their combinations to act as a dual coagulant for turbidity removal is to use alum as a primary coagulant and natural coagulant as a coagulant aid. Both primary coagulant and coagulant aid are used in one treatment. This conventional approach has several advantages such as reducing the alum dose and minimizing the sludge volume (i.e., decreasing the cost) (Cui et al., 2020; Asharuddin et al., 2018; Ali et al., 2019). However, the applied dose of alum used in this approach is generally still higher because of using alum as a primary coagulant to get a maximum removal efficiency of turbidity. Also, this higher dose of alum is still of concern due to its impact on human health and the environment.

To reduce this impact of alum in terms of decreasing the alum dose required for treatment of turbid water as much as possible (i.e., partial replacement of the alum dose required by the natural coagulant dose), a novel approach for turbidity removal has been developed in our previous research (Al-Sameraiy, 2012) for this purpose. Experimentally, this approach consisted of two consecutive treatments (primary and secondary) using coagulation, flocculation and sedimentation processes for each treatment under certain operating conditions of mixing speed, mixing time and setting time. The concept behind this approach was that a natural coagulant at its predetermined optimum dose was firstly used as a primary coagulant to decease the turbidity level of treated water as much as possible in the primary treatment. The supernatant produced from the primary treatment was transferred only (without sludge) to the secondary treatment. Then alum used as a secondary coagulant was added at various investigated doses to significantly decrease the residual turbidity of the supernatant. This novel approach was successfully applied for the treatment of three different levels of bentonite synthetic turbid water (low-75 NTU, medium-150 NTU and high-300 NTU) using a selected natural coagulant (date seeds or pollen sheath) at their predetermined optimum doses. The performance of this approach was validated with conventional approach that used a dual coagulant of either date seeds or pollen sheath at their predetermined optimum doses with various investigated doses of alum in one treatment only under the same operating conditions of the novel approach. At the optimum investigated dose of alum for both approaches, the performance of the novel approach was better than that of the conventional approach under all examined levels of turbid water. It achieved several environmental, economical and operational advantages in terms of minimizing the alum dose required (i.e., partial replacement of alum to minimize its adverse effects on health and the environment, and decrease in the cost of alum use), reducing the settling time required (i.e., decreasing the operational cost-energy saving) and decreasing the residual turbidity to be less than 5 NTU, thus satisfying the WHO guidelines for drinking-water quality. These are very encouraging findings to verify if the concept of the novel approach developed is feasible for the treatment of another type of synthetic turbid water, for example, kaolin.

Therefore, the aim of the current research is to further verification on the concept of novel approach developed in our previous research for the treatment of bentonite synthetic turbid water to be feasible for the treatment of kaolin synthetic turbid water using palm bark (*PB*) and watermelon (*W*) as natural coagulants and alum as chemical coagulant. The performance of novel approach will be evaluated and compared with the performance of conventional approach. The control treatment using alum coagulant will be selected as a basis for achieving the comparative performance between these approaches based on the proposed evaluating parameters in terms of satisfying the WHO guidelines for drinking-water quality, decreasing the alum dose required and reducing the settling time required.

MATERIALS AND METHODS

Collection of kaolin samples

The pieces of white kaolin clay (Fig. 1, a) from local Iraqi location (Dwekla), Al-Anbar Governorate, Western Desert were collected by the State Company for Mining Industries-Ministry of Industry and Minerals. These pieces were obtained from the supplier (State Company for Mining Industries) and manually chopped off and then subjected to grinding using a high-speed powder smasher (model 223FS, 28000 r/min, 1000 W, China). A powder of kaolin clay (Fig. 1, b) was used in the current research to prepare synthetic turbid water. The chemical composition of kaolin clay was provided from the supplier and is shown in Table 1. Particle size analysis of these samples was carried out using Brookhaven Instruments Corp. (90Plus Particle Sizing Software Ver. 5.34). This analysis showed that the minimum, maximum and median (effective) diameters of kaolin clay samples were 1.135, 1.223 and 1.1756 µm respectively.

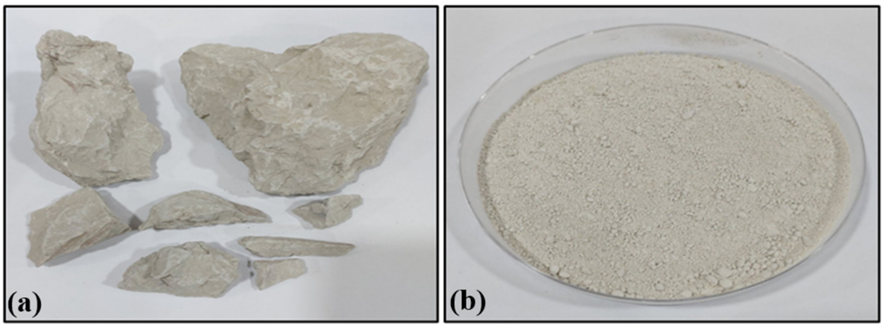

Fig. 1. Real photograph of used kaolin clay in the current research: (a) Pieces and (b) Powder.

Table 1. Chemical composition of kaolin caly provided from the supplier.

Composition	Al_2O_3	SiO_2	Fe_2O_3	Loss of Ignition (L.O.I)	Others
Weight (%)	33.27	50.46	0.67	12.90	2.70

Preparation of kaolin synthetic turbid water

Samples of powdered kaolin clay were used as a model suspension to provide the desired turbidity. Different weights of these samples in (g) were separately added to 1 L of deionized water in a standard six paddle jar apparatus (Compact Laboratory Mixer, ECE CLM6, USA) and resuspended by rapid mechanical agitation of 300 rpm for 30 min to prepare different concentrations of kaolin synthetic turbid water. Turbidities of these concentrations were plotted against the concentrations of kaolin clay powder in (g/L). The linear model was fit well the obtained experimental data. This model was used to obtain the desired turbidity of kaolin synthetic turbid water in the current research, which was 950 ± 25 NTU.

Preparation of alum stock solution

Alum ($Al_2(SO_4)_3.16H_2O$, Thomas Baker, India) was used to prepare a stock solution by dissolving 10 g of alum in deionized water. The pH of prepared stock solution was measured using a pH meter (EZDO PP-203, USA) and found to be 3.4. Desired diluted concentrations of alum were prepared and used as inorganic coagulant in the current research.

Preparation of natural coagulant solution

The pieces of palm bark (*PB*), brown hair and fibrous texture on trunk palm tree, from local Iraqi palm tree were collected (Fig. 2, a). The pieces of direct disposal of the rind waste of watermelon (*W*) after eating the watermelon fruit were collected (Fig. 3, a). Separately, the pieces of *PB* and *W* were washed with tap water and then distilled water to remove any impurities. These pieces were put and dried in oven at 40 °C for one day. Dried pieces (Fig. 2-3, b) were subjected to grinding using a domestic grinder (a high-speed powder smasher, model 223FS, 28000 r/min, 1000 W, China). A powdered *PB* and *W* were sieved to obtain particle sizes of 300 µm (Fig. 2-3, c). 10 g of powdered *PB* and *W* was separately added to 1 L of distilled water and stirred vigorously for 1 h using magnetic stirrer (Model L-81, Rlabinco) at room temperature. Then, the mixture was gravity filtered through 0.45 µm filter paper to separate residual particles from the solution (Fig. 2-3, d). Filtered solution of *PB* and *W* (Fig. 2-3, e) was diluted to the desired concentrations and used as natural coagulants in the current research. The pH of filtered coagulant solution of *PB* and *W* were 6.5 and 5.5 respectively.

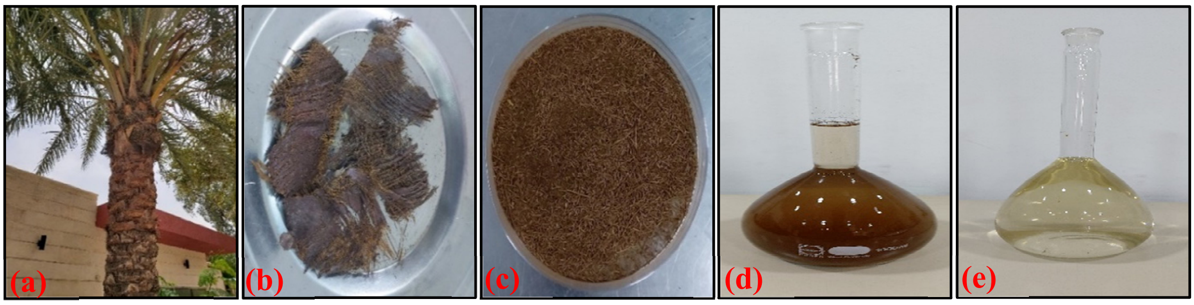

Fig. 2. (a) Local Iraqi palm tree, (b) Dried *PB*, (c) Powdered *PB*, (d) Heterogeneous solution of *PB* coagulant before filtration and (e) Homogeneous solution of *PB* coagulant after filtration.

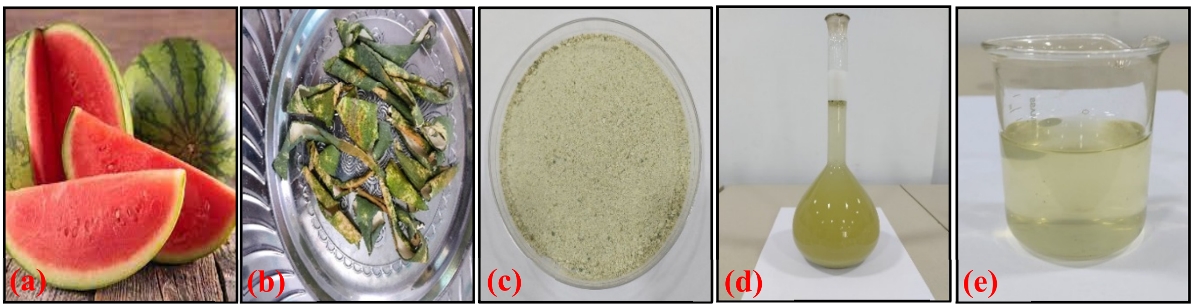

Fig. 3. (a) Local Iraqi watermelon fruit, (b) Dried rind of *W*, (c) Powdered rind of *W*, (d) Heterogeneous solution of rind of *W* coagulant before filtration and (e) Homogeneous solution of rind of *W* coagulant after filtration.

Experimental procedure

A conventional six paddle jar apparatus was utilized for coagulation-flocculation experiments. These experiments were conducted on the samples of kaolin synthetic turbid water with 950 ± 25 NTU at room temperature. The pH of kaolin synthetic turbid water at this range was 6.1. The mixing speed and mixing time were for coagulation (300 rpm, 1 min) and for flocculation (40 rpm, 20 min). The settling time for sedimentation was chosen to be 60 min under quiescent conditions. Upon completion of settling time, the supernatant samples of each beaker in the jar were withdrawn from the located 10 cm below the water level. Turbidities of these samples were measured by turbidity meter (Turbi Direct, TB300-IR Tintometer, Lovibond, Germany) and expressed in nephelometric turbidity unit (NTU) (APHA, 2017). The percentage of turbidity removal, *R* (%) for each coagulant used was calculated using Eq. (1) where T_0 and T_f are the initial turbidity and final turbidity of the suspension respectively.

$$R\ (\%) = \left[\frac{T_0 - T_f}{T_0}\right] x100 \quad (1)$$

To evaluate the coagulating performance of each coagulant used in terms of meeting the WHO guidelines for drinking-water quality (the upper limit of turbidity for finished water is ≤ 5 NTU (WHO, 2017), a residual turbidity (*RT*) was used as an evaluating parameter and indicator of this evaluation.

Note that the pH was left uncontrolled when developed the novel approach in our previous research for the treatment of bentonite synthetic turbid water (Al-Sameraiy, 2012). To make a fair comparison between the previous and current findings, the scope of the current research was to monitor the pH under different investigating conditions.

All experiments were performed in duplicate at room temperature and the obtained results were reported as the mean values ± one standard deviation in the presented figures. The error bars representing ± one standard deviation was used in some experimental data in the presented figures to avoid the overlap between the error bars of repeated experiments.

Control treatment

The coagulant dose is one of the most significant parameters in affecting the performance of turbidity removal where the maximum performance of turbidity removal occurs at the optimum coagulant dose (Benalia et al., 2022; Asharuddin et al., 2018). To achieve this performance, a control treatment in terms of the preliminary investigation on finding the optimum dose for single coagulant of *PB, W* and alum was carried out. A kaolin synthetic turbid water was prepared in six beakers of jar apparatus and various coagulant doses of either *PB* or *W* or alum in the range (10-100 mg/L) were separately added to start coagulation, flocculation and sedimentation processes under the operating conditions mentioned above (Fig. 4). The optimum coagulant dose for each coagulant used was identified depending on the maximum *R* (%). An optimum coagulant dose of control treatment for *PB*, *W* and alum found would be used for further investigation on the evaluation of conventional and novel approaches.

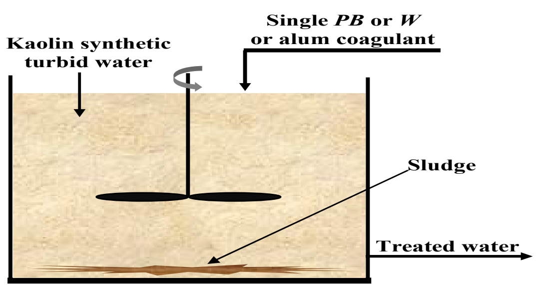

Fig. 4. A control treatment for finding the optimum dose of single coagulant used.

Conventional approach

A conventional approach was one treatment using the (CF) process, which was carried out in one tank as shown in Fig. 5. The conventional approach used a dual coagulant of either *PB* or *W* as primary coagulants and alum as coagulant aid based on previous research (Al-Sameraiy, 2012).

A predetermined optimum coagulant dose of *PB* or *W* was added to treat a kaolin synthetic turbid water and mixed at 300 rpm for 1 min. After that alum was added at various investigated doses ranging from 10 to 100 mg/L and mixed at 300 rpm for 1 min. The mixing speed was then reduced to 40 rpm for 20 min. After stopping the stirrer, the suspension was allowed to settle under quiescent conditions. At these conditions, the supernatant samples were periodically withdrawn for turbidity measurements at every 5 min.

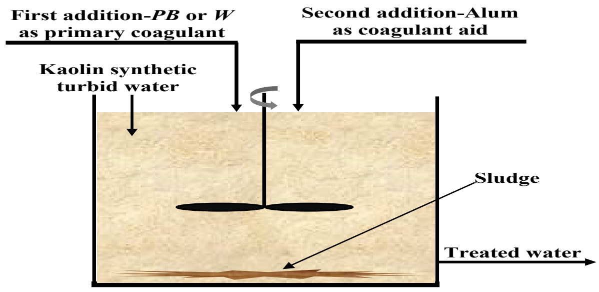

Fig. 5. A conventional approach using one treatment of the CF process.

Novel approach

A novel approach was two consecutive treatments (primary and secondary), Fig. 6, using coagulation, flocculation and sedimentation processes for each treatment under certain operating conditions of mixing speed, mixing time and setting time based on previous research (Al-Sameraiy, 2012). In primary treatment, the coagulant of *PB* or *W* at their predetermined optimum dose used as a primary coagulant was added to treat a kaolin synthetic turbid water and mixed at 300 rpm for 1 min followed by 10 min of gentle speed of 40 rpm. After stopping the stirrer, the suspension was allowed to settle for 10 min under quiescent conditions. The supernatant only was transferred to other empty beakers to start the secondary treatment. In secondary treatment, the alum coagulant used as a secondary coagulant was added under various investigated doses in the range of 5-30 mg/L and mixed at 300 rpm for 1 min followed by 10 min of gentle speed of 40 rpm. After stopping the stirrer, the suspension was allowed to settle under quiescent conditions. Then, the supernatant samples were periodically withdrawn for turbidity measurements at every 5 min.

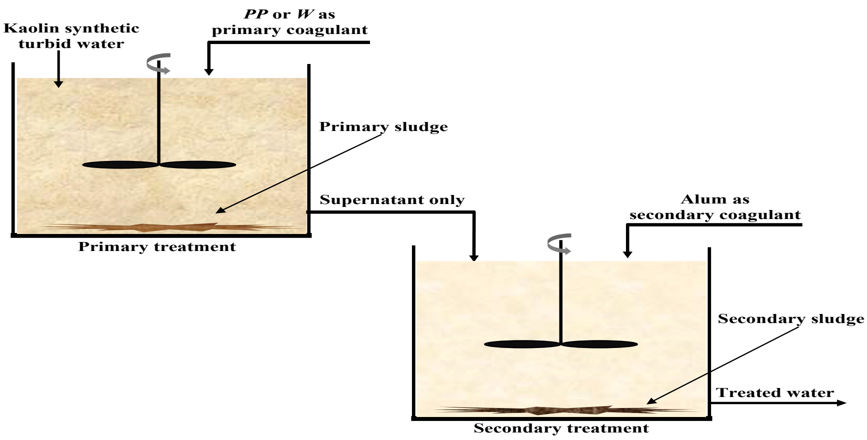

Fig. 6. A novel approach using two consecutive treatments (primary and secondary) of the CF process.

Note that the flocculation time in the conventional approach was 20 min. To do a fair comparison between novel and conventional approaches based on this time, the flocculation time for each of primary and secondary treatments in novel approach was selected to be 10 min where their summations are equal to 20 min.

RESULTS AND DISCUSSION

Control treatment

The optimum dose of control treatment for single coagulant of *PB*, *W* and alum in terms of the *RT* as a function of various settling times was investigated. For natural coagulants, Fig. 7 shows that the *RT* of kaolin synthetic water decreased gradually in comparison with control (blank sample-no coagulant addition) for all examined *PB* doses. The best results of the *RT* were found at the settling time of 60 min. At this time, increasing the *PB* dose from 10 to 40 mg/L led to decease the *RT*. A further increase in the *PB* dose from 50 to 100 mg/L (some data of coagulant doses are not shown in this Fig. to avoid the overlap between lines) increased the *RT*. This indicates that overdosing phenomenon led to charge reversal and subsequent re-stabilization of destabilized particles of turbid water. A dose of 40 mg/L achieved a minimum *RT* (corresponding to the maximum *R* (%) of 93.5%, Table 2) when compared with other doses due to a charge-neutralization mechanism. In literature, several authors showed that the kaolin particles are removed (i.e., aggregated) by the electrical charge neutralization mechanism when using either chemical or natural coagulants in coagulation-flocculation process (Xu et al., 2023; Hu et al., 2022; Kusuma et al., 2022). Thus, this dose can be considered as an optimum dose of the *PB* coagulant.

Similar observations were found for *W* natural coagulant as shown in Fig. 8. At the setting time of 60 min, a minimum *RT* was found at 80 mg/L (corresponding to the maximum *R* (%) of 97.4%, Table 2) when compared with other doses. This coagulating performance represents an optimum dose of the *W* coagulant.

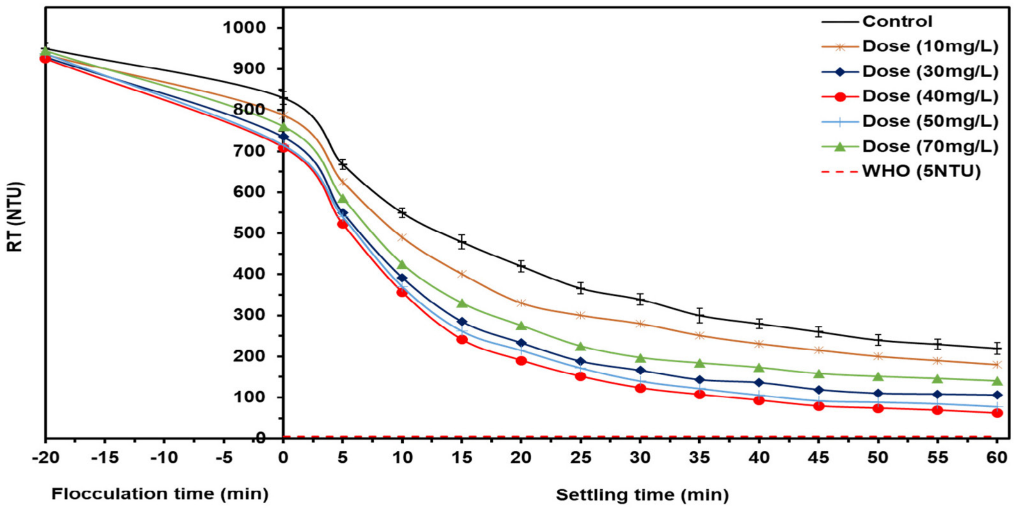

Fig. 7. Investigation on the performance of control treatment using *PB* coagulant.

Table 2. Investigation of the optimum cogulant dose of control treatment for *PB*, *W* and alum coagulants as a funtion of the *R* (%) and *RT* of kaolin synthetic water.

Coagulant type	Optimum dose (mg/L)	*R* (%)	*RT* (NTU)	pH	WHO guidines for drinkig-water quality (≤ 5NTU)
PB	40	93.5	61.9	6.5	Not satisified
W	80	97.4	24.3	6.6	Not satisified
Alum	30	99.6	3.7	4.6	Satisified

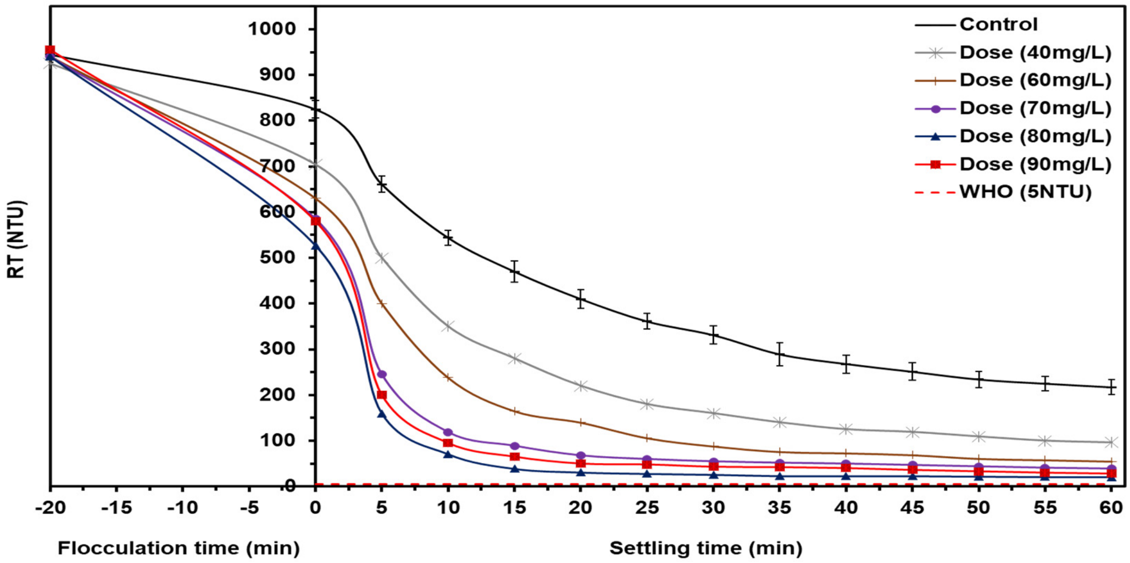

Fig. 8. Investigation on the performance of control treatment using *W* coagulant.

Similarly, the same behavior was found for alum coagulant as shown in Fig. 9. At the settling time of 35 min, the alum coagulant could produce the minimum *RT* at the dose of 30 mg/L (corresponding to the maximum *R* (%) of 99.6%, Table 2) when compared with other doses. Thus, it is an optimum dose of alum coagulant.

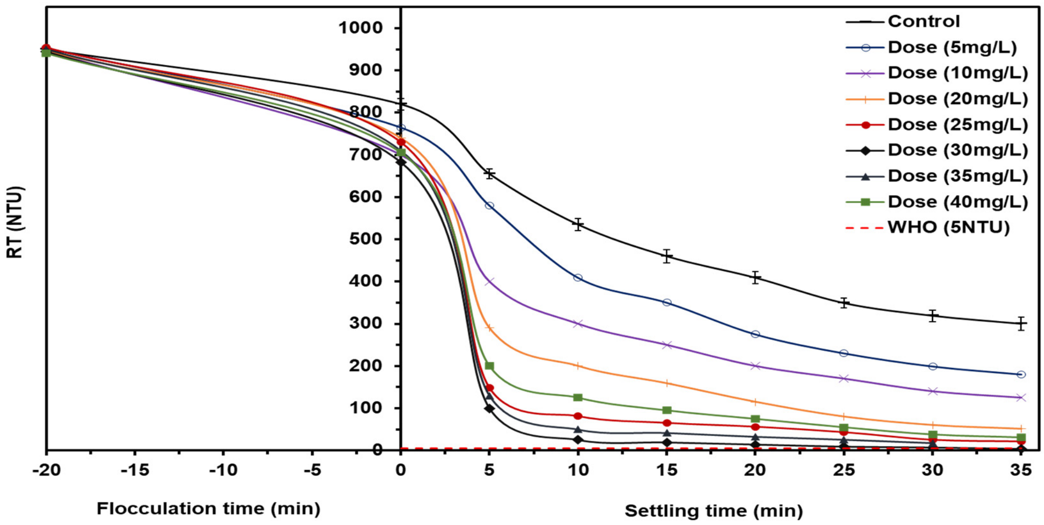

Fig. 9. Investigation on the performance of control treatment using alum coagulant.

As shown in Table 2, at predetermied optimum doses of natural coagualnts, the *PB* and *W* produced the *RT* higher than 5 NTU. This means that they could not satisfy the maximum permissible limit of the WHO guidelines for drinking-water quality. Thus, the performance of *PB* and *W* as single coagulant is so weak. While, the alum coagulant could produce the RT less than 5 NTU, and thus satisfying the WHO guideline. This implies that the alum coagulant showed an excellent coagulating activity for treatment of kaolin synthetic turbid water. This finding is expected since the general application of natural coagulants as single coagulant is not sufficient to work effectively in the removal of turbidity compared with inorganic coagulants such as alum except in some cases (Cui et al., 2020; Ramavandi, 2014; Zemmouri et al., 2012; Mohd-Salleh et al., 2019). So, limiting their real applications in the field of water treatment. The experimental results shown above confirm that the *PB* and *W* natural coagulants cannot be an alternative coagulant instead of alum since their coagulating performances were so poor. However, this is very encouraging result for using them in the novel approach as is shown later. The experimental results in Table 2 can be used to evaluate the performance of conventional and novel approaches as is shown in the coming section.

The monitored pH values for the control treatment at the optimum dose of each coagulant used were recorded in Table 2. It was found that the pH values for natural coagulant are within the range of the WHO guidelines of drinking-water quality (6.5-8.5). While for alum, it was below the recommended range.

Evaluation of performance

To establish a comparable coagulating performance between conventional and novel approaches based on the proposed evaluating parameters in terms of satisfying the WHO guidelines for drinking-water quality, decreasing the alum dose required and reducing the settling time required, the alum control treatment was selected to be used as a basis for achieving the comparative performance between the conventional and novel approaches separately under the optimum conditions.

Conventional approach vs. control treatment

The performance of conventional approach using dual coagulant of either *PB* at predetermied optimum dose (40 mg/L) or *W* at predetermied optimum dose (80 mg/L) with various doses of alum (5-30 mg/L) is shown in Fig. 10 and Fig. 11 respectively.

As observed in Fig. 10, the *RT* of kaolin synthetic water decreased gradually when increasing the dose of alum from 5 to 25 mg/L. At the dose of 30 mg/L, the *RT* of kaolin synthetic water increased. This behavior is normally expected due to overdosing phenomenon (i.e., destabilization of the colloid particles and flocs) (El-Gaayda et al., 2022; Zedan et al., 2022). Thus, the optimum dose of alum was 25 mg/L. At this dose, the conventional approach could successfully achieve a good coagulating performance in terms of producing the *RT* of kaolin synthetic water to be less than 5 NTU at settling time of 30 min, thus satisfying the WHO guidelines for drinking-water quality. Also, it could decrease the alum dose and the settling time required by 17% and 14% respectively when comparing with alum control treatment as shown in Table 3. These advantages are due to the synergistic effect of dual coagulant of *PB* and alum, improving the coagulating performance of the conventional approach (Mungondori et al., 2021; Gandiwa et al., 2020; Al-Anzi et al., 2022; Al-Sameraiy, 2023; Yehia and Said, 2021).

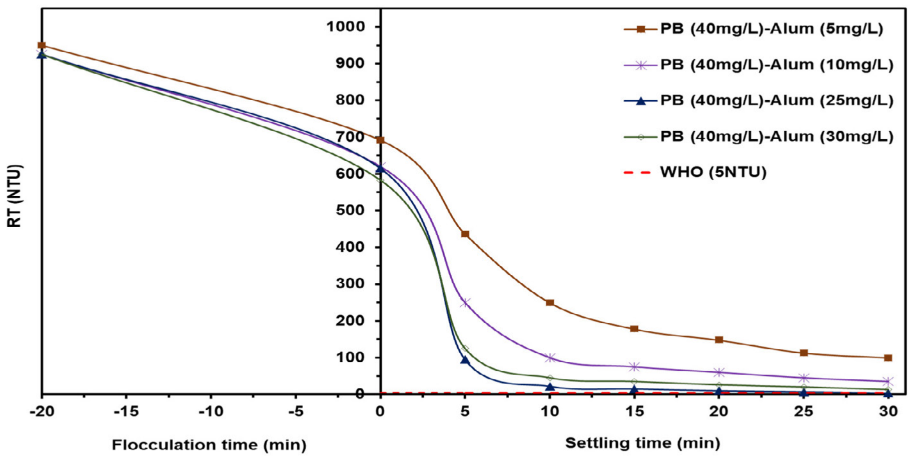

Fig. 10. Investigation on the performance of conventional approach using dual coagulant of *PB* and alum.

Table 3. Comparative performance between conventional approach and alum control treatment.

Treatment type	Coagulant type	Optimum alum dose (mg/L)	Settling time (min)	Alum dose decrease (%)	Settling time decrease (%)	pH
Control	*Alum*	30	35	-	-	4.6
Conventional	*PB-alum*	25	30	17	14	4.4
	W-alum	20	30	33	14	4.5

Similar observations were found in finding the optimum dose of conventional approach using dual coagulant of *W* and alum as shown in Fig. 11. An excellent coagulating performance in achieving the minimum *RT* of kaolin synthetic water was obtained at the optimum alum dose of 20 mg/L. At this dose, conventional approach could successfully satisfy the WHO guidelines for drinking-water quality (i.e., producing the *RT* less than 5 NTU) at the settling time of 30 min. When comparing the performance of conventional approach using dual coagulant of *W* and alum control treatment, the conventional approach was capable of decreasing the alum dose required by 33% and the settling time required by 14% (Table 3). This performance is related to the best synergistic effect of alum coagulant in conjunction with *W* coagulant (Mungondori et al., 2021; Gandiwa et al., 2020; Al-Anzi et al., 2022; Al-Sameraiy, 2023; Yehia and Said, 2021). In terms of decreasing the alum dose required, it is clear to see from Table 3 that coagulating performance of conventional approach using *W* coagulant is better than that of using *PB* coagulant. This may be related to the coagulating ability of *W* as single natural coagulant with respect to the *R* (%) where it was higher that of *PB* coagulant as shown in Table 2.

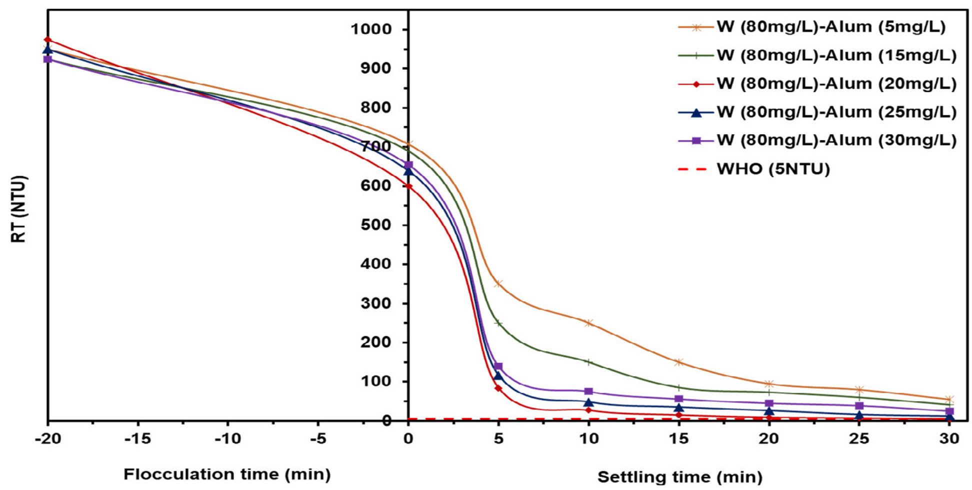

Fig. 11. Investigation on the performance of conventional approach using dual coagulant of *W* and alum.

Table 3 shows the monitored pH values of treated water produced by the conventional approach at the optimum dose of each coagulant used. These values were found to be 4.4 and 4.5 for the use of *PB-alum* and *W-alum* respectively. This implies that these pH values are below the recommended range by the WHO guidelines for drinking-water quality (6.5-8.5). Therefore, the treated water by the conventional approach is required to be adjusted at the stage of post-treatment (Yehia and Said, 2021).

Novel approach vs. control treatment

The performance of novel approach using natural coagulant of either *PB* at predetermied optimum dose (40 mg/L) or *W* at predetermied optimum dose (80 mg/L) in primary treatment and various doses of alum (5-30 mg/L) in secondary treatment is shown in Fig. 12 and Fig. 13 respectively.

The performance of novel approach in Fig. 12 shows that the primary treatment using *PB* natural coagulant only at the predetermied optimum dose of 40 mg/L could decrease the *RT* of the kaolin synthetic water by 67%. After that the present of various alum doses in the secondary treatment could effectively reduce the *RT* of kaolin synthetic water. A maximum coagulating performance in decreasing the *RT* to be less than 5 NTU was recorded at the optimum dose alum of 20 mg/L and the settling time of 25 min. Thus, satisfying the WHO guidelines for drinking-water quality. Beyond this dose, the *RT* increased as expected due to overdosing phenomenon. At the optimum conditions of alum dose and settling time (20 mg/L and 25 min), the novel approach could successfully decrease the alum dose and settling time required by 33% and 29% respectively when comparing with alum control treatment (Table 4).

The performance of novel approach in Fig. 13 shows that the primary treatment using *W* natural coagulant only at the predetermied optimum dose of 80 mg/L could decrease the *RT* of the kaolin synthetic water by 88%. In the secondary treatment, various alum doses could effectively reduce the *RT* of kaolin synthetic water. The highest performance in producing the *RT* of kaolin synthetic water was achieved at 15 mg/L alum dose and 20 min settling time. This dose resulted in decreasing the *RT* to be less than 5 NTU, and thus satisfying the WHO guidelines for drinking-water quality. Above this dose, the *RT* increased as expected due to overdosing phenomenon. At the optimum conditions of alum dose and settling time (15 mg/L and 20 min), the novel approach could successfully decrease the alum dose and settling time required by 50% and 43% respectively when comparing with alum control treatment (Table 4).

In terms of decreasing the alum dose and setting time required, it is clear to see from Table 4 that coagulating performance of novel approach using *W* coagulant is better than that of using *PB* coagulant. This may be related to the coagulating ability of *W* as single natural coagulant with respect to the *R* (%) where it was higher that of *PB* coagulant as shown in Table 2.

The monitored pH values of treated water produced by the novel approach at the optimum dose of each coagulant used are shown in Table 4. These values were found to be 4.5 and 4.8 for the use of *PB-alum* and *W-alum* respectively, which are below the recommended range by the WHO guidelines for drinking-water quality (6.5-8.5). Therefore, the treated water by the novel approach is required to be adjusted at the stage of post-treatment (Yehia and Said, 2021).

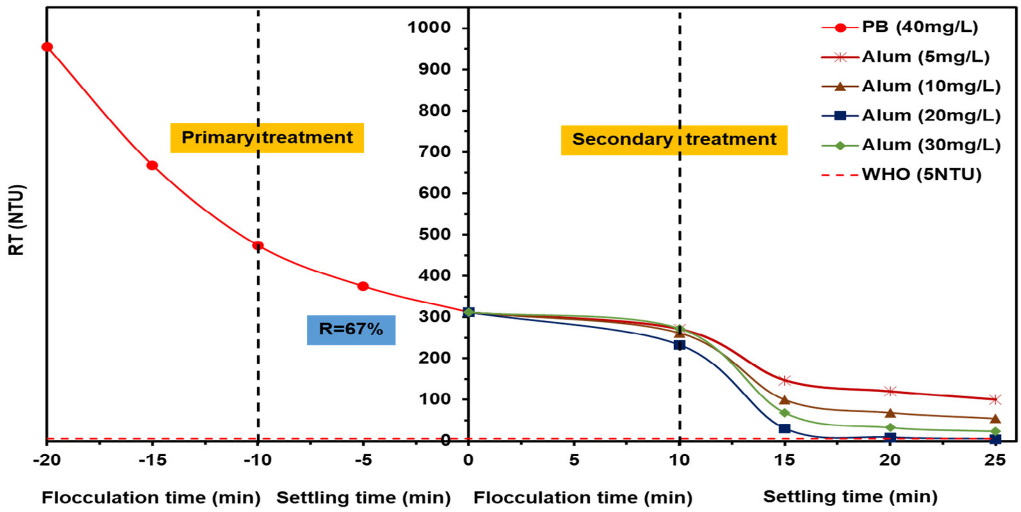

Fig. 12. Investigation on the performance of novel approach using *PB* coagulant in primary treatment and alum coagulant in secondary treatment.

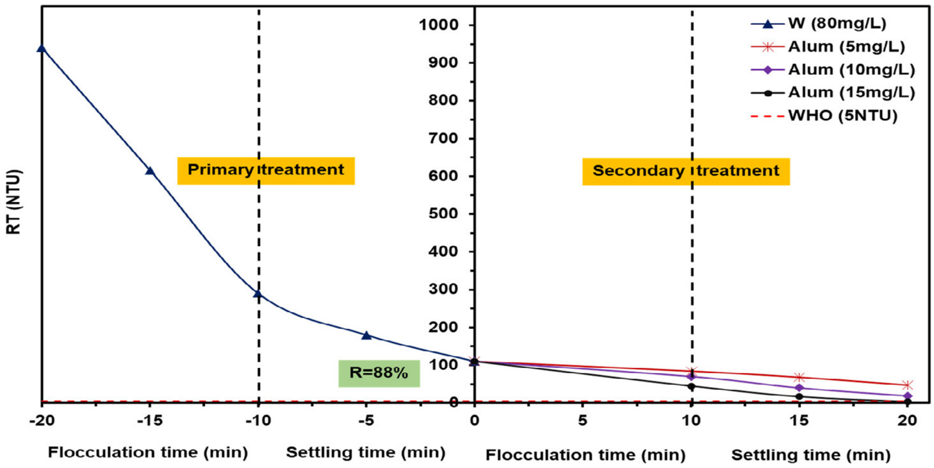

Fig. 13. Investigation on the performance of novel approach using *W* coagulant in primary treatment and alum coagulant in secondary treatment.

Table 4. Comparative performance between novel approach using either *PB* or *W* coagulant in primary treatment and alum coagulant in secondary treatment and alum control treatment.

Treatment type	Coagulant type	Optimum alum dose (mg/L)	Settling time (min)	Alum dose decrease (%)	Settling time decrease (%)	pH
Control	*Alum*	30	35	-	-	4.6
Novel	*PB-alum*	20	25	33	29	4.5
	W-alum	15	20	50	43	4.8

Novel approach vs. conventional approach

Experimental results of conventional and novel approaches shown in Tables 3-4 clearly showed that both could successfully achieve a good coagulating performance in terms of producing the RT less than 5 NTU, and thus satisfying the WHO guidelines for drinking-water quality. However, further comparison is needed to evaluate precisely, which of them is better in achieving additional advantages in terms of decreasing the alum dose and settling time required as much as possible. This comparison can be found in Fig. 14 based on the experimental results in Tables 3-4.

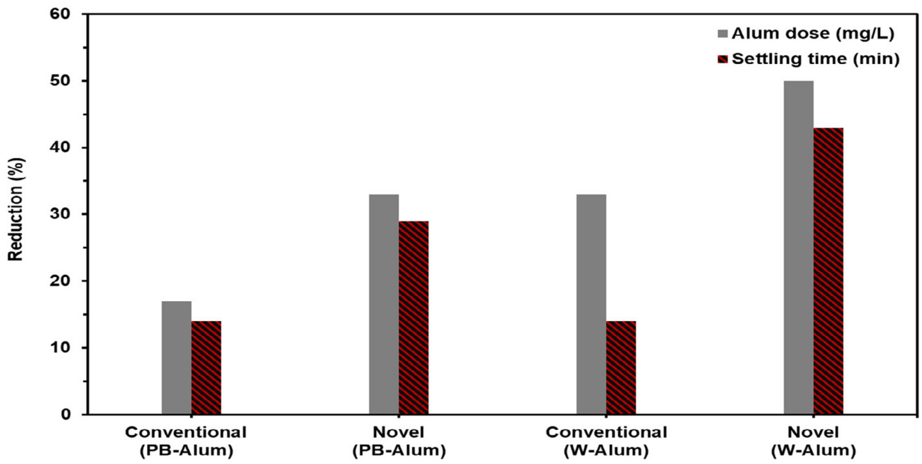

Fig. 14. Evaluation of the performance of conventional and novel approaches.

Fig. 14 shows that the novel approach achieved higher performance in decreasing the alum dose and settling time required than that of the conventional approach for both *PB* and *W* natural coagulants. For example, when *PB* or *W* were natural coagulants, the novel approach decreased the alum dose required by 33 and 50% respectively compared with the conventional approach of 17 and 33% respectively. Also, it reduced the settling time required by 29 and 43% respectively compared with the conventional approach of 14 and 14% respectively. When using the novel approach, the *W* natural coagulant showed better performance than *PB* natural coagulant. This is related to the coagulating activity of *W* coagulant as a single coagulant in deceasing the *RT* of kaolin synthetic water in the primary treatment where it decreased the *RT* by 88% when compared with *PB* coagulant (67%).

CONCLUSION

The concept of novel approach developed in our previous research for turbidity removal from bentonite synthetic turbid water was investigated in the current research, to be feasible, for the treatment of kaolin synthetic turbid water using either *PB* or *W* natural coagulants with alum chemical coagulant.

Experimentally, preliminary investigations into the optimum conditions of coagulating doses and settling times for *PB*, *W* and alum were found to be 40, 80, 30 mg/L and 60, 60, 35 min respectively. Both *PB* and *W* coagulants could not meet the WHO guidelines for drinking-water quality when compared with alum coagulant that could meet it. Thus, it was selected as a basis of the control treatment for further evaluation of the performance of conventional and novel approaches.

In spite of both conventional and novel approaches could successfully satisfy the WHO guidelines for drinking-water quality, the performance of novel approach was better than that of conventional approach in achieving several environmental, economical and operational advantages. When using *PB* or *W* natural coagulants, the novel approach decreased the alum dose required by 33 and 50% respectively compared with the conventional approach of 17 and 33% respectively (i.e., partial replacement of alum to minimize its adverse effects on health and the environment, and decrease in the cost of alum use) and the settling time required by 29 and 43% respectively compared with the conventional approach of 14 and 14% respectively (i.e., decreasing the operational cost-energy saving). This excellent performance of the novel approach is related to its novel concept where the coagulating activity of natural coagulant used as a single coagulant decreased the *RT* of kaolin synthetic water as much as possible in the primary treatment. This performance facilitated the significantly reduction of alum coagulant dose required (i.e., partial replacement of alum dose required) when treating the residual turbidity of supernatant of synthetic water in secondary treatment. The pH was monitored under different investigating conditions. The monitored pH values of treated water by conventional and novel approaches were found to be below the recommended range of the WHO guidelines for drinking-water quality. Therefore, the treated water by these approaches is required to be adjusted at the stage of post-treatment.

The performance of novel approach in the current research is in agreement with our previous research findings. The conclusion is that the verification of its concept is proved and validated experimentally with two different types of bentonite and kaolin synthetic turbid waters. This research is the starting point for potentially applying it in the field of practical applications of real water treatment (river surface water), the following paper will be in this respect.

ACKNOWLEDGEMENT

The author would like to acknowledge the Department of Mineral Extraction, State Company for Mining Industries-Ministry of Industry and Minerals for providing the samples of white kaolin clay. The author thanks the staff at Environment Research Center, University of Technology, namely Assist. Lecturer Talib K. Abed for assistance in collection of kaolin clay samples and Dr. Rana R. Al-Ani (supervisor of soil and water lab) for her support to achieve this research. Many thanks to the staff at the Nanotechnology and Advanced Material Research Center-University of Technology, namely Prof. Dr. Abbas Kh. Hussein (the director of center), Assist. Dr. Ali A. Ati for achieving the particle size analysis and Eng. Thulfiqar Ali for assistance in grinding kaolin clay samples.

GRANT SUPPORT DETAILS

The present research did not receive any finical support.

CONFLICT OF INTEREST

The author declares that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy has been completely observed by the author.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

REFERENCES

Al-Anzi, B. S., Naik, M. U. D., & Ahmad, M. (2022). The Imperative Need of Metal Salt for the Treatment of Industrial Wastewater via the Synergic Coagulation-Flocculation Method. *Polymers*, *14*(9). https://doi.org/10.3390/polym14091651

Alazaiza, M. Y. D., Albahnasawi, A., Ali, G. A. M., Bashir, M. J. K., Nassani, D. E., Al Maskari, T., Abu Amr, S. S., & Abujazar, M. S. S. (2022). Application of Natural Coagulants for Pharmaceutical Removal from Water and Wastewater: A Review. In *Water (Switzerland)* (Vol. 14, Issue 2). MDPI. https://doi.org/10.3390/w14020140

American Public Health Association (APHA). Standard Methods for the Examination of Water and Wastewater, 23thed.; American Public Health Association/American Water Works Association/ Water Environment Federation: Washington, DC, USA, 2017.

Ali, A. H., Tlaiaa, Y. S., & Razak Nasir, Z. A. (2019). Sustainable Used of Natural Coagulants Aid for Enhancing the Performance of Alum to Treat Turbid Water. *IOP Conference Series: Materials Science and Engineering*, *518*(2). https://doi.org/10.1088/1757-899X/518/2/022014

Al-Sameraiy, M. (2012). A Novel Water Pretreatment Approach for Turbidity Removal Using Date Seeds and Pollen Sheath. *Journal of Water Resource and Protection*, *04*(02), 79–92. https://doi.org/10.4236/jwarp.2012.42010

Al-Sameraiy, M. (2023). Application of Dual Coagulant with Two Modes for Treatment of Dust Storms Synthetic Turbid Water: Comparative Performance. *AIP Conference Proceedings*, *2775*(1). https://doi.org/10.1063/5.0140287

Benalia, A., Derbal, K., Khalfaoui, A., Bouchareb, R., Panico, A., Gisonni, C., Crispino, G., Pirozzi, F., & Pizzi, A. (2021). Use of aloe vera as an organic coagulant for improving drinking water quality. *Water (Switzerland)*, *13*(15). https://doi.org/10.3390/w13152024

Benalia, A., Derbal, K., Khalfaoui, A., Pizzi, A., & Medjahdi, G. (2022). The use of aloe vera as natural coagulant in algerian drinking water treatment plant. *Journal of Renewable Materials*, *10*(3), 625–637. https://doi.org/10.32604/jrm.2022.017848

Beyene, H. D., Hailegebrial, T. D., & Dirersa, W. B. (2016). Investigation of Coagulation Activity of Cactus Powder in Water Treatment. *Journal of Applied Chemistry*, *2016*, 1–9. https://doi.org/10.1155/2016/7815903

Birhanu, Y., & Leta, S. (2021). Application of response surface methodology to optimize removal efficiency of water turbidity by low-cost natural coagulant (Odaracha soil) from Saketa District, Ethiopia. *Results in Chemistry*, *3*. https://doi.org/10.1016/j.rechem.2021.100108

Cui, H., Huang, X., Yu, Z., Chen, P., & Cao, X. (2020). Application progress of enhanced coagulation in water treatment. *RSC Advances*, *10*(34), 20231–20244. https://doi.org/10.1039/d0ra02979c

Davarpanah, L., & Abdollahzadeh Sharghi, E. (2019). Performance of Continuous Electrocoagulation Process for Turbidity Removal from Sand Filter Backwash Water. *International Journal of Engineering Transactions C: Aspects*, *32*(12), 1696–1703. https://doi.org/10.5829/ije.2019.32.12c.01

Dayarathne, H. N. P., Angove, M. J., Paudel, S. R., Ngo, H. H., Guo, W., & Mainali, B. (2022). Optimisation of dual coagulation process for the removal of turbidity in source water using streaming potential. *Groundwater for Sustainable Development*, *16*. https://doi.org/10.1016/j.gsd.2021.100714

El-Gaayda, J., Titchou, F. E., Barra, I., Karmal, I., Afanga, H., Zazou, H., Yap, P. S., Abidin, Z. Z., Hamdani, M., & Akbour, R. A. (2022). Optimization of turbidity and dye removal from synthetic wastewater using response surface methodology: Effectiveness of Moringa oleifera seed powder as a green coagulant. *Journal of Environmental Chemical Engineering*, *10*(1). https://doi.org/10.1016/j.jece.2021.106988

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

Hu, X., Hu, P., & Yang, H. (2022). Influences of charge properties and hydrophobicity on the coagulation of inorganic and organic matters from water associated with starch-based coagulants. *Chemosphere*, *298*. https://doi.org/10.1016/j.chemosphere.2022.134346

Jamshidi, A., Rezaei, S., Hassani, G., Firoozi, Z., Ghaffari, H. R., & Sadeghi, H. (2020). Coagulating potential of Iranian oak (Quercus Branti) extract as a natural coagulant in turbidity removal from water. *Journal of Environmental Health Science and Engineering*, *18*(1), 163–175. https://doi.org/10.1007/s40201-020-00449-0

Katrivesis, F. K., Karela, A. D., Papadakis, V. G., & Paraskeva, C. A. (2019). Revisiting of coagulation-flocculation processes in the production of potable water. *Journal of Water Process Engineering*, *27*, 193–204. https://doi.org/10.1016/j.jwpe.2018.12.007

Kusuma, H. S., Amenaghawon, A. N., Darmokoesoemo, H., Neolaka, Y. A. B., Widyaningrum, B. A., Onowise, S. U., & Anyalewechi, C. L. (2022). A comparative evaluation of statistical empirical and neural intelligence modeling of Manihot esculenta-derived leaves extract for optimized bio-coagulation-flocculation of turbid water. *Industrial Crops and Products*, *186*. https://doi.org/10.1016/j.indcrop.2022.115194

Mahanna, H., Fouad, M., Zedan, T., & Mossad, M. (2024). Effective turbid water treatment using natural eco-friendly coagulants derived from oat and onion seeds. *International Journal of Environmental Science and Technology*, *21*(5), 4773–4787. https://doi.org/10.1007/s13762-023-05326-5

Megersa, M., Gach, W., Beyene, A., Ambelu, A., & Triest, L. (2019). Effect of salt solutions on coagulation performance of Moringa stenopetala and Maerua subcordata for turbid water treatment. *Separation and Purification Technology*, *221*, 319–324. https://doi.org/10.1016/j.seppur.2019.04.013

Mohd Asharuddin, S., Othman, N., Mohd Zin, N. S., Tajarudin, H. A., Md. Din, M. F., & Kumar, V. (2018). Performance Assessment of Cassava Peel Starch and Alum as Dual Coagulant for Turbidity Removal in Dam Water. *International Journal of Integrated Engineering*, *10*(4). https://doi.org/10.30880/ijie.2018.10.04.029

Mohd-Salleh, S. N. A., Mohd-Zin, N. S., & Othman, N. (2019). A review of wastewater treatment using natural material and its potential as aid and composite coagulant. In *Sains Malaysiana* (Vol. 48, Issue 1, pp. 155–164). Penerbit Universiti Kebangsaan Malaysia. https://doi.org/10.17576/jsm-2019-4801-18

Mungondori, H. H., Muchingami, T. A., Taziwa, R. T., & Chaukura, N. (2021). Performance intensification of the coagulation process in drinking water treatment. *Water SA*, *47*(2), 154–161. https://doi.org/10.17159/wsa/2021.v47.i2.10911

Ramavandi, B. (2014). Treatment of water turbidity and bacteria by using a coagulant extracted from Plantago ovata. *Water Resources and Industry*, *6*, 36–50. https://doi.org/10.1016/j.wri.2014.07.001

Skaf, D. W., Punzi, V. L., Rolle, J. T., & Cullen, E. (2021). Impact of Moringa Oleifera extraction conditions on zeta potential and coagulation effectiveness. *Journal of Environmental Chemical*

Engineering, *9*(1). https://doi.org/10.1016/j.jece.2020.104687

World Health Organization (WHO). (2017). *Potable reuse: guidance for producing safe drinking-water.*

Xu, S., Shi, J., Deng, J., Sun, H., Wu, J., & Ye, Z. (2023). Flocculation and dewatering of the Kaolin slurry treated by single- and dual-polymer flocculants. *Chemosphere*, *328*. https://doi.org/10.1016/j.chemosphere.2023.138445

Yehia, H. M. A.-S., & Said, S. M. (2021). Drinking Water Treatment: pH Adjustment Using Natural Physical Field. *Journal of Biosciences and Medicines*, *09*(06), 55–66. https://doi.org/10.4236/jbm.2021.96005

Zedan, T., Mossad, M., Fouad, M., & Mahanna, H. (2022). Potential application of natural coagulant extraction from walnut seeds for water turbidity removal. *Water Practice and Technology*, *17*(3 684), 698. https://doi.org/10.2166/wpt.2022.019

Zemmouri, H., Drouiche, M., Sayeh, A., Lounici, H., & Mameri, N. (2012). Coagulation flocculation test of Keddara's water dam using chitosan and sulfate aluminium. *Procedia Engineering*, *33*, 254–260. https://doi.org/10.1016/j.proeng.2012.01.1202