Water Science & Technology

Water Science & Technology Vol 88 No 1, 35 doi: 10.2166/wst.2023.204

Optimum conditions for high-speed solid–liquid separation by ballasted flocculation

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ABSTRACT

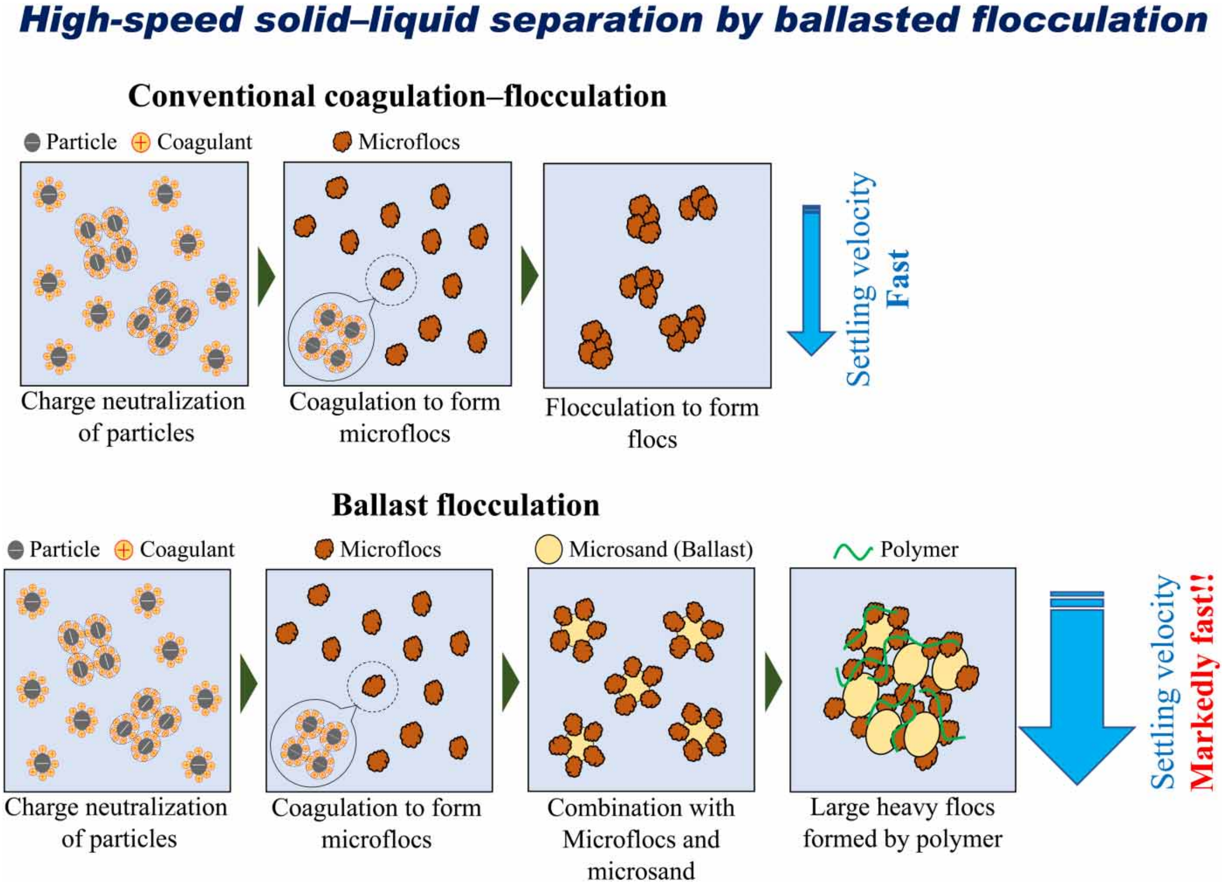
In the ballasted flocculation, high-speed sedimentation of suspensions is achieved using a microsand as a ballast material and a polymer flocculant combined with microflocs made of polyaluminum chloride (PAC) as an inorganic coagulant. In this study, three turbid water samples containing kaolin clay (kaolin concentration: 20, 200, and 500 mg/L) were treated by coagulation–sedimentation and ballasted flocculation. The effects of pH and PAC dosage, which are the controlling parameters for coagulation, and the microsand (silica sand) and polymer dosages, which are the controlling parameters for ballasted treatment, on the treatment efficiency and floc settling velocity were examined. The floc settling velocity under the optimum conditions was 17 times higher than that of the conventional coagulation–sedimentation process using PAC. The turbidity was 0.54 turbidity unit (TU) (TU as the kaolin standard), and its removal efficiency was 99.7%. Furthermore, turbid water samples with different kaolin concentrations (20 and 500 mg/L) were treated via the ballasted flocculation. In this study, fundamental information on the optimization of each dosage condition of coagulant, ballast, and polymer and pH condition in ballasted flocculation was obtained, and the removal mechanisms under optimal, underoptimistic and overoptimistic conditions were proposed.

Key words: kaolin turbid water, microsand, polyaluminum chloride, polymer flocculant, settling velocity

HIGHLIGHTS

- Conditions for ultrahigh-speed ballast flocculation were investigated.
- Floc settling velocity increased and showed a peak at 10 g/L of microsand.
- Excess addition of microsand significantly reduced the floc settling velocity.
- Hugh floc settling velocity was achieved in the treatment of high-turbidity water.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Coagulation–sedimentation is an important solid–liquid separation process (Lee *et al.* 2014; Jiang 2015; Dao *et al.* 2016; Khettaf *et al.* 2021a, 2021b) in water treatment and has been adopted in several water treatment plants. To remove suspended solids from water, a coagulant is used for efficient solid–liquid separation. In general, coagulants widely used in water treatment are aluminum-based inorganic coagulants, including aluminum sulfate and polyaluminum chloride (PAC) (Sinha *et al.* 2004; Wang *et al.* 2009). In particular, PAC has excellent treatment capacity compared to other coagulants (Sinha *et al.* 2004; Wang *et al.* 2009). Coagulation plays important removing colloidal and fine particles from surface water during water treatment (Wang *et al.* 2009). However, the flocs formed only with inorganic coagulant include water in the flocs, and the amount of water increases as the size of the flocs increases, resulting in a small density, low settling velocity, and low strength of the flocs (Matsui *et al.* 2003; Sinha *et al.* 2004; Wang *et al.* 2009). Therefore, optimizing the floc size and the strength is a key in coagulation–sedimentation to limit the settling velocity of coagulated flocs formed by inorganic coagulants such as PAC. In a water purification plant for processing large amounts of tap water, the area of the settling basin must be large to reduce surface loading. However, it is difficult to secure a large installation area for settling basins in urban areas due to land restrictions (Kumar *et al.* 2016). Therefore, to date, there is a need to develop a solid–liquid separation technique that is faster than the conventional coagulation–sedimentation.

Ballasted flocculation (trade name: ACTIFLO) was developed in the 1990s as an innovative solid–liquid separation technique (Desjardins *et al.* 2002). This process uses microsand and polymer flocculants to accelerate the sedimentation process by forming large flocs with a high specific density (Lapointe & Barbeau 2016). Thus, it makes floc sedimentation faster than coagulation–sedimentation based on conventional inorganic flocculants (Brahmi *et al.* 2018). Ballasted flocculation has been employed in various solid–liquid separation processes, including water purification (Lapointe & Barbeau 2018; Kumar *et al.* 2019; Qasim *et al.* 2019; Murujew *et al.* 2020).

In the early 2000s, ballasted flocculation was used as a solid–liquid separation process in water purification systems for low-turbidity water (turbidity of 10 nephelometric turbidity unit (NTU) or less) (Desjardins *et al.* 2002; Lapointe & Barbeau 2016, 2018). On the other hand, in monsoon regions, such as Japan, surface water, which is the raw water for tap water, is highly turbid due to heavy rainfall, exceeding 500 turbidity unit (TU) (unit as kaolin standard) most times (Saito *et al.* 2013). Such high turbidity of raw water must be considered to maintain high-standard tap water. As a pretreatment process for such high-turbidity water, ballasted flocculation has been studied and employed in some facilities in practice. Considering water whose turbidity significantly varies, it is difficult to achieve suitable conditions for ballasted flocculation. Based on experience, such conditions have been adjusted. However, the treatability in underconditioning and overconditioning, high turbidity, and extensive ballast addition is unclear. In fact, onsite adjustment of dosage conditions is still an essential task at water treatment plants to ensure the quality of the treated water.

In this study, we prepared three turbid water samples composed of kaolin clay (kaolin concentrations: 20, 200, and 500 mg/L) and examined the factors that affect the processability and floc settling velocity during ballasted flocculation. In addition, the mechanism of ballasted flocculation was investigated based on the results of the water treatment under short, optimum, and excess dosage conditions to provide a stable supply of treated water even for large fluctuations in the turbidity of raw water.

2. MATERIALS AND METHODS

2.1. Turbid water and agents

Kaolin (FUJIFILM Wako Pure Chemical Co., Osaka, Japan) was used as suspended clay particles to prepare a 10-g/L slurry-like stock solution. PAC (concentration as Al_2O_3, 10–11%; basicity, 45–65%; density, $\geq$1.19; Asahi Kasei Advance Co., Tokyo, Japan) was used as an inorganic flocculant and was diluted 10-fold immediately before use to prepare a stock solution. The concentration of sodium hydrogen carbonate ($NaHCO_3$, FUJIFILM Wako Pure Chemical Co.), as an alkali, was adjusted to 100 mg/L in distilled water, and the kaolin stock solution was added to obtain turbid water. In this study, turbidity was evaluated by an integrating sphere type turbidimeter with a turbidity standard solution made of standard kaolin as specified in the Japanese Waterworks Law. The turbidity is defined as that the turbidity equivalent to 1 degree of TU when 1 L of purified water contains 1 mg of standard kaolin. Kaolin turbidity of 1.00 is 0.57 as the equivalent turbidity NTU. Three levels of kaolin turbid water (low: 20 mg/L; medium: 200 mg/L; high: 500 mg/L) were prepared to investigate the effect of turbidity loads. Silica sand (SiO_2 content: 98%; specific gravity: 2.63; particle size: 100–300 μm; Mikawa Keiseki Co., Okazaki, Japan) was used as microsand. The silica sand is industrially available with uniform specific gravity and high SIO_2 purity. The particle size was selected to be dispersed in the beaker under the stirring conditions during the jar test. Six polymer flocculants (anion: AP335PWS, AP120PWS, AP410PWS, Mitsubishi Chemical Co., Tokyo, Japan; nonion: NP800PWS, Mitsubishi Chemical Co.; SS-500PWG, HYMO Co., Tokyo, Japan; cation: KP1200H, Mitsubishi Chemical Co.) were examined to obtain the best suited for ballasted flocculation (Table 1). The stock solution of the polymer flocculant was dissolved in distilled water immediately before use to adjust the content to 0.1%. In addition, 1-mol/L hydrochloric acid (HCl) and 1-mol/L sodium hydroxide (NaOH) were added to adjust the pH of the solution.

2.2. Coagulation–sedimentation by jar test

To investigate the relationship between PAC dosage and the pH of the solution, we conducted conventional coagulation–sedimentation tests using a jar test apparatus (MJ-8, Miyamoto Co., Osaka, Japan). First, PAC was added to a turbid water sample

Table 1 | Properties of polymer flocculants

Polymer trade name	Ionic strength	Molecular weight × 10^4	Major component	Manufacturer
DIAFLOC AP335PWS	Anionic high	1,600	Polyacrylamide, acrylic acid	Mitsubishi Chemical Co., Japan
DIAFLOC AP120PWS	Anionic middle	1,300	Polyacrylamide, acrylic acid	Mitsubishi Chemical Co., Japan
DIAFLOC AP410PWS	Anionic low	1,300	Polyacrylamide, acrylic acid	Mitsubishi Chemical Co., Japan
DIAFLOC NP800PWS	Nonpolar	1,300	Polyacrylamide	Mitsubishi Chemical Co., Japan
HYMOFLOC SS-500PWG	Nonpolar	1,600	Polyacrylamide	HYMO Co., Japan
DIAFLOC KP1200H	Cationic high	700	Polyacrylic ester	Mitsubishi Chemical Co., Japan

and rapidly mixed (150 rpm, the estimated gradient velocity 201/s) for 3 min. The PAC dosages were as follows: low-turbidity water 20 mg/L, PAC 0–50 mg/L; medium-turbidity water 200 mg/L, PAC 0–100 mg/L; high-turbidity water 500 mg/L, PAC 0–120 mg/L. The pH of the solutions was controlled by adding HCl or NaOH. Then, the mixtures were slowly stirred (40 rpm, 28/s) for 15 min. After coagulation, the mixtures were allowed to settle for 10 min, after which 100 mL of the supernatant water was gently collected as the treated water using a syringe. The turbidity of the untreated and treated water was measured using a turbid meter (PT-200, Nittoseiko Analytech Co., Kanagawa, Japan) to determine the purification efficiency. The pH and electrical conductivity of the treated water were measured using a pH bench meter (LAQUA F-74, 9615-10D, HORIBA Co., Tokyo, Japan).

2.3. Ballasted flocculation using coagulant, microsand, and polymer

To ensure the uniform stirring and mixing of the suspensions obtained using PAC, microsand, and polymer flocculant, four baffle plates (width: 15 mm; height: 140 mm) were fixed inside the beaker (Okoro *et al.* 2021). The PAC stock solution was added to 1,000 mL of the sample in a 1,000 mL-beaker set in the jar tester and rapidly stirred (200 rpm, 302/s) for 1 min. Thereafter, microsand (0–30 g/L) was added directly under rapidly stirred (200 rpm), and after 2 min, the predetermined dosage (0–10 mg/L) of the polymer flocculant was added to the samples. Thereafter, the mixture was further stirred for 3 min at 140 rpm. After the flocculation, the upper treated water layer and the floc layer formed an interface, and the upper interface of the floc layer settled uniformly. Therefore, immediately after the stirring, the settling velocity of the flocs was measured as the settling depth at the interface between the floc suspension and the supernatant water per unit time (cm/s). The mixture was allowed to stand for 3 min, after which 100 mL of the supernatant water (treated water) was gently collected using a syringe.

3. RESULTS AND DISCUSSION

3.1. Optimum PAC dosage and pH for coagulation

Coagulation of suspended particles by PAC is the most important for ballasted flocculation.

In the three untreated water samples with different kaolin concentrations, the efficiency of coagulation–sedimentation was evaluated from the residual turbidity for different PAC dosages (0–120 mg/L) and pH ranges (2–12). The removal efficiencies at different PAC dosages and pH for the medium-turbidity water (kaolin 200 mg/L) are shown in Figure 1. As the PAC dosage increased, the turbidity of the treated water remained less than 1 TU in the pH range of 7–9. Similarly, in the cases of low-turbidity (kaolin 20 mg/L) and high-turbidity (kaolin 500 mg/L) waters, low turbidity was observed at the pH range of 7–9 (Figure S1). When alum was used as the coagulant, the pH of the solution of the best removal efficiency was 6.3–7.8 (Desjardins *et al.* 2002), and a region overlapping the pH range of 7–9 as the optimum pH range obtained in this study was confirmed. The changes in the optimum condition with the PAC dosage and pH are consistent with those of coagulation–sedimentation-treated water (Watanabe 2017). Based on the results of the standard jar test, the optimum pH for coagulation was set as 8.0. In addition, in each untreated water, the optimum PAC dosage, which could obtain a turbidity removal efficiency of more than 99%, was set as follows: low-turbidity water, 30 mg/L PAC (1.7 mg Al/L); medium-turbidity water, 50 mg/L PAC (2.8 mg Al/L); high-turbidity water, 60 mg/L PAC (3.3 mg Al/L). Subsequent ballasted flocculation experiments were performed based on the optimum conditions for coagulation.

3.2. Selection of suitable polymer flocculant and optimum pH range for ballasted flocculation

The polymer flocculant best suited for ballasted flocculation of kaolin turbid water (medium-turbidity water, 200 mg/L kaolin) was investigated. The PAC and microsand dosages were fixed at 50 mg/L (obtained from the coagulation–sedimentation test; Figure 1) and 3 g/L (adapted from Lapointe & Barbeau 2018), respectively. The dosage of each polymer flocculant (anion: AP335PWS, AP120PWS, AP410PWS; nonion: NP800PWS, SS-500PWG, cation: KP1200H) ranged from 0 to 2.0 mg/L. Figure 2 shows the relationship between the dosage of each polymer flocculant and the turbidity of the treated water. The turbidity of the water samples decreased sharply with the addition of polymer flocculants, confirming that polymer flocculants are vital in ballasted flocculation. The optimum dosage of polymer flocculants such as AP120PWS, NP800PWS, and SS-500PWG was 0.5–1.0 mg/L, and the turbidity of the treated water was less than 1 TU (removal efficiency based on the raw turbid water $\geq$99%). However, some polymers, including AP335PWS and AP120PWS, which have mild to high ionic strength, increased the turbidity of the water at overdosages of 1.5–2.0 mg/L. In addition, the cationic polymer KP1200H did not improve the turbidity of the treated water even when the dosage was increased. In contrast, the turbidity

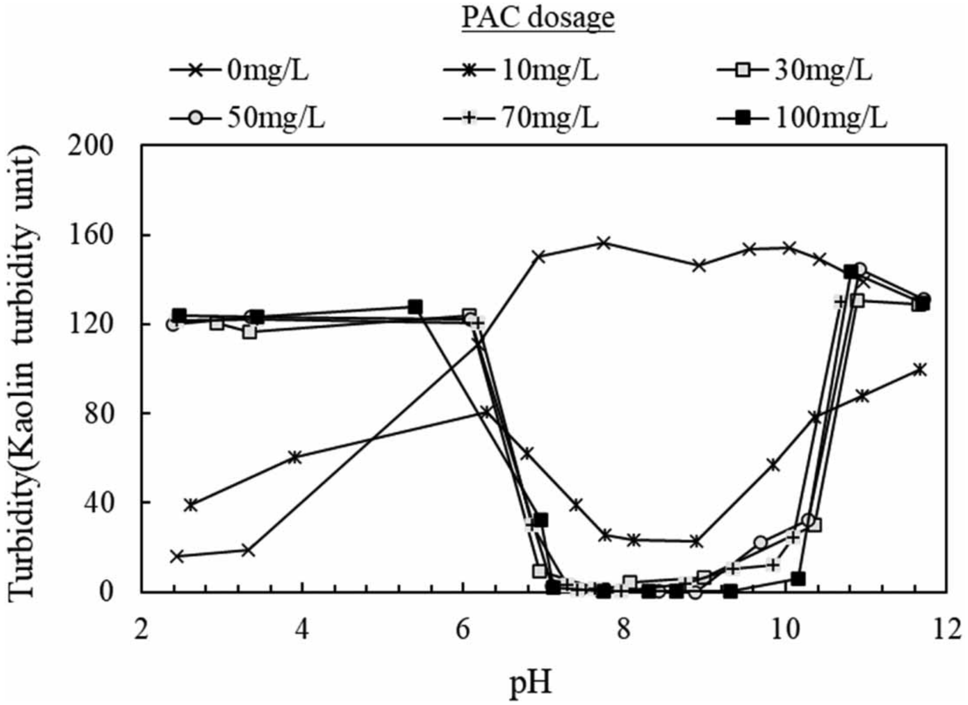


Figure 1 | Turbidity of water treated by coagulation with different PAC dosages as a function of pH (middle-turbidity water; 200 mg/L of kaolin).

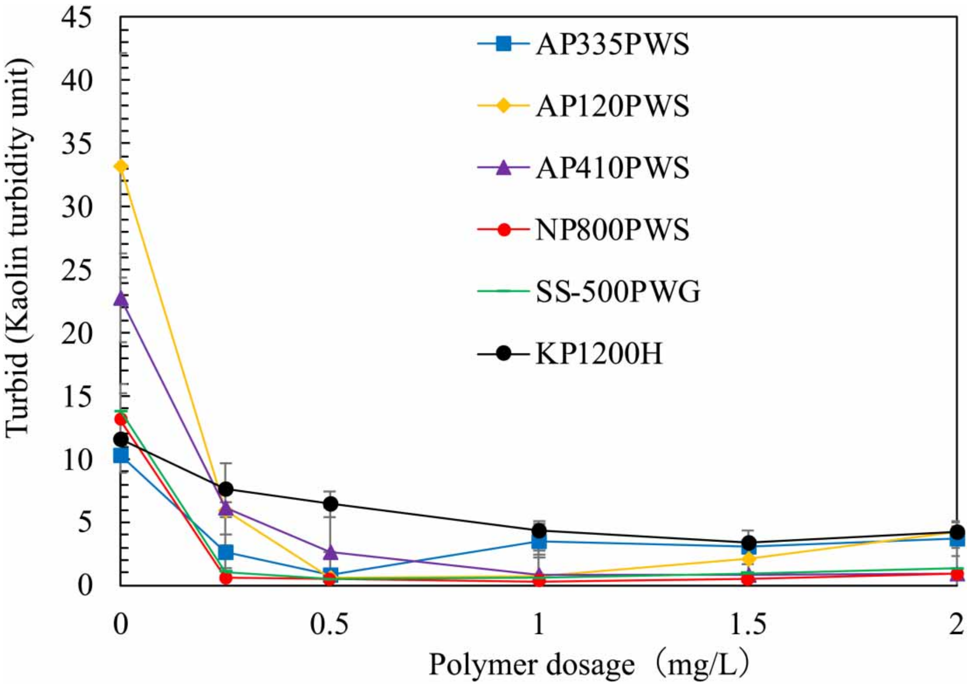


Figure 2 | Comparison between the dosage of polymers for ballasted flocculation (middle-turbidity water; 200 mg/L of kaolin, $n = 3$, mean ± standard deviations). Conditions: PAC dosage, 50 mg/L; pH control, 8.0 ± 0.2; rapid mixing for PAC coagulation, 200 rpm, 1 min; microsand addition, 3 g/L; polymer flocculant dosage, 0–2.0 mg/L; mixing for flocculation, 140 rpm, 3 min; settling time, 3 min.

removal efficiencies of NP800PWS and SS-500PWG remained high, even at the lowest dosage of 0.25 mg/L. The treated turbidity was <0.5 TU at 0.5 mg/L, and low turbidity was maintained even at high dosages. The ability of kaolin particles to crosslink microflocs made of kaolin and aluminum hydroxide and microsand by PAC was suitable for nonionic polymer flocculants. Figure 3 plots the floc settling velocity versus the dosage of each polymer flocculant in the ballasted flocculation process using the medium-turbidity water. Herein, the PAC and microsand dosages were fixed at 50 mg/L and 3 g/L, respectively. When the polymers were added to the coagulant dosed water, the settling velocity increased with the increasing polymer dosages, except for KP1200H. Among them, the settling velocity of NP800PSW was the highest, reaching 0.26 cm/s (=9.4 m/h) at 1.0 mg/L and 0.53 cm/s (=19 m/h) at 2.0 mg/L. Nonionic polymer exhibited the best ionic properties compared to other polymers used to bind the microsand to the microflocs with kaolin and PAC. It is believed that microflocs (positive charge) and microsand (negative charge) are charge neutralized and nonionic polymers are more likely to function. In contrast, the floc of KP1200H was small with many residual particles and a low settling velocity. However, the cationic polymer flocculant KP1200H, which has extremely high cationic strength, did not exhibit any ballasted flocculation effect.

Notably, pH is vital for coagulation. In addition, the effect of pH on ballasted flocculation needs to be determined. Thus, we varied the pH of the samples to examine its effect on the ballasted flocculation. Figure 4 shows the relationship between the pH and turbidity of the treated water for each polymer flocculant after ballasted flocculation. All polymer flocculants showed low turbidity (<2 TU) in the pH range of 7.5–8.8. The samples treated with NP800PWS showed low turbidity at a wider pH range than those treated with other polymer flocculants. The pH and turbidity profiles for the samples treated by coagulation–sedimentation and ballasted flocculation are in good agreement, indicating that coagulation also dominates the ballasted flocculation process. Thus, the optimum PAC dosage and pH for the coagulation process are the same for ballasted flocculation. Based on the flocculant dosage, treatment efficiency, and floc settling velocity, the most effective polymer flocculant was nonionic NP800PWS. Thus, NP800PWS was used as the flocculant for subsequent experiments, pH was set as 8.0, and PAC dosages were 30, 50, and 60 mg/L for the low, medium, and high-turbidity water samples, respectively.

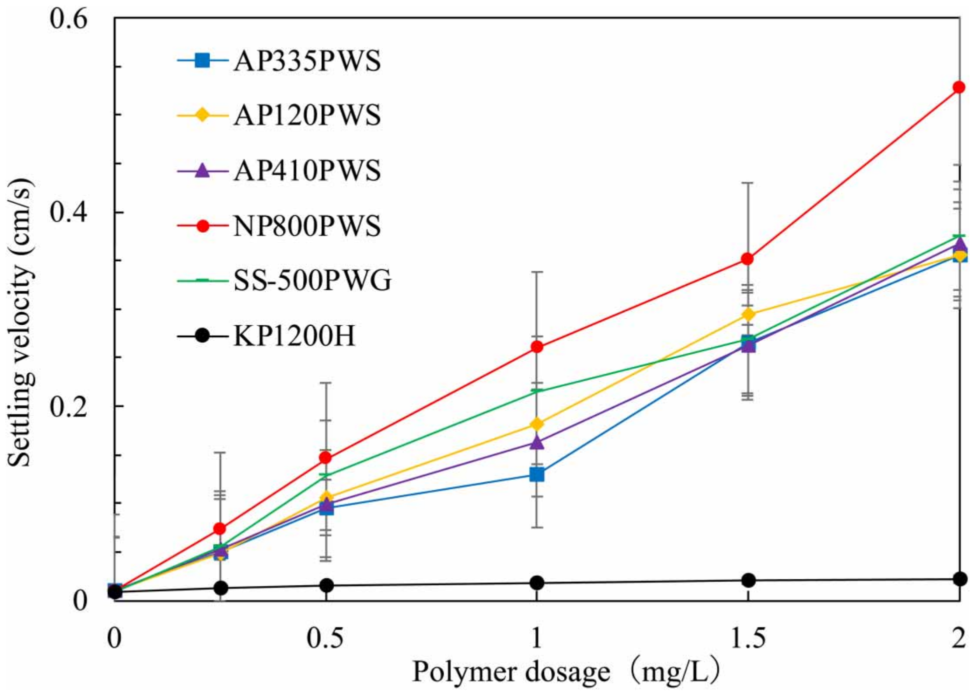


Figure 3 | Floc settling velocity versus flocculent dosage for different polymer flocculants in ballasted flocculation of medium-turbidity water (200 mg/L of kaolin; $n = 3$, mean ± standard deviations).

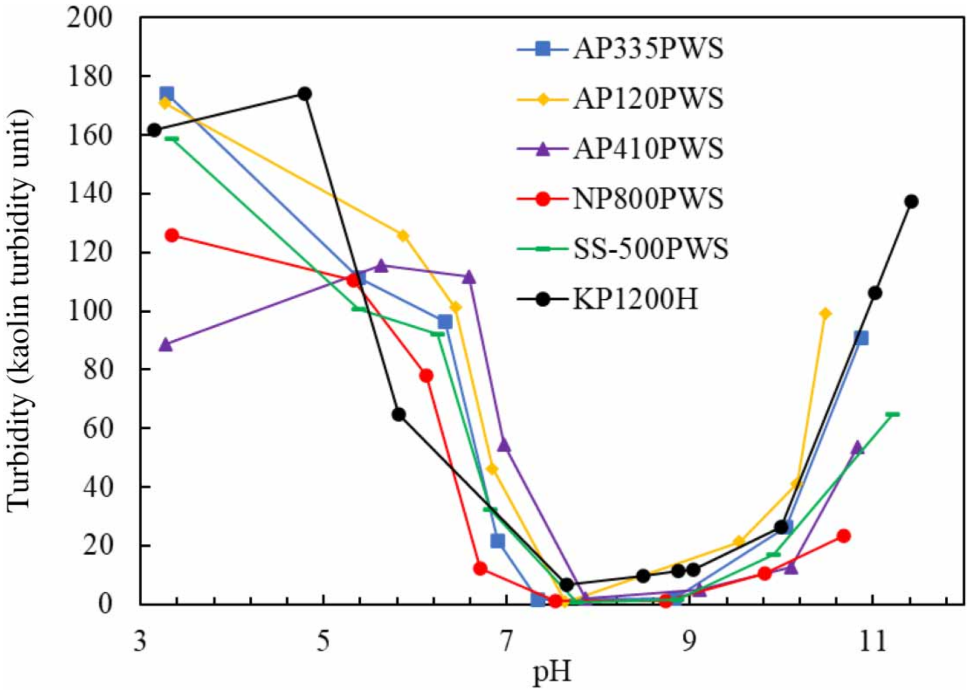


Figure 4 | Turbidity of water treated by ballasted flocculation using different polymer flocculants as a function of pH (middle-turbidity water; 200 mg/L of kaolin). Conditions: PAC dosage, 50 mg/L; rapid mixing for PAC coagulation, 200 rpm, 1 min; microsand addition, 3 g/L; polymer flocculant dosage, 0.5 mg/L; mixing for flocculation, 150 rpm, 3 min; settling time, 3 min.

3.3. Conditions for ultrahigh settling velocity in ballasted flocculation

In ballasted flocculation, the factors that determine the settling speed of the samples include the amount of microsand, which determines the weight of flocs, and the dosage of the polymer flocculants, including microflocs comprising PAC and microsand. Therefore, for the three water samples of different turbidity, the optimum treatment conditions for ballasted flocculation were investigated to determine the relationship between the turbidity of the treated water and the settling velocity of the flocs as the amounts of microsand and the polymer flocculant dosage vary (Figure 5).

Figure 5(a) shows the effect of microsand and flocculant dosages on the treatment efficiency and settling velocity of the low-turbidity water (20 mg/L kaolin). For the sample with no polymer flocculant, the turbidity of the treated water was high (8–14 TU), and the floc settling velocity was extremely low (0.003–0.008 cm/s) for all microsand dosages. The PAC microflocs could not be enlarged because they did not aggregate with the microsand without a polymer flocculant. When both microsand and polymer flocculant were added, the floc settling velocity markedly increased. As the dosage of the polymer flocculant increased, the settling velocity increased. Owing to the addition of a polymer flocculant, the microflocs and microsand aggregated and agglomerated to form large flocs with high tare weight. The optimum amount of microsand was 3.0 g/L, at which the turbidity of the treated water was less than 0.6 TU, and the floc settling velocity was the highest (1.34 cm/s). The average standard settling velocity for the ACTIFLO process is 1.11 cm/s (Desjardins *et al.* 2002), which is comparable with the value obtained herein. With the further addition of microsand above the optimum dosage, the settling velocity decreased. Sediments were observed when excess microsand was added, confirming that microsand was not included in the flocs. The unaggregated microsand contacted with the flocs due to rapid mixing and fragmented the flocs. The decrease in the settling velocity is attributed to the fragmentation of the flocs. When the dosage of the microsand was 10 g/L, the turbidity of the treated water was more than 1 TU for all flocculant dosages, which is attributed to the residual floc fragmentation. For the low-turbidity water, the highest floc settling velocity was achieved at microsand and polymer flocculant dosages of 3.0 g/L and 2.0 mg/L, respectively, with 97% turbidity removal efficiency.

Figure 5(b) shows the effect of microsand and polymer flocculant dosages on the treatment efficiency and floc settling velocity of the medium-turbidity water (200 mg/L kaolin). Similar to the case of low-turbidity water (Figure 5(a)), the turbidity of the treated water was high, and the settling velocity was extremely low when no polymer flocculant was added, even with

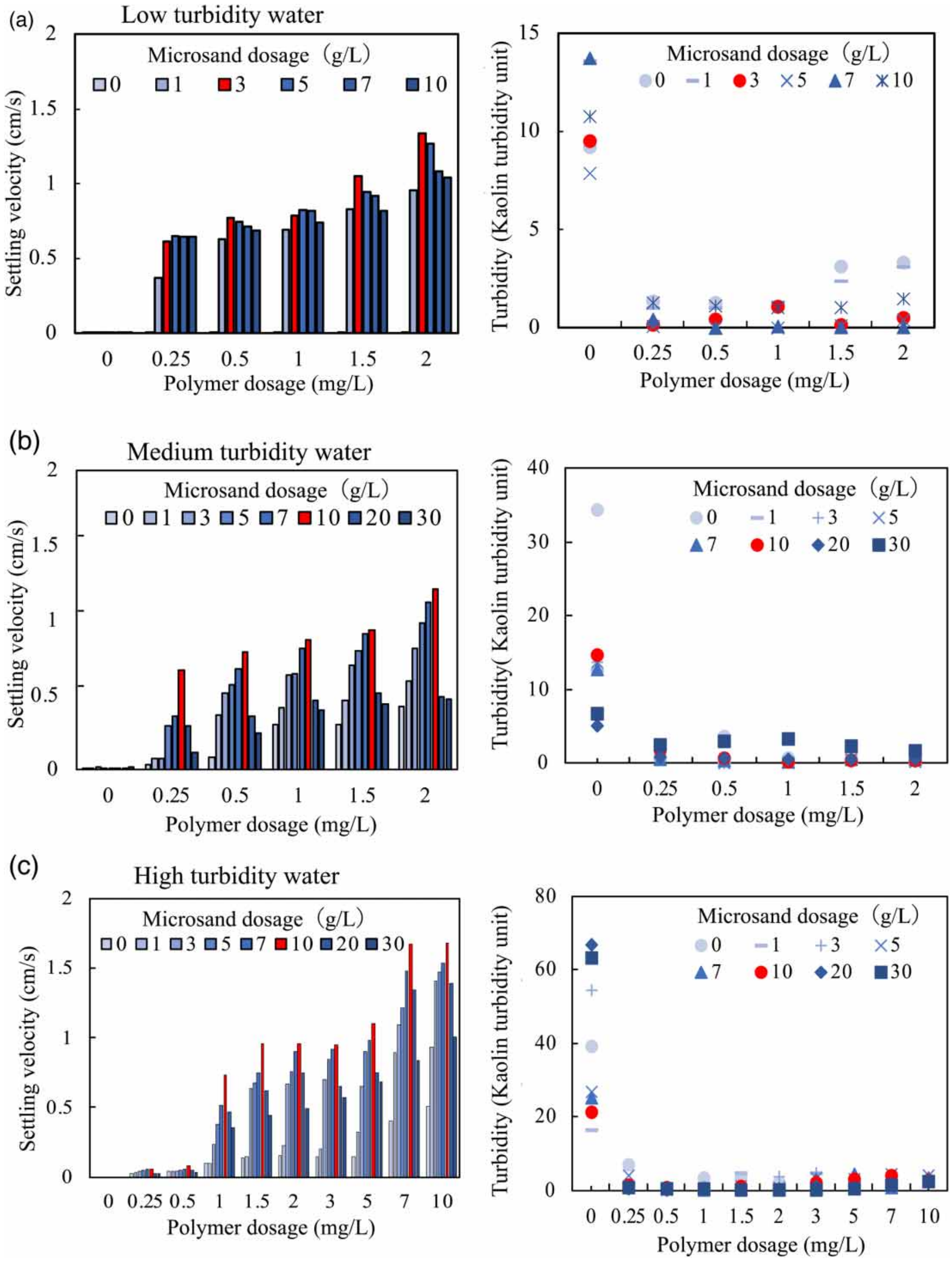


Figure 5 | Variation of residual turbidity and settling velocity with polymer flocculant and microsand dosages. (a) Low-turbidity water (20 mg/L of kaolin). Conditions: PAC dosage, 30 mg/L; pH, 8.0 ± 0.2; rapid mixing for PAC coagulation, 200 rpm, 1 min; microsand dosage, 0–10 g/L; polymer flocculant dosage, 0–2.0 mg/L; mixing for flocculation, 150 rpm, 3 min; settling time, 3 min. (b) Medium-turbidity water (200 mg/L of kaolin). Conditions: PAC dosage, 50 mg/L; pH, 8.0 ± 0.2; rapid mixing for PAC coagulation, 200 rpm, 1 min; microsand addition, 0–30 g/L; polymer flocculant dosage, 0–2.0 mg/L; mixing for flocculation, 150 rpm, 3 min; settling time, 3 min. (c) High-turbidity water (500 mg/L of kaolin). Conditions: PAC dosage, 60 mg/L; pH control, 8.0 ± 0.2; rapid mixing for PAC coagulation, 200 rpm, 1 min; microsand addition, 0–30 g/L; polymer flocculant dosage, 0–10.0 mg/L; mixing for flocculation, 150 rpm, 3 min; settling time, 3 min.

the addition of microsand. However, the floc settling velocity markedly increased with the flocculant and microsand dosages, reaching a maximum value of 1.2 cm/s at 10 g/L of microsand. With flocculant dosages of 0.25–2.0 mg/L and microsand of 1–10 g/L, the turbidity was less than 0.6 TU, indicating high treatment efficiency. However, excessive microsand (20–30 g/L) significantly reduced the floc settling velocity and increased the turbidity of the treated water, and unaggregated microsand was observed in the sediments.

Figure 5(c) demonstrates the effect of microsand and polymer flocculant dosages on the treatment efficiency and floc settling velocity for the high-turbidity water sample (500 mg/L kaolin). The treatment efficiency and floc settling velocity showed a trend similar to that of the medium-turbidity water, and the floc settling velocity significantly increased with the addition of microsand and polymer flocculant, reaching a maximum at 10-g/L microsand. However, even when the dosage of the polymer flocculant was 2.0 mg/L, the settling velocity was 1.0 cm/s, which is lower than that of the low- and medium-turbidity water samples. At high flocculant dosages of 7.0–10 mg/L, the floc settling velocity reached 1.7 cm/s with 10 g/L of microsand. In the case of the high-turbidity water, a high flocculant dosage was required to obtain a large amount of microflocs with microsand. The optimum amount of microsand and the decrease in the floc settling velocity with the excessive addition of microsand can be explained by the same mechanism as the cases of low and medium-turbidity water.

3.4. Treatment efficiency under optimum conditions of ballasted flocculation

Table 2 compares the treatment efficiencies of the normal coagulation–sedimentation and ballasted flocculation for the three water samples under the optimum conditions. The flocculant dosage was 1.0 mg/L, which satisfies the regulations of the Japanese Water Supply Act. We set the higher conditions that exceeded the regulation limit experimentally. The turbidity of the treated water was less than 1.0 TU under all the conditions. Figure 6 shows a schematic of the ballasted flocculation mechanism. For the normal coagulation–sedimentation treatment, the floc settling velocity in the high-turbidity water was lower because of the decrease in the specific density of the flocs with an increase in the quantity and interstitial water. For the low-turbidity water treated by ballasted flocculation with the regulation of polymer flocculants satisfied, the floc settling velocity was eight times higher than that treated by coagulation–sedimentation, and the highest velocity was 17 times higher than that of the coagulation–sedimentation treatment. For the medium-turbidity water under the regulation and optimum conditions of the polymer flocculant, the lowest and highest floc settling velocities were 17 and 24 times higher than those of coagulation–sedimentation, respectively. Furthermore, for the high-turbidity water, the floc settling velocity for the ballasted flocculation was 37 times higher than that for the coagulation–sedimentation treatment under the optimum conditions. In the treatment of the water sample with high turbidity, that is, the sample with high kaolin concentration, a high settling velocity was obtained by adjusting the microsand and polymer flocculant dosages. In the ballasted coagulation–sedimentation treatment, the floc settling velocity was high at high dosages of suspended solids (200–500 mg/L).

3.5. For practical use of ballasted flocculation

In an actual continuous treatment process of ballasted flocculation system called ACTIFLO (https://www.veoliawatertechnologies.com/en/technologies/actiflo), most of the sand is recovered from the settled sludge by a hydrocyclone and reused again. In our practical management experience for a ballasted flocculation system, the amount of sand replenishment is less than 1/1,000 of the set sand concentration in the system. The dosing cost (inorganic coagulant, polymer flocculant, and sand replenishment) is 0.015–0.029 USD/m^3, depending on the water quality and other conditions. In the case of inorganic

Table 2 | Optimal conditions and processing capacity under those conditions for ballasted flocculation

Raw water	Optimal conditions						Processing characteristics (repeated three times)		
Turbid load	**Kaolin concentration (mg/L)**	**PAC (mg/L)**	**pH (–)**	**Sand (g/L)**	**Polymer (mg/L)**		**Removal (%)**	**Turbidity (kaolin turbidity unit)**	**Sedimentation rate (cm/s), mean ± SD**
Low	20	30	8.0	–	–	–	97.1 ± 1.1	0.58 ± 0.23	0.078 ± 0.005
		30	8.0	3	Regulation	1.0	94.6 ± 1.2	1.08 ± 0.24	0.79 ± 0.02
		30	8.0	3	Optimum	2.0	96.6 ± 0.6	0.68 ± 0.13	1.3 ± 0.1
Medium	200	50	8.0	–	–	–	99.7 ± 0.17	0.56 ± 0.34	0.050 ± 0.002
		50	8.0	10	Regulation	1.0	99.7 ± 0.1	0.54 ± 0.18	0.87 ± 0.07
		50	8.0	10	Optimum	2.0	99.8 ± 0.1	0.47 ± 0.14	1.2 ± 0.2
High	500	60	8.0	–	–	–	99.8 ± 0.1	0.90 ± 0.68	0.041 ± 0.001
		60	8.0	10	Regulation	1.0	99.9 ± 0.0	0.46 ± 0.20	0.74 ± 0.09
		60	8.0	10	Optimum	10.0	99.2 ± 0.1	3.76 ± 0.66	1.5 ± 0.2

PAC, polyaluminum chloride; Sand: microsand; Polymer: nonionic polymer flocculant; Turbidity: turbidity as kaolin unit: 1.0 mg/L of kaolin clay suspension = 1.0 degree as kaolin unit; SD, standard deviation.

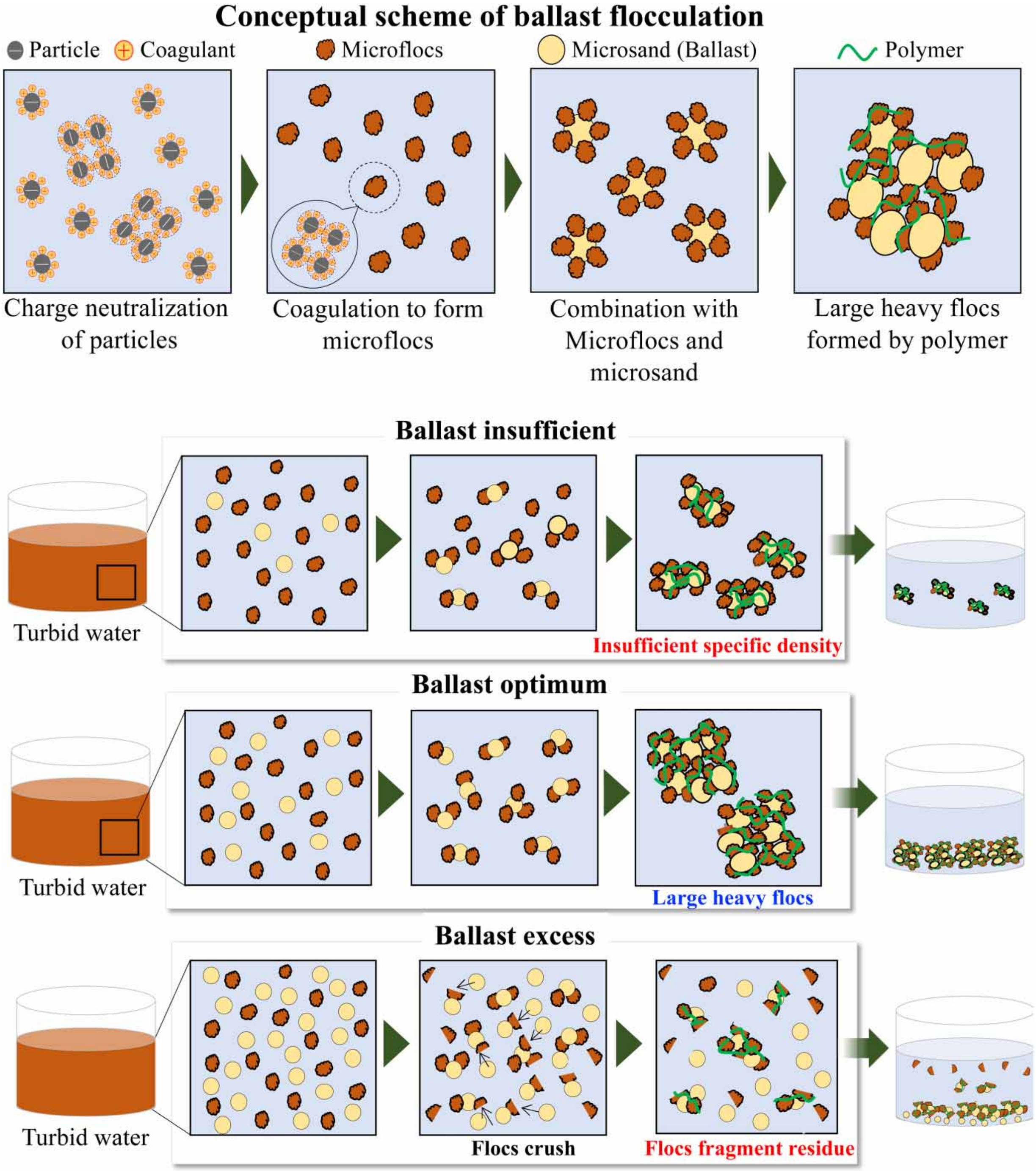


Figure 6 | Schematic of the ballasted flocculation mechanism for suspension removal.

coagulation only, the cost is 0.007–0.022 USD/m^3. In the actual system of ballasted flocculation in water treatment plants, it is also necessary to determine the aluminum (especially when pH is high) and polymer persistence in the final treated water, as well as the actual carryover of microsand.

4. CONCLUSION

We investigated the optimum ballasted flocculation treatment conditions for three water samples of different turbidity based on the variations in the turbidity of the treated water and floc settling velocity with the microsand and flocculant dosages. On the basis of the obtained results, we examined the factors affecting the ballasted flocculation treatment. The microflocs, which comprise suspended solids and PAC, did not aggregate with microsand when no polymer flocculant was added, and the size of the flocs did not increase; thus, high-speed separation can be achieved by ballasted flocculation. Microflocs are constituents of large flocs, which include microsand, and a polymer flocculant promotes the flocculation of microflocs and microsand by cross-linking. Since the formation of microflocs depends on the turbidity of the water, which is determined by the concentration of suspended particles and the dosage of PAC as a coagulant, microsand has an optimum amount when a polymer flocculant is added. The appropriate dosage of PAC varies with the concentration of suspended particles, and the amount of microflocs also varies; thus, the optimal amount of microsand is determined accordingly by turbidity. Excess microsand could not aggregate with the flocs and fragmented the flocs during agitation. Thus, the residual turbidity increased, and the floc settling velocity decreased. To achieve high-speed ballasted flocculation, the following are required: (1) a suitable dosage of coagulant to form microflocs of suspended solids (turbidity) as the constituent materials of flocs; (2) the maximum amount of microsand that can be included in the flocs; (3) a polymer flocculant required to maintain the strength of the flocs.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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First received 11 November 2022; accepted in revised form 17 June 2023. Available online 30 June 2023