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Chitosan enhanced coagulation of algal turbid waters – Comparison between rapid mix and ultrasound coagulation methods

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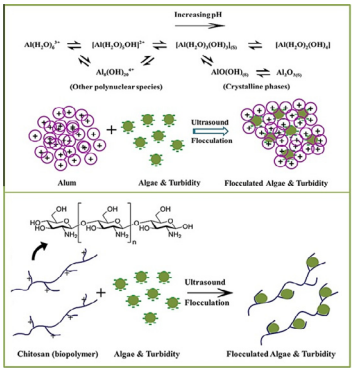
HIGHLIGHTS

- Ultrasound enhanced coagulation/flocculation of low algal turbid waters was studied.
- Simultaneous effect of chitosan and ultrasound on turbidity removal was studied.
- A comparison with conventional rapid mixing/flocculation process was conducted.
- Ultrasound mixing may be performed in lieu of rapid mixing for coagulation process.
- Ultrasound power density, flocculation time, pH-chemical-dosage effects were studied.

GRAPHICAL ABSTRACT



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ABSTRACT

Presence of algae is considered as an undesirable water pollutant in drinking water sources such as reservoirs and at water and wastewater treatment plants causing odor, taste and other severe health issues. In this study, ultrasound-chitosan enhanced coagulation/flocculation process for treating algal turbid water was developed. The possibility of performing ultrasound mixing in lieu of conventional rapid mixing was evaluated. The effects of several process parameters such as chemical dosages, pH, ultrasound exposure time, concentration factors and flocculation and sedimentation times were studied. Two comparative studies, i.e., a comparison between ultrasound-alum and ultrasound-chitosan flocculation of algal turbid waters as well as a comparison with conventional rapid mix and direct flocculation were conducted. The results from this study reveal that ultrasound enhanced method can produce clear supernatant water with greater than 98% turbidity reduction. A power density of 0.1–0.25 W/mL was sufficient to provide adequate mixing for chemical distribution and pin-floc formation. The concentration factor for ultrasound-enhanced coagulation/flocculation was determined to be 30 with an optimum ultrasound exposure of 1 min followed by a 20 min flocculation process. This study confirms that ultrasound-chitosan enhanced flocculation process may provide additional benefits for algal cell harvesting compared to the conventional rapid mix method.

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1. Introduction

Presence of algae is considered as an undesirable water pollutant in drinking water sources such as reservoirs and at water and wastewater treatment plants causing odor, taste and other severe health issues [1]. They pose serious concerns for water as well as process safety at the water supply systems, especially for membrane water treatment systems [2,3]. General methods to remove or control algal growth include physical processes such as media filtration and membrane separation, chemical processes such as

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coagulation, flocculation, and chlorination and electromagnetic radiation such as ultraviolet light exposure [4]. Among these methods, the filtration and membrane separation option is cost- and energy-intensive while use of oxidizing agents like chlorine or ozone may disrupt the cell walls and release the intracellular compounds into the water. Ultraviolet light application has major limitations of high capital and maintenance costs. Chemical coagulation–flocculation process has been proven to be safe and most economical among the existing methods to remove algae [5]. However, there are two major challenges for removing the algae from the surface waters that are utilized for drinking water and process water: (1) a suitable method for effective removal of the algal suspensions, (2) the toxic effects of the chemicals used or produced from these processes. Since microalgae possess a negative surface charge, the surface charge can be neutralized by introducing multivalent cationic ions namely ferric and aluminum ions. These cationic ions easily flocculate algae cells and form flocs. But they require high dosages and form large volumes of sludge that need to be disposed. Apart from that the sludge produced by these inorganic metallic coagulants are reported to be toxic to the environment. One previous study used polyaluminum chloride (PACl) and clay coagulation respectively to remove algae [6]; however, PACl and other chemical reagents may not be environmental friendly when used in large quantities, while clay requires a large dosage and a long time for sedimentation. Additionally, the flocs formed by traditional coagulation are hard to settle down due to the low density [5]. In some cases, other organic biopolymers such as cactus, cationic starch or even bio-flocculation were evaluated; however, these techniques may have specific process related limitations [7–9].

Considering the above issues, use of natural biopolymers in coagulation/flocculation processes seems to be a more feasible and sustainable alternative [10,11]. Biopolymers, especially, chitosan are non-toxic and are derived from natural sources. Chitosan is a linear poly-amino-saccharide, which is produced by alkaline deacetylation of chitin. It is insoluble in water and soluble in acids. Generally, chitosan has a viscosity of 20–300 centipoises, molecular weight of $(5–19) \times 10^4$, density of 0.15–0.3 g/cm^3 (in 1% acid solution), and deacetylation degree of 75–85%. Chitosan has distinct advantages over commonly used flocculants for microalgae harvesting [12]. Chitosan has been recommended for use as a coagulant since it is non-toxic, non-corrosive and safe to handle [13]. It is biodegradable and biocompatible and has attractive adsorption properties, flocculating ability and polyelectrolicity; additionally, it can be regenerated in a number of applications [14]. The high cationic charge density of chitosan allows it to strongly adsorb negative regions on other particles and effectively destabilize them (high flocculation ability). This mechanism may act either through polymer bridging or charge neutralization (electrostatic patch effects) requiring very low dosages [10].

For removal of algae from water, other non-conventional techniques such as ultrasound may provide effective coagulation. The application of ultrasound to improve coagulation of algal cells was recently studied [15,16]. Ultrasound was used to treat bacterial suspensions in a pilot scale water disinfection system [17]. The objective of this study is to investigate the combined effect of ultrasound and chitosan on the turbidity removal efficiency of algal turbid waters. This combined effect of ultrasound and chitosan on algal cell harvesting has not been studied before. Also, another important aim of this study was to evaluate the possibility of replacing traditional rapid mix method by ultrasound enhanced coagulation for chemical distribution and pin-floc formation. The effects of dosage and pH conditions were determined for different algal turbid waters. The effect of chitosan as coagulant/flocculant was compared with the conventional inorganic coagulant aluminum sulfate. The ultrasound-chitosan enhanced coagulation/flocculation method was compared with the conventional rapid mix method. Ultrasound power and power density effects were also studied. The effects of ultrasound exposure time, flocculation time as well as sedimentation time on the concentration factor were studied. To understand the special effects of ultrasound-chitosan enhanced coagulation/flocculation process, a comparison between the ultrasound, rapid mixing and direct flocculation methods was performed.

2. Materials and methods

2.1. Low algal turbid waters and coagulants

Concentrated *Chlorella sp.* paste was obtained from a commercial producer which was used to prepare a stable algal cell suspension of 10–40 NTU of measurable turbidity. The suspension was tested to ensure 99.9% of turbidity over 24 h settling period. A 1% chitovan coagulant polymer was purchased from a commercial water chemicals company Dungeness Environmental Inc., Washington, USA. We also prepared a different chitosan solution by using dry chitosan powder purchased from Fisher Scientific (Acros-Organicas) with molecular weight in the range of 600,000–800,000. This chitosan aqueous solution was prepared by dissolving chitosan in a 1% dilute aqueous acetic acid solution (1% v/v) with a 90% degree of deacetylation and mixed with a magnetic stirrer at 100 rpm for over 24 h to obtain a 1% (w/w) stock solution. The aluminum sulfate [$Al_2(SO_4)_3nH_2O$; $n = 12–14$] coagulant was procured from Fisher Scientific™. 5.8 g of aluminum sulfate was added to 50 ml of DI water to form a concentrated solution of 100,000 ppm, while the chitovan or chitosan concentrations were 10,000 ppm.

2.2. Live algae culture

To further investigate the special effects of ultrasound on the inactivation and harvesting capability of algal cells, live algae cell suspensions were used. The microalgae, *Chlorella vulgaris*, used in these experiments were grown in the following mineral solution: $CaCl_2$ (25 mg/L), NaCl (25 mg/L), $NaNO_3$ (250 mg/L), $MgSO_4$ (75 mg/L), KH_2PO_4 (105 mg/L), K_2HPO_4 (75 mg/L), and 3 ml of trace metal solution with the following concentration was added to 1000 ml of the above solution: $FeCl_3$ (0.194 g/L), $MnCl_2$ (0.082 g/L), $CoCl_2$ (0.16 g/L), $Na_2MoO_42H_2O$ (0.008 g/L), and $ZnCl_2$ (0.005 g/L). This growth medium provides optimum conditions for maximized algal growth [18]. Sodium carbonate was supplied at different concentrations at different days of growth period to match the growth stages. The live algal suspensions were harvested at the seventh day by ultrasound coagulation/flocculation experiments performed in this study.

2.3. Coagulation/flocculation experiments

Several experiments were conducted to study the combined effect of alum-ultrasound, and chitosan-ultrasound. The effects of alum/chitosan dosage and ultrasound application were tested in low algal turbid waters with a turbidity ranging between 10 and 40 NTU at 10 NTU intervals. The ultrasound enhanced coagulation/flocculation was performed using a NO-MS100 ultrasonicator manufactured by Columbia International Technologies with 1000 watts power output capacity. The ultrasonic frequency was 25 kHz. The horn is made of titanium alloy with ten levels of amplitude to vary the effect of ultrasonic application. An ultrasound exposure time of 1 min was applied in lieu of rapid mixing process. After the simultaneous ultrasound exposure and coagulant addition (alum or chitovan), the algal suspension was subjected to slow mixing at 50 rpm for 20 min. The tests which followed

conventional rapid mixing, a 200 rpm mixing speed was applied for 2 min. For both methods (conventional rapid mix-flocculation-sedimentation vs. ultrasound–flocculation–sedimentation), the sedimentation time was 24 h. The turbidity was measured at 1 h of settling time and at 24 h settling time to capture the maximum removal efficiency.

The algal suspension sample volumes were fixed at 1000 mL in a 1500 mL standard jar for both conventional rapid mix (RM) and non-conventional ultrasound (US) methods. This study consisted of batch experiments, using a Phipps and Bird jar tester unit (model 7790-400; 120 V, 60 Hz and 220 V, 50/60 Hz) which accommodates six 2-L jars/beakers. The beakers were filled with 1000 ml of the microalgae culture for each test run. Six stainless steel 1″ × 3″ paddles are spaced six inches apart and are adjustable to a maximum depth of nine inches with a highly reliable electronic motor control system regulated at variable speeds (of all paddles simultaneously), from 1 to 200 rpm. The contents of each beaker were simultaneously stirred at the same speed with a six-spindle of steel paddles.

The experiments started with the effect of coagulant dosage for both alum and chitosan. For the coagulant dosage effect test the pH was maintained between 7 and 8. To measure the effect of optimum pH, the pH was varied between 5 and 9 units, i.e. at 5, 6, 7, 8, and 9 while fixing the coagulant dosage determined from the previous experiments. The pH of the algal suspension was adjusted by adding either NaOH (base) or HCl (acid) prior to flocculation. Also, the effect of ultrasound power on the algal cell removal efficiency was tested at different power levels 100, 250, 500 and 1000 W which gives a power density of 0.1 W/ml; 0.25 W/ml; 0.5 W/ml; and 1.0 W/ml respectively. All the experiments were conducted in triplicate and the average of the three results were evaluated.

2.4. Flocculation removal efficiency

The samples were collected at the start of the experiments, after 1 h sedimentation time as well as 24 h sedimentation time. The turbidity of the water samples was measured at these specified steps and time intervals. The turbidity was measured using HACH 2100 N Turbitimeter® turbidity meter. The turbidity removal efficiency (RE) was calculated using the following equation:

$$\mathrm{RE}(\%) = \left[1 - \frac{T_I}{T_F}\right] \times 100\% \quad (1)$$

where T_I is the initial turbidity and T_F is the final turbidity of the algal suspension.

The concentration factor (CF) was measured using the following equation [11]:

$$\mathrm{CF} = \frac{V * OD_I - V_S * OD_F}{(V - V_S) * OD_I} \quad (2)$$

where OD_I is the optical density of the algal turbid water sample, OD_F is the optical density of the clarified water sample after flocculation and sedimentation, V is the total sample volume, V_S is the volume of the clarified water after flocculation and sedimentation.

3. Results and discussion

3.1. Effect of coagulant dosage

The effect of coagulant dosage was tested using different algal cell suspensions resulting in a turbidity of 10, 20, 30, and 40 NTU. The coagulant dosages were varied with respect to the water turbidity. Fig. 1a shows the effect of coagulant dosage for alum at 1 h sedimentation time. It can be noted that 0.1–0.6 mL dosage worked well for 10 NTU turbidity, whereas 20, 30 and 40 NTUs required higher alum dosages. At lower turbidity, the flocculation was easier for alum, perhaps, caused by sweep coagulation, a widely practiced technique. Fig. 1b shows the turbidity removal efficiencies at 24 h sedimentation time. It should be noted that the removal efficiencies improved with sedimentation time. From these experiments, it was concluded that the 0.1–0.2 mL of alum dosage was adequate for 10 NTU suspension, while, 0.2–0.4 mL for 20 NTU; 0.3–0.4 mL dosages for 30 and 40 NTU water turbidities. The turbidity removals between 95% and 99% were observed in these tests. Fig. 1c shows the removal efficiencies for chitovan dosages at 1 h sedimentation time for different water turbidities. It was noted that at 10 NTU, higher dosages of chitovan resulted

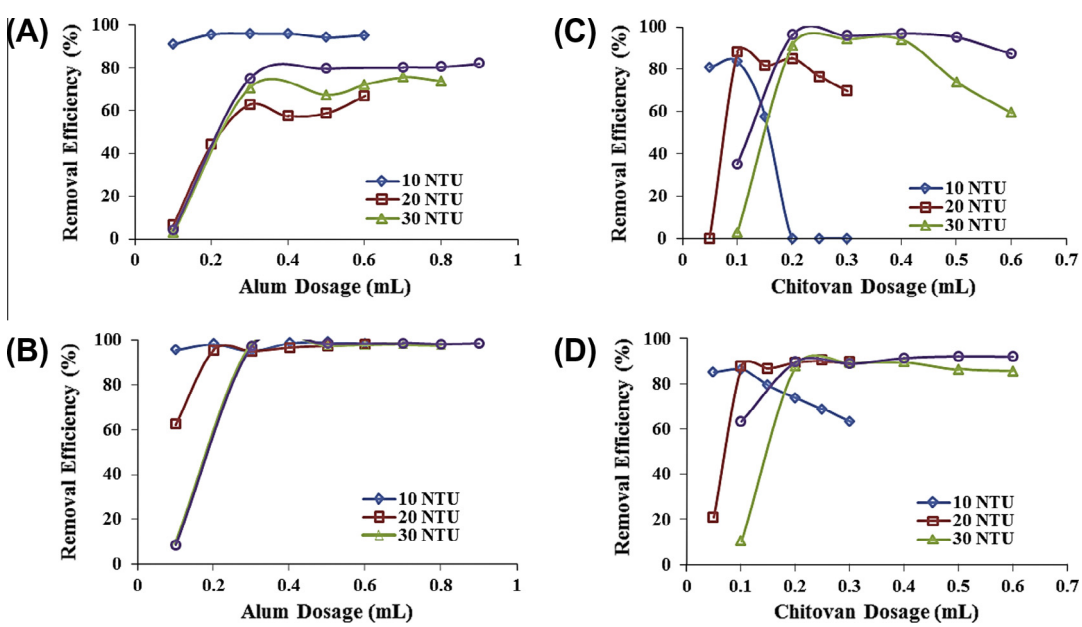

Fig. 1. (a) Flocculation removal efficiency (%) for Alum using ultrasound (1 h sedimentation); (b) (24 h sedimentation); (c) flocculation removal efficiency (%) for Chitovan using ultrasound (1 h sedimentation) and (d) (24 h sedimentation).

in even more turbid waters, possibly due to restabilzation process that occurs at slightly over dosages. Fig. 1d shows the turbidity removal efficiencies at 24 h sedimentation time. From these experiments, it was concluded that 0.05–0.1 mL of chitovan dosage was adequate for 10 NTU suspension, while, 0.1 for 20 NTU; 0.3–0.4 mL dosages for 30 and 40 NTU water turbidities. Overall turbidity removals between 86.5% and 92.5% were observed in these tests. The relation between the coagulant dosage and water turbidities are shown in Fig. 2. Alum, in general, requires a higher dosage compared to the chitovan, biopolymer. This is one clear advantage of applying inorganic or organic polymers for coagulation/flocculation processes. Lower coagulant dosages also indicate lower volumes of sludge formation which eventually reduced the amounts of wastes to be disposed. Additional benefit of utilizing organic, biopolymers is that they are biodegradable and non-toxic to the environment as explained earlier. The chitovan (10,000 ppm) dosages in this study were 15–50 times lower than alum (100,000 ppm) dosages for different turbidities.

3.2. Effect of pH

The effect of pH on the turbidity removal was tested at different pHs between 5 and 9. Fig. 3a shows the effect of pH on alum as coagulant for turbidity removal. It can be noted that alum worked reasonably well in the wide range of pH tested. Fig. 3b shows the effect of pH on chitovan as coagulant/fllocculant for turbidity removal. It can be noted that chitovan was sensitive to pH changes and requires near neutral-pH conditions for effective turbidity removal. The pH of 7 or 8 was found to be ideal for higher performance of chitovan. This can be considered as a drawback for chitovan use. Fig. S1a shows the relationship between turbidity and turbidity removal efficiencies for alum. It can be noted that the removal efficiencies are in the range of 86–97% for different pH values, lower removal efficiencies observed at pH of 8 and 9. For chiotvan (Fig. S1b), pH conditions 5, 6, and 9 were not ideal for turbidity removal. However, pH conditions 6 and 9 seem to work well for 20–40 NTU turbid waters. Fig. S2 shows the pH differentials for alum and chitosan addition after ultrasound exposure and after flocculation (slow mixing for 20 min) times. Both coagulants have a very small effect on the final pH of the treated waters. The maximum pH differentials were between -0.20–0.25 units.

3.3. Coagulation/flocculation mechanisms for Alum and Chitosan

The coagulation/flocculation mechanisms for alum and chitovan are quite different in nature. Fig. 4 depicts the mechanisms for alum (inorganic coagulant) and chitovan (organic coagulant/flocculant). Alum when added to water, it becomes hydrolyzed

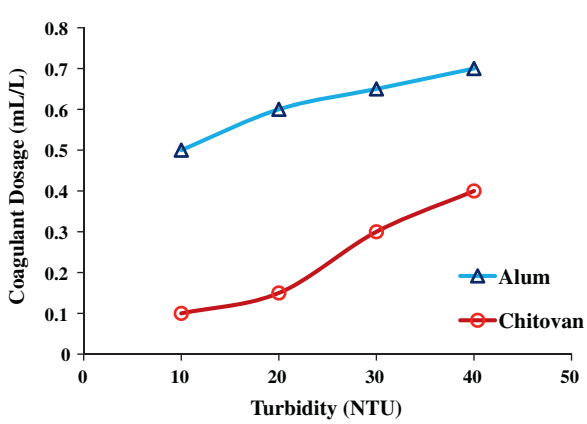

Fig. 2. Coagulant dosage requirements for alum and chitovan at different algal water turbidities.

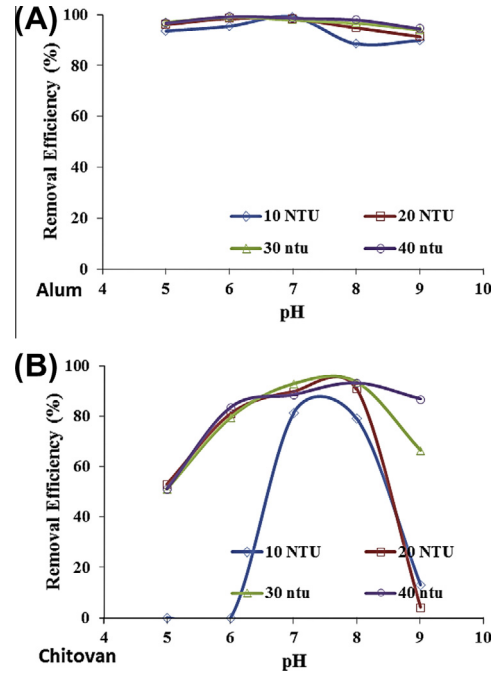

Fig. 3. Effect of pH on flocculation removal efficiency (%) using ultrasound: (a) alum and (b) chitovan.

and forms aquometal complexes such as $Al(H_2O)_6^{3+}$. These complexes then pass through a series of hydrolytic reactions in which H_2O molecules in the hydration shell are replaced by OH-ions. This gives rise to the formation of a variety of soluble species, including mononuclear species (one aluminum ion) such as $Al(OH)^{2+}$ and $Al(OH)_2^{+}$, and polynuclear (several aluminum ions) such as $Al_8(OH)_{20}^{4+}$. Despite the fact that some of these products have only one or two positive charges, they are quite effective as coagulants because they adsorb very strongly onto the surface of most negative colloids. As the pH increases, negatively charged species $[Al(OH)_4^-]$ predominate which are ineffective for destabilization of negatively charged algal cells [19]. The coagulation/flocculation mechanism for chitovan is primarily based on two sub-mechanisms called bridging and patching [9]. Chitosan is a high molecular weight, long chain polymer with a large number of active cationic sites. The positively charged polymers bind partly or completely to microalgal cells. If the polymers bind partly, the unoccupied part of the polymers can bind to other microalgal cells, thereby bridging them and resulting in a network of polymers and microalgal cells. If the polymers bind the microalgal cells completely because they are too short to bind others as well, they adsorb (patch) to the surface and can create positive charges locally. These charges attract other microalgal cells and also result in flocculation of the cells.

3.4. Comparison between the rapid mix and ultrasound coagulation/flocculation

A set of experiments were conducted with the pre-determined coagulant dosages for different algal water turbidities (10–40 NTU) to compare the performance of conventional rapid mixing and non-conventional ultrasound mixing for coagulation process and chemical distribution. In this test, the rapid mixing at 200 rpm was provided for 2 min while ultrasound exposure was provided for 1 min. In both cases, 20 min of slow mixing was provided to facilitate agglomeration of algal cells. Fig. 5a shows that the turbidity removal efficiency for ultrasound enhanced coagulation (97.8–99% removal efficiencies) was comparable to

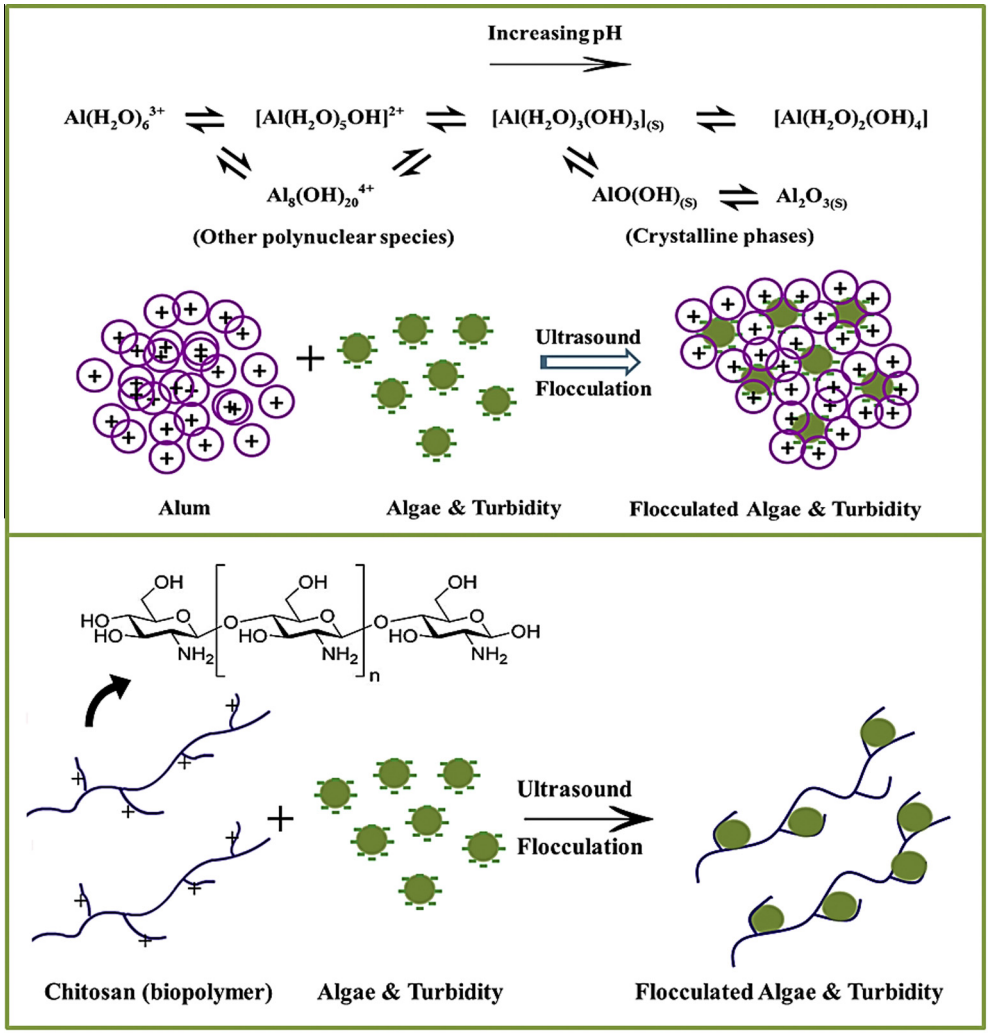

Fig. 4. Mechanisms responsible for alum and chitosan or chitovan enhanced coagulation/flocculation processes.

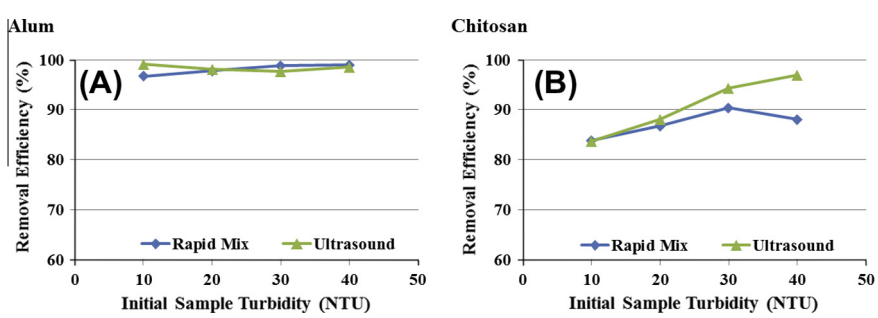

Fig. 5. Comparison between the conventional rapid mixing and non-conventional ultrasound enhanced coagulation–flocculation processes for alum and chitosan.

conventional rapid mix coagulation (96.8–99% removal efficiencies) for alum as well as for chitosan (84.1–90.5% for RM and 84–97% for US; Fig. 5b) and ultrasound worked better for chitosan coagulation/flocculation.

3.5. Coagulation/flocculation mechanisms for rapid mixing and ultrasound

3.5.1. Ultrasonic coagulation/flocculation mechanism

The complex mechanism of the acoustic or ultrasonic agglomeration involves *orthokinetic* and *hydrokinetic* interactions [20,21]. The *orthokinetic* interaction is based on the principle that collisions are produced by different entrainment experienced by particles of different size or weight while *hydrodynamic* mechanism is produced by particle interaction through the surrounding fluid due to hydrodynamic forces. The ultrasonics can remove turbidity as well as algae cells in this manner as demonstrated in many research studies. In a recent study, it was noted that the reduction in the water turbidity levels corresponds well with the algal cell removal [16].

3.5.2. Conventional coagulation/flocculation mechanism

Flocs are formed by two principal mechanisms: (1) *perikinetic* and (2) *orthokinetic* flocculation. When the particle contact is

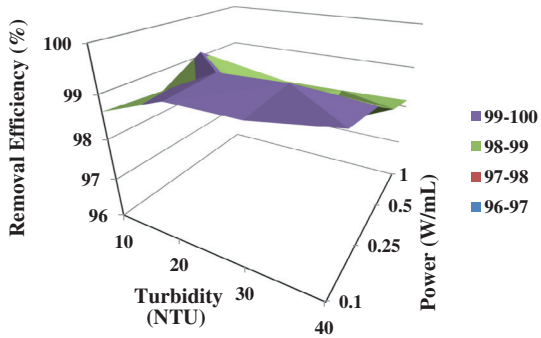

Fig. 6. Relation between the power density and flocculation removal efficiency (%) for ultrasound-chitosan enhanced coagulation–flocculation process.

achieved by the Brownian motion, it is called *perikinetic* flocculation and when the floc is formed by stirring or settling, it is called *orthokinetic* flocculation similar to ultrasonic flocculation. Perikinetic flocculation dominates for particles with size less than 0.1 μm in diameter and orthokinetic flocculation becomes dominant once these particles reach a size of 1 μm by particle contact which requires a very low velocity gradient to promote particle contact and flocculation [19].

3.6. Effect of ultrasound power and power density

The effect of ultrasound power on the turbidity removal efficiency was tested. It was determined that 100 W ultrasound power was adequate to provide 98.5% or greater turbidity removal efficiencies. Higher ultrasound power application did not show a positive trend while a 50 W power application has resulted in low efficiencies. Fig. 6 shows the response surface for the relationship between the power density (W/mL), turbidity (NTU) and the turbidity removal efficiency. Velocity gradients in flocculation basins must be high enough to achieve the particles contact necessary to promote aggregation; however, they must not be so high that they shear the flocs apart. Flocs produced by organic polymers may be stronger than those produced from aluminum salts and can withstand higher shearing stresses. However, if flocs are ruptured, reaggregation is more likely to occur for aluminum flocs than for polymer flocs because the polymer segments once detached by mixing, may fold back and restabilize the particles.

3.7. The effect of flocculation and sedimentation time

Further, the effect of different flocculation times following the ultrasound mixing was studied. Different flocculation times (5, 10, 15, 20, 30, and 40 min) were applied followed by 20-h sedimentation process. An initial water turbidity of about 40 NTU was maintained in these tests. Fig. 7a shows the turbidity removal efficiencies for different flocculation and sedimentation times (1 h, 2 h, and 24 h). In these tests, it was noted that the final turbidity of the supernatant was lower 1 NTU for flocculation time between 20 and 40 min. The removal efficiencies did not improve considerably after 20 min of flocculation time. It was confirmed from this test that about 20–30 min of flocculation time was adequate to produce high quality treated water with removal efficiencies higher than 98%.

3.8. Effect of ultrasound mixing

The effect of ultrasound exposure on the removal efficiency was evaluated at different exposure times between 15 s and 3 min (15 s, 30 s, 45 s, 60 s, 120 s, and 180 s) as shown in Fig. 7b.

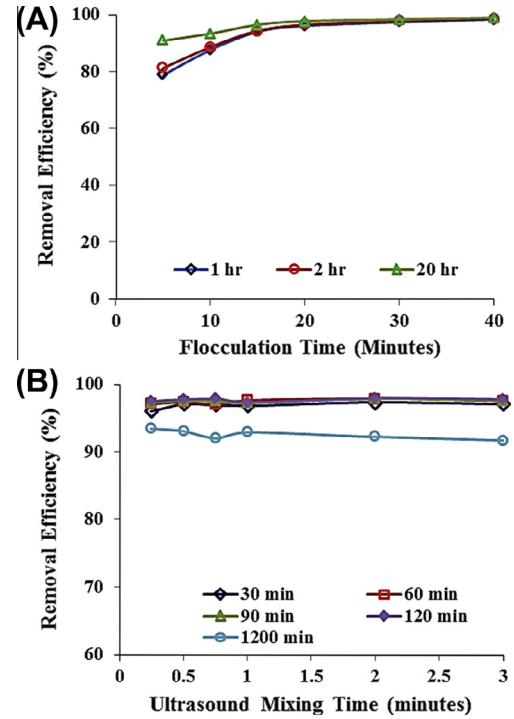

Fig. 7. (a) Effect of flocculation/sedimentation time on ultrasound-chitosan enhanced coagulation–flocculation process and (b) effect of ultrasound exposure on ultrasound-chitosan enhanced coagulation–flocculation process.

Ultrasound exposure times less than 60 s have resulted in higher removal efficiencies (>97%). Continued ultrasound exposure did not improve the efficiencies as observed previously by Zhang et al. [16].

3.9. Concentration factor

Fig. 8 shows the concentration factor of the ultrasound enhanced process for different flocculation times as well as for different ultrasound exposure times. It is important to determine concentration factor which gives an idea of effectiveness of the ultrasound mixing (for coagulation), slow mixing (flocculation) and sedimentation time. Lower ultrasound exposure times resulted in lower concentration factors up to 1 min exposure time. At 15 s of exposure time the concentration factor was 23.5 and the concentration factor increased to 29.76 at 1 min exposure time. As shown in Fig. 8, the concentration factor was only 15 for 5 min while at 20 min of slow mixing a concentration factor of 30.51 was

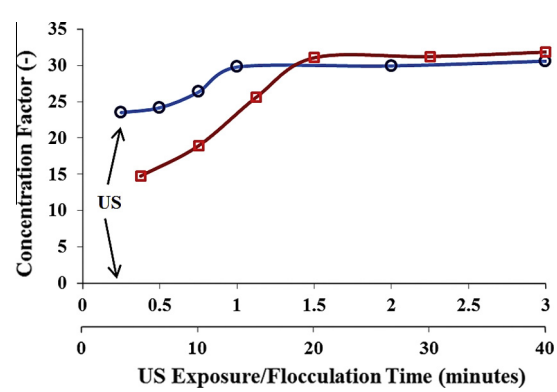

Fig. 8. Effect of ultrasound exposure and flocculation time on concentration factor.

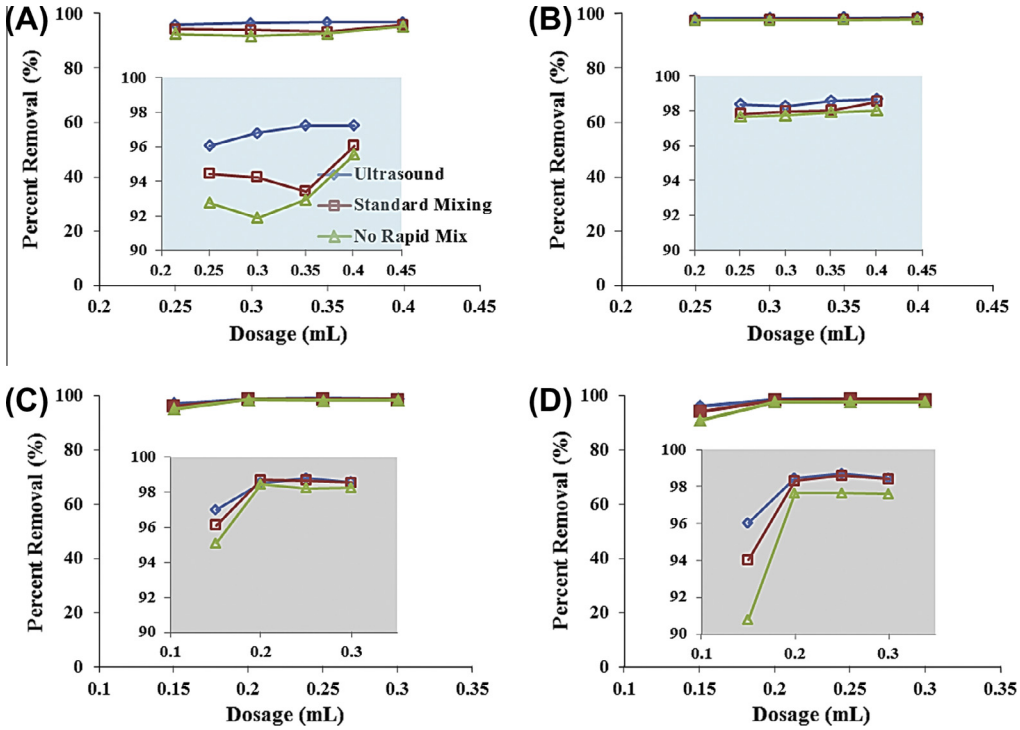

Fig. 9. Removal efficiencies of live algal suspension by ultrasound-alum enhanced coagulation/flocculation: (a) alum-1hr sedimentation; (b) alum-24 h sedimentation; (c) chitosan-1 h sedimentation and (d) chitosan-24 h sedimentation.

observed. Longer flocculation times did not show significant effect on the concentration factor. Higher concentration factor indicates lower sludge volumes and vice versa.

3.10. Live algae suspension tests

It is important to understand the effect of different conditions of the algal suspensions, i.e. whether they are live or dead. We investigated the effect of ultrasound on the removal efficiency of live algal cells. Live algal suspensions grown in our laboratory were tested using ultrasound-chitosan enhanced coagulation/flocculation process. The initial algal suspension had a turbidity of 60 NTU. To further investigate the special effects of ultrasound on the inactivation of live algal cells, we tested three different process configurations: (1) ultrasound exposure for 1 min followed by 20 min flocculation; (2) 2 min rapid mixing (200 rpm) followed by 20 min flocculation; and (3) no rapid mixing, direct flocculation time of 20 min followed by 24 h settling time. Fig. 9a shows the comparison of these three methods for alum as coagulant at 1 h settling time. It can be agreed that ultrasound has performed on the top among the three methods with removal efficiencies higher than 98% (Fig. 9b). This reveals the special effects of ultrasound on the algal cells. Fig. 9c and d show the removal efficiencies for chitosan coagulant at 1 h and 24 h sedimentation times. Ultrasound process performed better than the conventional rapid mix and direct flocculation processes with higher than 98% removal efficiencies. Further the effect of ultrasound-chitosan enhanced method on high algal turbid water was tested. For this test the algal suspension having a turbidity of 298 NTU was collected on the fifteenth day of the growth period. A comparison between the conventional rapid mix process and the ultrasound process is shown in Fig. 10. Different chitosan dosages were applied at

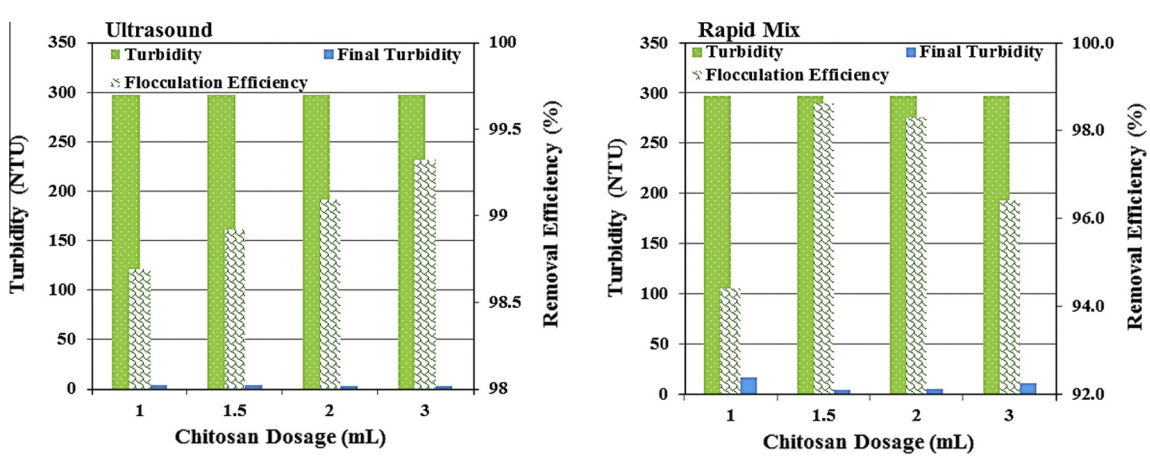

Fig. 10. Effect of flocculation time on ultrasound-chitosan enhanced coagulation–flocculation process.

1 mL, 1.5 mL, 2 mL, and 3 mL. A small chitosan dosage of 1 mL was adequate to remove 98.5% of the algal turbidity increasing the removal efficiency up to 99.3% at 3 mL of dosage for ultrasound method. A large floc size of 5 mm was observed in this test. In comparison, the rapid mixing method resulted in removal efficiencies higher than 98% at 1.5–2 mL chitosan dosages. Overall, the ultrasound-chitosan enhanced coagulation/flocculation process has proven to be a better alternative for low as well as high algal turbid waters.

4. Conclusion

This study has shown that ultrasound mixing can be performed in lieu of conventional rapid mixing for chemical distribution and to promote pin-floc formation. The ultrasound-chitosan enhanced coagulation/flocculation process has resulted in comparable or superior turbidity removal efficiencies compared to conventional rapid mixing-flocculation process and direct flocculation processes. The use of chitosan as coagulant may offer benefits such as environmental-friendliness and small volumes of non-toxic sludge. Apart from initiating agglomeration of algal cells, ultrasound application may provide additional effects including inactivation of algal cells which results in efficient algal turbidity removal in water and wastewater treatment.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cej.2014.01.081.

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