Polyaluminium chloride dosing effects on coagulation performance: case study, Barekese, Ghana

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ABSTRACT

Alum, the predominant coagulant in conventional drinking water treatment schemes, has various disadvantages including the production of large volumes of sludge, lowering water pH (requiring pH adjustment using lime), limited coagulation pH range of 6.5 to 8.0, etc. At the Barekese Water Treatment Plant in Ghana, an alternative, the polyelectrolyte – polyaluminium chloride (PAC) is also used in coagulation but limited information is available on the operating conditions required to achieve better performance than alum-based coagulation. The aim of this study was to determine the optimal coagulant dose, mixing speed and operating pH for enhanced performance in water treatment. The effects on the treatment process of three different sets of mixing speed pairs – 180/40, 180/25 and 150/25 revolutions per minute (fast/slow) – in a pH range of 6.5 to 8.0 were investigated. The mixing speed and PAC dose yielding the best coagulation were 150/25 rpm and 15 mg/L respectively. The optimal pH range for PAC coagulation performance was 7.5 to 8.0.

Key words: coagulant dose, coagulation, mixing speed, polyaluminium chloride, polyelectrolyte

HIGHLIGHTS

- The coagulation process in conventional water treatment could be enhanced and the ensuing water pH decline reduced appreciably by applying the right dosage of polyaluminium chloride and appropriate process conditions of pH, fluid mixing speed matrix and residence time.
- Application of polyaluminium chloride under the recommended process conditions produces relatively better quality treated water than alum application.

INTRODUCTION

Freshwater is finite and required for human and ecosystem survival. However, freshwater resources have become repositories of contaminants discharged into the environment – for example, in industrial effluents, domestic and commercial wastes, and agricultural wastes – as well as natural factors such as volcanic eruptions, and so on (Bulut et al. 2010; Zheng et al. 2017). The supply of safe drinking water is crucial to human health and economic productivity (Malik & Khan 2016). About 1.4 billion people worldwide lack access to safe drinking water, resulting in an estimated 5 million deaths per year through water-borne disease (Hossain et al. 2016).

In trying to supply safe water for human consumption, raw water is treated to remove toxic suspended and dissolved substances. Typically, drinking water treatment processes include aeration, coagulation, clarification (or sedimentation), filtration, disinfection and conditioning (if necessary). In coagulation, coagulants are used to neutralize and destabilize charges on suspended and colloidal particles in the raw water (Sahu & Chaudhari 2013). In coagulation, these particles and any pathogens attached to them are removed, enhancing the water's quality (Miller et al. 2008). Coagulation efficiency is greatly influenced by factors such as the type of coagulant and dose used, mixing speed and duration, operating pH, temperature, ionic strength, nature and concentration of organic matter, total dissolved solids, and the size and distribution of suspended particles (Zainal-Abideen et al. 2012; Sher et al. 2013).

Aluminium sulphate ($Al_2(SO_4)_3$), commonly called alum, has long been used as a coagulant in conventional water treatment but has numerous disadvantages including the production of large volumes of post-treatment sludge, high post-treatment aluminium residue, limited coagulation pH range of 6.5 to 8.0, etc, associated with

its use (Gebbie 2001; Miller *et al.* 2008). These shortfalls in the use of alum have led to the synthesis of improved, aluminium-based polymers, which have been used extensively, over the few last decades, for treating water due to their high efficiency at lower dosages, and wider pH and temperature application ranges (Sahu & Chaudhari 2013). Different varieties have been synthesized, including polyaluminium chloride (PAC), aluminium chloro-hydrate (ACH) and polyaluminium sulphate (PAS) (Pernitsky & Edzwald 2006). Their individual performances are influenced by the raw water characteristics and the operating conditions – for example, coagulant dosage, mixing speed, mixing time, retention time and raw water pH.

PAC is the polymer adopted by the Ghana Water Company Limited (GWCL) and the Barekese Water Treatment Plant management in Ghana. However, limited information is available on the optimal dosage and operating conditions for PAC-based water treatment. This study was designed to determine the optimum operating conditions (coagulant dosage, mixing speed and pH) for the efficient performance of PAC in the treatment process.

MATERIALS AND METHODS

The Barekese Water Treatment Plant (BWTP) management were interviewed at the start to determine the plant's operating practices, the mixing speed and time; the maximum contact time used in routine jar tests (Figure 1) were learnt. Water quality records were also obtained for the period 2013 to 2018. The water quality data included the pH, the colour and turbidity (physical parameters) of the raw, settled, filtered and final treated water. The average daily volume of water treated and average PAC dose applied were also noted.

Figure 1 | Jar test setup.

Raw water sampling and preparation

Raw water from Barekese Reservoir was sampled into clean, sealed containers, and the initial pH, turbidity and colour determined on site. The samples were then transported to the KNUST Civil Engineering and Environmental Quality Laboratory for jar tests and subsequent analysis.

Jar tests

Various sets of jar flocculation tests were conducted at pre-determined pH values to establish the effect of pH changes on coagulation (Figure 1). Prior to the start of each jar test, the raw water's pH was adjusted to a pre-determined pH value within the range 6.0 to 8.5, using 0.10 N HCl or NaOH. For the tests, the jars were initially mixed at a fast speed to ensure rapid coagulant mixing, followed by relatively slow mixing to achieve flocculation – the differing mixing speeds constitute a mixing speed pair. Three different mixing speed pairs (i.e., 180/40, 180/25 and 150/25 rpm) were employed in the trial set.

For the first test, the raw water pH was adjusted to 6.0. The six 1 L flocculator jars (Figure 1) were each filled with raw water, and five were dosed with PAC to attain concentrations of 15, 20, 25, 30 and 35 mg/L. The sixth jar was maintained as the blank (i.e. no PAC was dosed). The mixing times adopted were 5 minutes fast and 10 minutes slow; in other words, the stirrers for the individual jars were set to revolve at 180 rpm for 5 minutes (fast

mixing), followed by 40 rpm for 10 minutes. When the prescribed mixing time had elapsed, the samples were allowed to stand for 15 minutes. The supernatants from the jars were then sampled, and their turbidity and colour determined using a HANNA turbidity meter and HACH Spectrophotometer (DR 3900 model), respectively. To ensure a high level of accuracy, the experiment was repeated five times in total, and the mean water quality parameter values determined. Other experimental sets at the same pH were performed using different mixing speed pairs – 180/25 and 150/25 rpm). This experimental cohort was repeated for sample sets with their pH adjusted, respectively, to 6.5, 7.0, 7.5, 8.0 and 8.5.

RESULTS

Raw water pH from 2013 to 2018

Figure 2 shows the mean Barekese raw water pH from 2013 to 2018 inclusive. The raw water pH varies through time. Over the period, the minimum and maximum raw water pH recorded were 5.8 and 7.7 respectively. Possible causes of the pH variation include precipitation intensity and seasonal changes. When precipitation reacts with carbon dioxide (CO_2) in the atmosphere, it tends to lower the pH of receiving water bodies rendering them acidic and the extent depends on the CO_2 concentration in the atmosphere during the annual rainy season (March to November). Aside from the years 2014 and 2015, raw water pH has generally dropped significantly from March to late November (Figure 2), possibly due to high precipitation intensity and/or acidic effluent discharges into streams flowing into the impoundment.
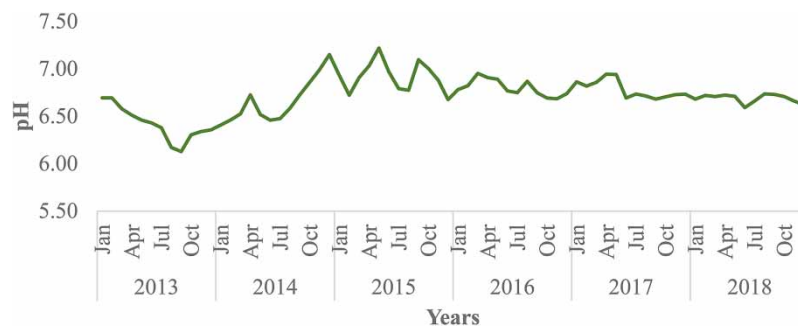

Figure 2 | Barekese raw water pH (2013 to 2018). (*Source:* Barekese Water Quality Laboratory, 2018.)

As reported, low raw water pH requires relatively low coagulant dose for coagulation. A similar trend was observed in alum consumption at BWTP, except in 2013 (Table 1) (Braul *et al.* 2001; Pernitsky & Edzwald 2006; Ezeh *et al.* 2017).

Table 1 | Raw and treated water quality and PAC dosages applied at BWTP

	pH			Turbidity (NTU)		Colour (PtCo)	
Year	Raw water	Flocculated water	Alum (φ)/PAC (*) Dose (mg/L)	Raw water	Flocculated water	Raw water	Flocculated water
2013	6.15–6.69	5.59–6.12	Φ62.09–78.24	8.04–20.48	2.86–6.41	145.87–422.53	13.23–32.55
2014	6.41–7.15	5.91–6.60	Φ60.34 –70.17	10.24–31.70	2.39–6.23	146.72–202.13	18.45–28.89
2015	6.67–7.22	6.18–6.71	Φ56.73–74.47	9.29–36.24	2.04–5.44	131.84–225.92	17.74–32.38
2016	6.68–6.95	5.91–6.44	Φ62.86–96.78	9.98–27.83	2.44–5.99	155.77–232.60	15.75–29.01
2017	6.68–6.94	6.01–7.01	*14.11–43.22	12.14–84.88	3.71–6.09	130.64–654.00	16.75–22.68
2018	6.59–6.74	6.56–6.83	*19.47–42.41	13.54–34.53	3.54–4.68	160.80–298.42	16.06–26.09

(*Source:* Barekese Water Quality Laboratory, 2018.)

Table 1 shows the annual minimum and maximum values of the Barekese raw and flocculated water pH, turbidity and colour and the corresponding amounts of coagulants used for treatment from 2013 to 2018. The highest maximum raw water turbidity and colour values were documented in 2017. Their corresponding average values 27.0 NTU and 271.0 Pt-Co could be due to the high precipitation recorded in and around Kumasi then (1,448 mm). The minimum values were recorded in 2015 (Figures 3–6).
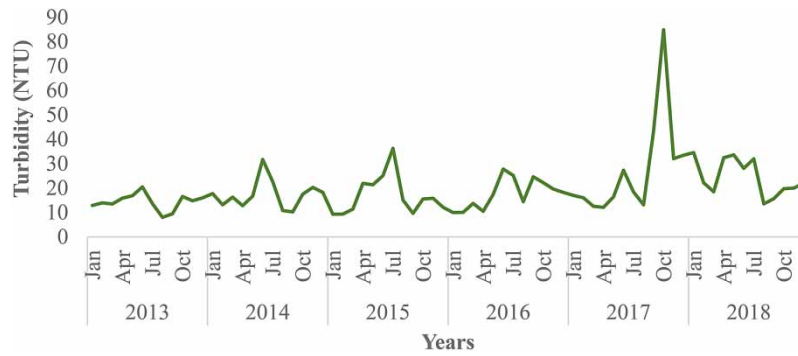
Figure 3 | Barekese raw water turbidity from 2013 to 2018. (*Source*: Barekese Water Quality Laboratory, 2018.)
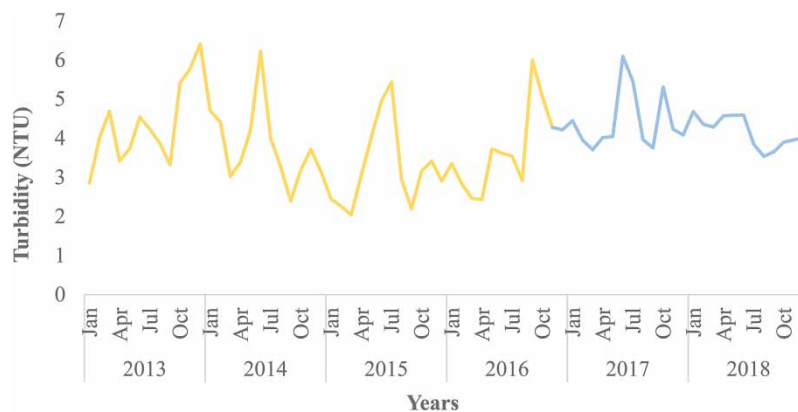

Figure 4 | Barekese flocculated water turbidity from 2013 to 2018. (*Source*: Barekese Water Quality Laboratory, 2018.) *The yellow and blue lines represent the flocculated water turbidities when Alum and PAC were used respectively.
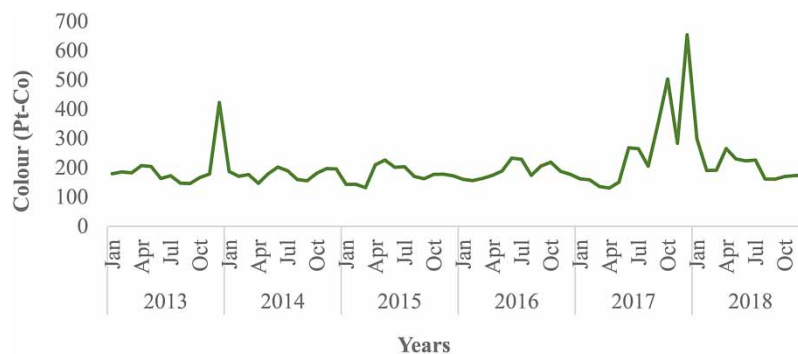

Figure 5 | Barekese raw water from 2013 to 2018. (*Source*: Barekese Water Quality Laboratory, 2018.)

Raw water turbidity and flocculated (settled) water turbidity from 2013 to 2018

The turbidity of Barekese raw water from 2013 to 2018 was generally between 10 and 30 NTU (Figure 3). Between 2013 and 2017, the average alum dose applied at BWTP was 70.4 mg/l, with minimum and maximum dosages of 56.7 and 96.8 mg/l respectively. The average PAC dose, since its introduction in December 2016, was 33.2 mg/l, with minimum and maximum dosages of 14.1 and 43.8 mg/l. Since PAC's introduction, the turbidity of the flocculated water has remained fairly stable, within the range 3.5 to 6.1 NTU. When alum was in use, the range was 2.0 to 6.4 NTU (Figure 4). Over the years, high turbidity values have been recorded in the raw water in roughly the middle of the year – from around April to August – the peak of the rainy season. The high turbidity levels could, therefore, arise from the storm waters entering the Barekese impoundment then with probably high amount of particulate matter (Figure 3).
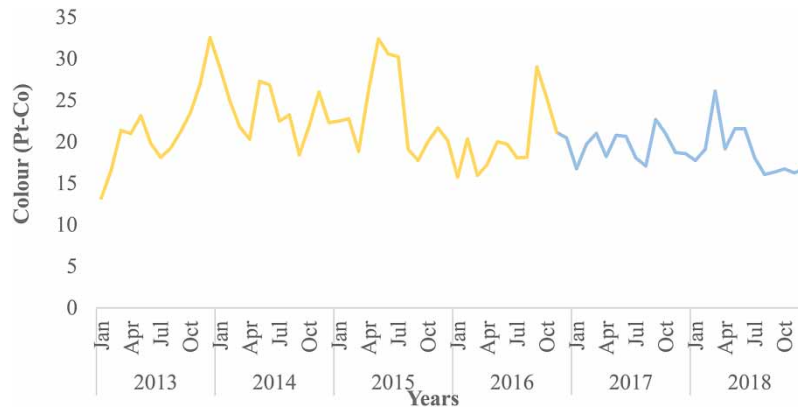
Figure 6 | Mean monthly colour of the Barekese flocculated water from 2013 to 2018. (*Source*: Barekese Water Quality Laboratory, 2018.) *The yellow and blue lines represent the flocculated water colour values when Alum and PAC were used respectively.

Raw and flocculated (settled) water colour from 2013 to 2018

The colour of the raw water – Figure 5 – is generally around 180 to 220 Pt-Co units. In December 2013 and late 2017, there were unusual spikes in colour intensity, possibly due to the presence of high concentrations of organics in effluents discharged by riparian aquaculture communities around some of the tributaries. As for turbidity, the raw water colour usually rises in the middle of the year. Notably in 2017, the period from July to October had high incidence of both colour and turbidity. As noted above, an important factor in this could be the very high precipitation recorded in Kumasi then. It is worth noting – Figure 6 – that the colour of the flocculated water remained fairly steady around 20 to 22 Pt-Co when PAC was introduced (December 2016).

Flocculation results – jar test analysis

Effect of pH on coagulation

Figure 7 shows that at pH 6.0, increasing the PAC dose from 15 to 35 mg/L caused an increase in the flocculated water's turbidity. However, when the pH was raised, as seen in figures 8 and 9, high PAC doses were required to remove turbidity sufficiently. This might be because, at low pH, the negative charges on the colloidal particles and the dissolved organic carbon decrease, and a relatively small amount of coagulant is required for neutralization. When the water's pH is high, however, the negative charge on these particles increases and high PAC concentrations would be required for destabilization.
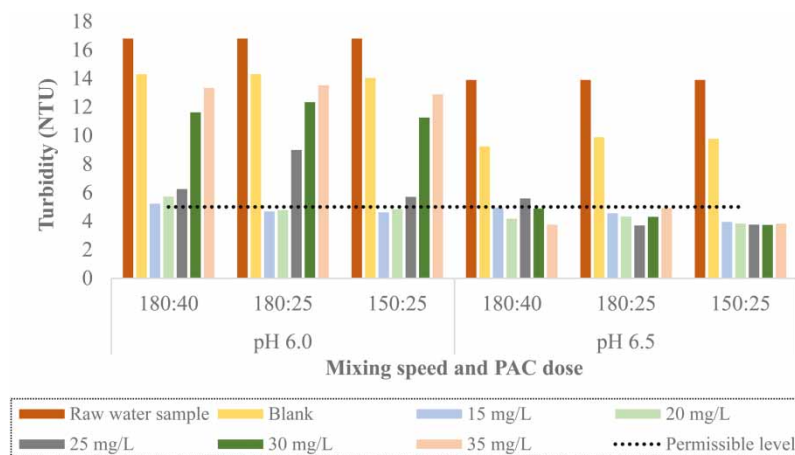

Figure 7 | Effect of low pH, PAC doses and mixing speed on turbidity removal of PAC-flocculated water. *The pecked, horizontal line represents the WHO- and GWCL-recommended maximum for flocculated water.

For pH below 5, the predominant Al species produced from hydrolysis is Al^{3+}. As the pH increases to about 6.5, the predominant Al species become Al^{2+} and Al^+, and for pH values exceeding 6.5, the predominant species in solution is $Al(OH)_4^-$. For effective colloid destabilization to occur, therefore, high PAC concentrations are
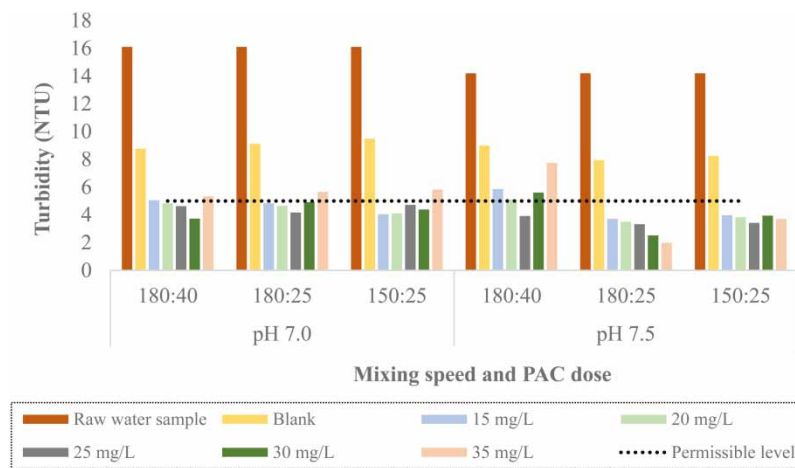
Figure 8 | Effect of mid-level pH 7.0 & 7.5, PAC doses and mixing speed on turbidity removal of PAC-flocculated water. *The pecked, horizontal line represents the WHO- and GWCL-recommended maximum for flocculated water.
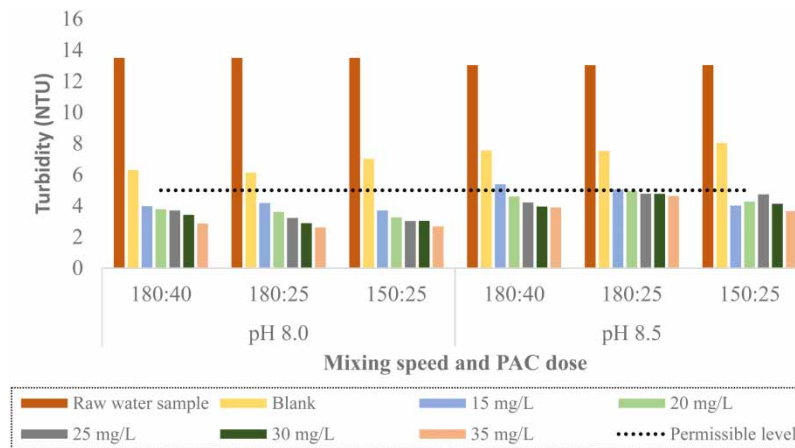

Figure 9 | Effect of pH 8.0 & 8.5, PAC doses and mixing speed on turbidity removal (PAC-flocculated water). *The pecked, horizontal line represents the WHO and GWCL-recommended maximum for flocculated water.

required (Braul *et al.* 2001; Pernitsky & Edzwald 2006; Ezeh *et al.* 2017). A similar observation was made for colour removal (Figures 10–12). It is therefore concluded that for raw water pH <6.5 a relatively lower amount of PAC is required to destabilise colloidal and suspended particles.
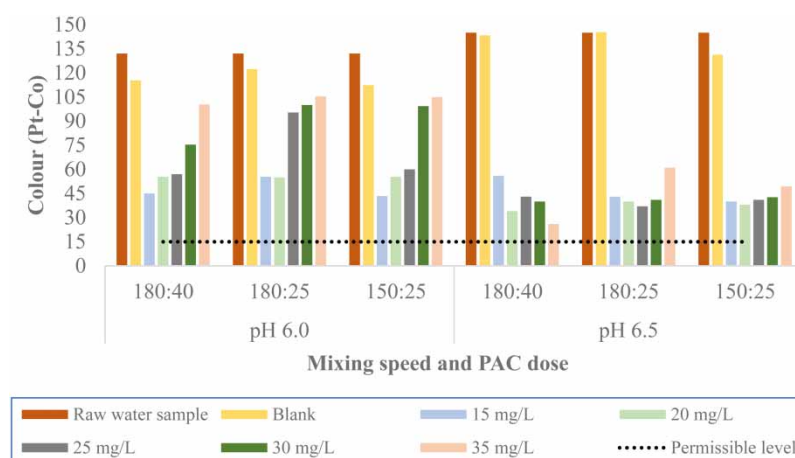

Figure 10 | Effect of lower pH, PAC doses and mixing speed on colour removal of PAC-flocculated water. *The pecked, horizontal line represents the WHO- and GWCL-recommended maximum for flocculated water.
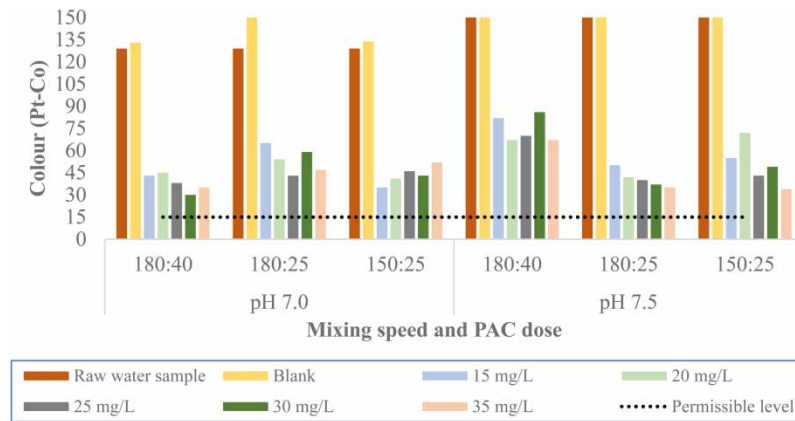
Figure 11 | Effect of different higher pHs, PAC doses and mixing speed on colour removal of PAC-flocculated water. *The horizontal red line represents the WHO and GWCL guideline value for flocculated water.

Figure 12 | Effect of different higher pHs, PAC doses and mixing speed on colour removal of PAC-flocculated water. *The horizontal red line represents the WHO and GWCL guideline value for flocculated water.
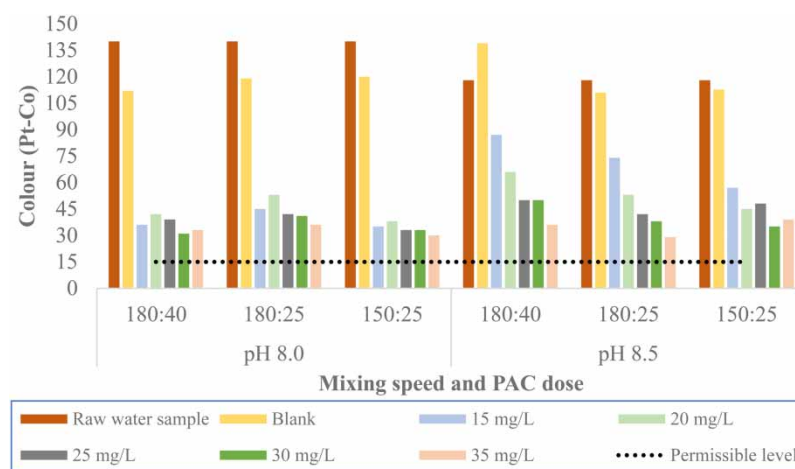
Effects of mixing speed on coagulation

All three mixing speeds (180/40, 180/25 and 150/25 rpm) employed over the pH range 6.0 to 8.5 facilitate colloid and suspended particle destabilisation effectively using 15 mg-PAC/L.

Turbidity in the flocculated water obtained with the 150/25 rpm mixing speed pair was lower than with the other two pairs, except at pH 7.5 where 180/25 rpm produced supernatant with lower turbidity and colour levels (Figures 7–9 and Figures 10–12). The turbidity removal efficiencies recorded for the 180/25 and 150/25 rpm mixing speeds were 73.9 and 72.0% respectively. Similarly, for colour removal, 180/25 rpm mixing speed produced supernatant with lower colour than 150/25, although the difference in their values was not statistically significant at the 95% confidence level. Practically, therefore, since more electrical energy is required to operate at 180/25 rpm than 150/25 rpm, the latter is recommended as optimal. It is also noted in this context that both mixing speed pairs removed turbidity to acceptable levels.

Effects of PAC dose on coagulation

Generally, increasing the PAC dose with pH above 6.5 was found to lower the flocculated water's turbidity (Figures 7–9). This is consistent with the findings of Yang *et al.* (2010), Mirzaiy *et al.* (2012), and Zand & Hoveidi (2015). Similarly, the colour of the flocculated water also improved generally when the PAC dose was increased (Figures 10–12), matching the findings of Aziz *et al.* (2009). On the contrary, at pH 6.0, as the PAC dose increased, the supernatant turbidity and colour also increased. The deteriorating quality of the flocculated water signifies that high PAC dosages at relatively low pH are not efficient in turbidity or colour removal. The

higher PAC dosages – that is, those exceeding 20 mg/L, probably caused the colloidal particle surfaces to become saturated with positively charged Al ions from the PAC, thereby creating a repulsive environment. Repulsive forces impede agglomeration, which results in high turbidity and colour.

Figures 8 and 9 show that the lowest turbidities were obtained at pH 7.5 and 8.0. The pH 6.5 experiment (Figure 7) showed appreciable turbidity removal but less than that obtained at pHs 7.5 and 8.0. The mixing speed pairs of 150/25 rpm at pHs 7.5 and 8.0, and 180/25 rpm at pH 7.5 recorded the lowest turbidities (Figures 8 and 9). It is also noted that the 15 mg/L PAC dosage removed turbidity so that it was below the 5 NTU recommended maximum level for pHs 7.5 and 8.0. Considering the cost of treatment, therefore, it is economically prudent to recommend 15 mg-PAC/L dosage, and pHs 7.5 and 8.0 as the optima for treating water from the Barekese impoundment.

CONCLUSIONS

From the results of the study, it is concluded that:

1. The pH of the Barekese raw water has typically been between 6.4 and 6.8 from 2013 to 2018. Generally, during that period there has been a significant drop in raw water pH between March and late November, annually.
2. Of the three mixing speed pairs investigated – 180/40, 180/25 and 150/25 rpm – in jar tests, 150/25 rpm provided the optimum conditions for efficient coagulation using PAC over the pH range 6.0 to 8.5
3. The optimum PAC dosage required for sufficient coagulation within the pH range 6.5 to 8.0 was 15 mg/L.
4. Optimal pH range for PAC coagulation with water from Barekese impoundment is 7.5 to 8.0.
5. High PAC doses – that is, exceeding 20 mg/L – seem to cause colloidal particle surfaces to become saturated with positively charged Al ions, thereby creating a repulsive environment that impedes agglomeration, resulting in high turbidity and colour levels in the treated water.
6. The use of PAC for coagulation resulted in better turbidity and colour removal for the treated water than alum treatment.

ACKNOWLEDGEMENTS

DATA AVAILABILITY STATEMENT

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

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