

Effect of clariflocculator and pulsator based sedimentation technology and poly-aluminium chloride coagulant type on the efficiency of the water treatment plant

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ABSTRACT

Polyaluminium chloride (PAC) with different basicity is used as a coagulant in most drinking water treatment plants (WTP). The aluminium concentration in PAC and its hydrolysis mechanism varied with the basicity of PAC. Incremental addition of PAC changes various physico-chemical properties and turbidity removal mechanisms in water. Water treatment plants use the PAC concentration beyond its optimum dose without considering other aspects, including residual aluminium concentration. In the present work, the effect of high and medium basicity of PAC on different physico-chemical properties like pH, zeta potential, and residual aluminium concentration of water was investigated. The pH of treated water decreases with the incremental addition of PAC, and an increase in zeta potential and residual aluminium concentration in treated water was evidenced. The change in pH after PAC addition is responsible for deciding the coagulation mechanism and efficiency of the coagulation process. pH reduction is comparatively more in high basicity PAC than medium basicity. PAC hydrolysis mechanism is controlled by the zeta potential of water and can be used as an alternative method to decide the optimum coagulant dose. The performance of clariflocculator and pulsator-based WTP was also evaluated for raw water from the same source. To reduce down the turbidity below the acceptable level, the coagulant requirement for clariflocculator based WTP is comparatively less than pulsator based WTP. The floc blanket in the pulsator gets disturbed with a slight change in the coagulant chemistry and quantity.

Key words: clariflocculator, coagulant, poly-aluminium chloride, pulsator, water treatment plant, zeta potential

HIGHLIGHTS

- Performance of clariflocculator and pulsator-based WTP was studied for the same raw water source.
- Clariflocculator based WTP required comparatively less coagulant than pulsator based WTP to remove turbidity below 1 NTU.
- Incremental coagulant addition decreases pH and enhances zeta potential and residual Al in treated water.
- Floc blanket in the pulsator gets disturbed with a small change in the coagulant chemistry and quantity.

1. INTRODUCTION

In India, to cater for the drinking water demand of small and large urban settings, surface water is the first choice. The surface water-bodies get recharged during the rainy season to supply the requisite amount of water to adjacent cities for drinking purposes and agricultural use. The use of surface water for drinking purposes creates new challenges for water work engineers and technologies due to various factors not limited to water quality, natural organic matter (NOM), emerging soluble contaminants, and color, mainly due to turbidity and algal growth. Coagulation is a proven and widely used process worldwide to remove dissolved organic carbon and turbidity.

In the rainy season, the floodwater carries the turbidity. A significant portion of it gets settled down with time. The small-sized particles remain suspended for a longer time and contribute towards the non-settleable turbidity. These particles continuously remained in motion and repelled each other due to a slightly negative charge on them. In water treatment plants (WTP), the coagulant plays a significant role in neutralising these particles' electrostatic repulsive forces. The coagulant's metal ion attracts these negatively charged particles and coagulates with them to form small-sized floc. Mainly aluminium-based coagulants, e.g. alum, poly-aluminium chloride (PAC), are widely used worldwide. Out of all the available coagulants,

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PAC is the most economical and convenient in terms of lower dose concentration and less sludge generation, high durability and rapid flocculation (Van Benschoten & Edzwald 1990; Gregory & Dupont 2001; Aguilar *et al.* 2002; Yu *et al.* 2007; Yang *et al.* 2011; Kumar & Balasundaram 2017). The PAC coagulation mechanism depends on various raw water quality parameters, including water chemistry, pH of the water (Vepsalainen *et al.* 2012; Wang *et al.* 2014) and coagulant dose (Yu *et al.* 2010). The charge neutralization (Zhao *et al.* 2011), electrostatic patch (Popa *et al.* 2010), double-layer compression (Edzwald & Haarhoff 2011), sweep coagulation (Packham 1965; Zhao *et al.* 2011) and bridge aggregation (Wang *et al.* 2002; Wu *et al.* 2007; Ye *et al.* 2007) are the commonly studied mechanisms (Lin *et al.* 2008; Wei *et al.* 2015).

The activity of PAC in water is controlled by various factors, including the environmental temperature, pH of raw water, types of other ions, and their concentration. At high environmental temperature, the more amounts of less stable phases get formed and lead to enhanced residual Al in treated water. Similarly, solution pH also affects the types of phases formed in the water after addition. The presence of Al in treated water leads to various health problems beyond acceptable limits. In addition to that, it also creates various operational problems during water distribution, including loss of hydraulic capacity, increased turbidity and reduced disinfection efficiency. Therefore there is an urgent need to control the residual Al concentration in the treated water.

In conventional WTPs various processes are involved, including aeration, pre-chlorination, coagulation, flocculation, sedimentation or clarification, filtration by sand media and post-chlorination. Coagulation, flocculation, and clarification play a vital role in WTP's efficiency and efficacy (Camp 1946; Swamee & Tyagi 1996; Cripps & Bergheim 2000). It affects both the quality and quantity of the treated water. It also contributes towards the maximum WTP capital cost during the plant's execution, typically around one-quarter to one-third of the total cost of the WTP (Heikal *et al.* 2017). Various types of technologies are in use for clarification and flocculation, including the well known and widely installed clariflocculator and pulsator based technology. The flocculation followed by sedimentation and floc removal from the treatment unit is the function of the type of technology used. In view of the above, it is essential to optimize the settling tank's efficiency to reduce down the overall cost of water treatment. The different types of sedimentation technology have different flocculation mechanisms.

In clariflocculator, the flocculation and clarification coincide in a single tank. The raw water, along with added coagulant, enters into the inner flocculation tank. Continuously moving paddles help to grow the flocs. The heavy flocs settle down to the bottom, and clear water flows upwards into the outer clarifier zone. In the clarifier, the floc free water enters into peripheral launder through the peripheral weir and is sent to sand filtration media.

In pulsator based clarifiers, the developed floc gets separated from the water by a thick blanket of the floc. After adding coagulant, water enters directly into the clarifier's bottom and gets distributed uniformly through perforated pipes. Water along with flocs move upward through the sludge blanket where flocs get separated from the water. The clear water then enters into the launders, a channel situated at the top of the pulsator to collect the clear water. The clear water is then sent to the sand filtration media for further filtration. The sludge blanket increases in size due to the continuous accumulation of floc from water and, after reaching a certain height, goes into the concentrator.

Both technologies have their own merits and demerits. Clarifier based technology is easy to operate with very minimal maintenance and is an economically viable process. The continuous change in water chemistry does not create any hurdle in operation. The limitation of clarifier based technology is it requires more space. Pulsator-based technology can treat a large quantity of water due to compact design, coagulation, and flocculation, which occurs in one unit. In spite of this, it is susceptible to the change in water chemistry, including turbidity load. The sludge blanket gets disturbed due to the change in water chemistry and environmental temperature (Kawakami *et al.* 2016).

The present work investigated the effect of different basicity of PAC on various physico-chemical properties of water like pH, zeta potential, and residual aluminium concentration. In addition to that, the change in the zeta potential after incremental addition of PAC coagulant is explored as a tool to decide the optimum dose of coagulant. The effect of the gradual addition of coagulant on the residual Al of treated water is also discussed in detail. The pH of treated water decreases with the incremental addition of PAC, and an increase in zeta potential and residual aluminium concentration in treated water was evidenced. The change in pH after PAC addition is responsible for deciding the coagulation mechanism and efficiency of the coagulation process.

Despite both the conventional clariflocculator and advanced pulsator-based clariflocculator used worldwide for water treatment, no theoretical and experimental study has been reported regarding their real-time comparison. The stated comparative study is unique in nature, as getting different types of WTPs (clariflocculator and pulsator) installed on the same raw water

source is rare. During our study, both the WTPs were in operation at their total capacity of 125 and 600 MLD, catering to the need for drinking water of selected cities in various districts of Rajasthan, including the capital of the state. The results of various experiments presented in the manuscript are their real-time data collected during their 24×7 operation at its full-scale treatment capacity.

2. MATERIALS AND METHODS

The poly-aluminium chloride of high basicity (HB) and medium basicity (MB) was collected from Surajapura and Kekri WTP Rajasthan, India, respectively. The coagulants were supplied by industry and were of commercial-grade quality, and were used as received during all laboratory experiments. Raw water used for all laboratory experiments was collected from the Bisalpur dam.

2.1. Coagulation-flocculation experiments (jar test) of water (ASTM D2035)

The jar test experiments were performed as per the standard procedure depicted in ASTM D2035 (ASTM 2003). The Phipps and Bird jar tester as used during all experiments. Multiple stirrers with continuous speed variation from 20 to 200 RPM were used to perform experiments. One thousand mL turbid water was taken in six beakers of one-liter capacity each, and pre-determined doses of PAC were added and mixed at 120 rpm for 1 minute for flash mixing. The stirring speed was reduced to 50 rpm for 20 minutes. The developed flocs were allowed to settle for 15 minutes. Without disturbing the bottom layer, the samples were collected with the help of a pipette from 3 cm below the surface for further analysis.

2.2. Analysis of treated water for various physico-chemical parameters

Various physicochemical parameters of water samples were analysed by standard methods (APHA 2005). Metal ion concentration in the water samples was analysed using Inductively Coupled Plasma–Mass Spectrometer (ICP-MS). All samples were acidified up to pH 2–3 by using ultrapure nitric acid immediately after experiments and passed through the membrane filter prior to being analysed on ICP-MS. The chemical analysis of both the as-received PAC was done by ICP-MS, as shown in Table 1. All experiments were performed in triplicate, and the mean of the result was reported.

2.3. Detail about study location

The Bisalpur dam is a gravity-based dam on the Banas River near Deoli in Tonk district Rajasthan state, India. The dam was constructed in 1999 for irrigation and drinking water supply, with a total storage capacity of 1095 MCM. The reservoir is the source of drinking water for the Ajmer, Jaipur and Tonk districts of Rajasthan. Two WTPs were constructed on the dam, one at Kekdi with a total treatment capacity of 274 MLD to cater for the drinking water demand of Ajmer district and another at Surajapura with a treatment capacity of 600 MLD to supply drinking water to Jaipur and Tonk districts. The raw water for both the WTPs is collected from the same point and pumped in different pipelines, and transported to Kekri and Surajapura WTP.

The Kekri WTP is around 40 km from the Bisalpur dam and has two treatment units (old and new) for which the raw water is carried from Bisalpur dam in two separate pipelines. The flocculator at Kekri WTP is based on the clariflocculator based technology. The Kekri WTP has two different setups with four clari-flocculators in each setup, followed by filtration of treated water by the rapid sand method. WTP also follows pre and post-treatment disinfection by chlorination.

Surajapura WTP is around 10 km from the Bisalpur dam. The flocculators at Surajapura WTP are based on pulsator based technology. The plant has 12 working pairs of pulsators with one standby pair and 26 sand filtration beds. Aeration and pre

Table 1 | Chemical analysis of high and medium basicity PAC

	PAC-HB	PAC-MB		PAC-HB	PAC-MB
Aluminium (%) (w/w)	5.36	4.92	Arsenic (mg/L)	4.71	4.25
Chloride (%) (w/w)	10.35	12.38	Chromium (mg/L)	13.49	12.8
pH (5% Soln)	2.45	3.3	Iron (mg/L)	43.4	57.6
Basicity ‰	66	40	Cadmium (mg/L)	5.1	4.76
Sulphate (mg/L)	2.5	2.7			

and post chlorination is also part of the treatment at the WTPs. The tentative locations of the reservoir and WTPs are shown in Figure 1.

3. RESULTS AND DISCUSSION

The turbidity removal efficiency of high basicity PAC (PAC-HB) and medium basicity PAC (PAC-MB) on the raw water collected from the Bisalpur dam was studied in detail by various laboratory experiments (Section 3.1) This will help in understanding the mechanism of turbidity removal by PAC used and for comparing the performance of both the WTPs.

3.1. Effect of PAC dosage and basicity on the various properties water

The optimum dose of PAC was understood by residual turbidity and zeta potential of the raw water after incremental coagulant addition. The raw water turbidity is between 2–3 NTU. It reduces with increasing PAC dosage, as shown in Figure 2. It reached the stagnant and did not vary much with coagulant addition after an optimum dose of 10–15 mg/L. Enhancing PAC dosing ever more than 50 mg/L does not reduce the turbidity below 0.5 NTU, which may be due to the suppressed PAC hydrolysis after the optimum dose. The slight turbidity reduction is mainly due to the trapping of particles in PAC precipitates at higher doses. The various factors responsible for this behavior are described in detail below. The coagulant precipitate decreases with increasing PAC dosage. The optimum PAC coagulant precipitation occurs in the pH ranges of 7–9, and it is suppressed below and below the optimum pH.

The incremental addition of coagulant alters various factors in water chemistry, including zeta potential and pH. The zeta potential of raw water is -22.1 mv. Due to the adsorption of polar matrix ions on the surface of colloidal solids, the surface water zeta potential is generally negative (Salopek *et al.* 1992).

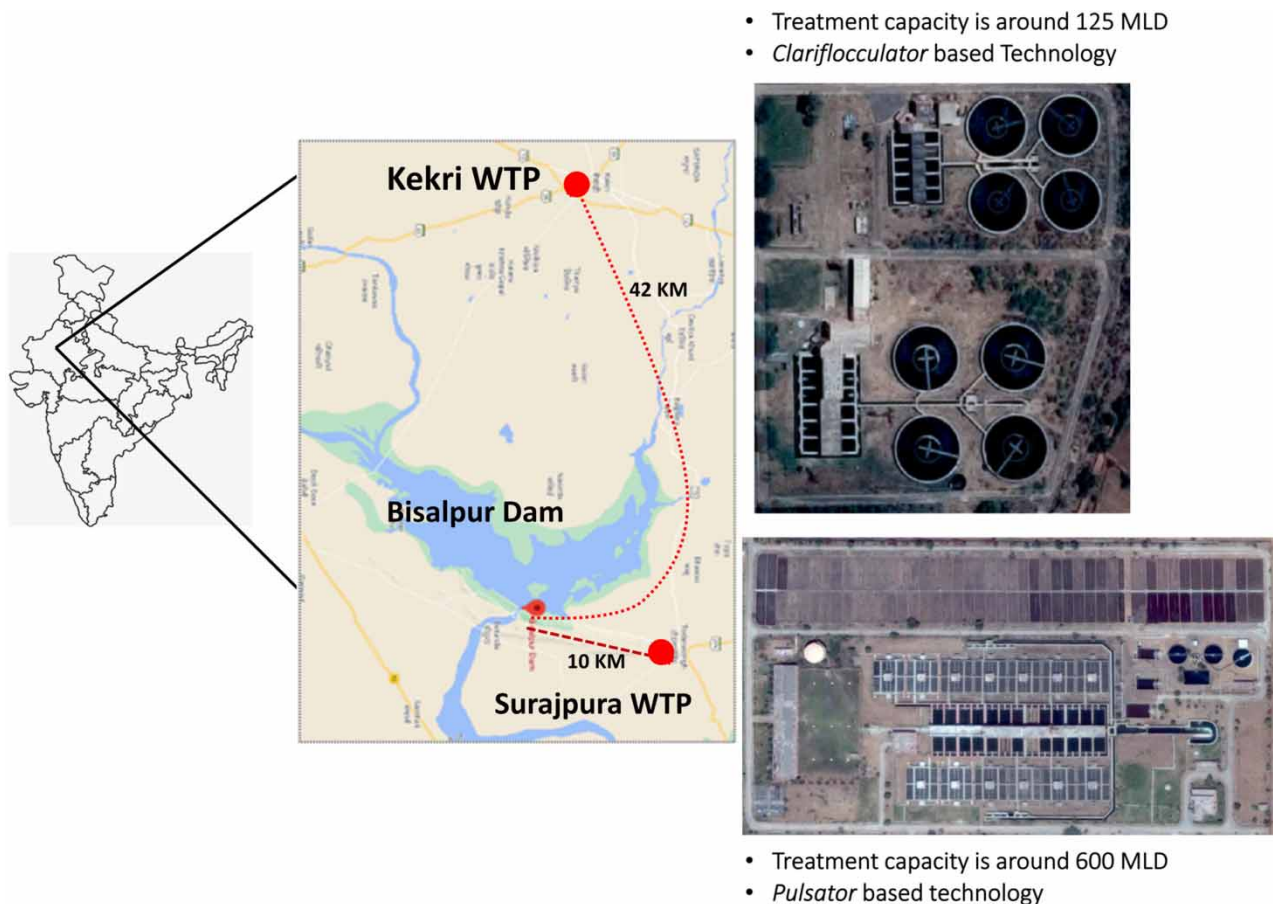


Figure 1 | Location map of Bisalpur dam and WTPs.

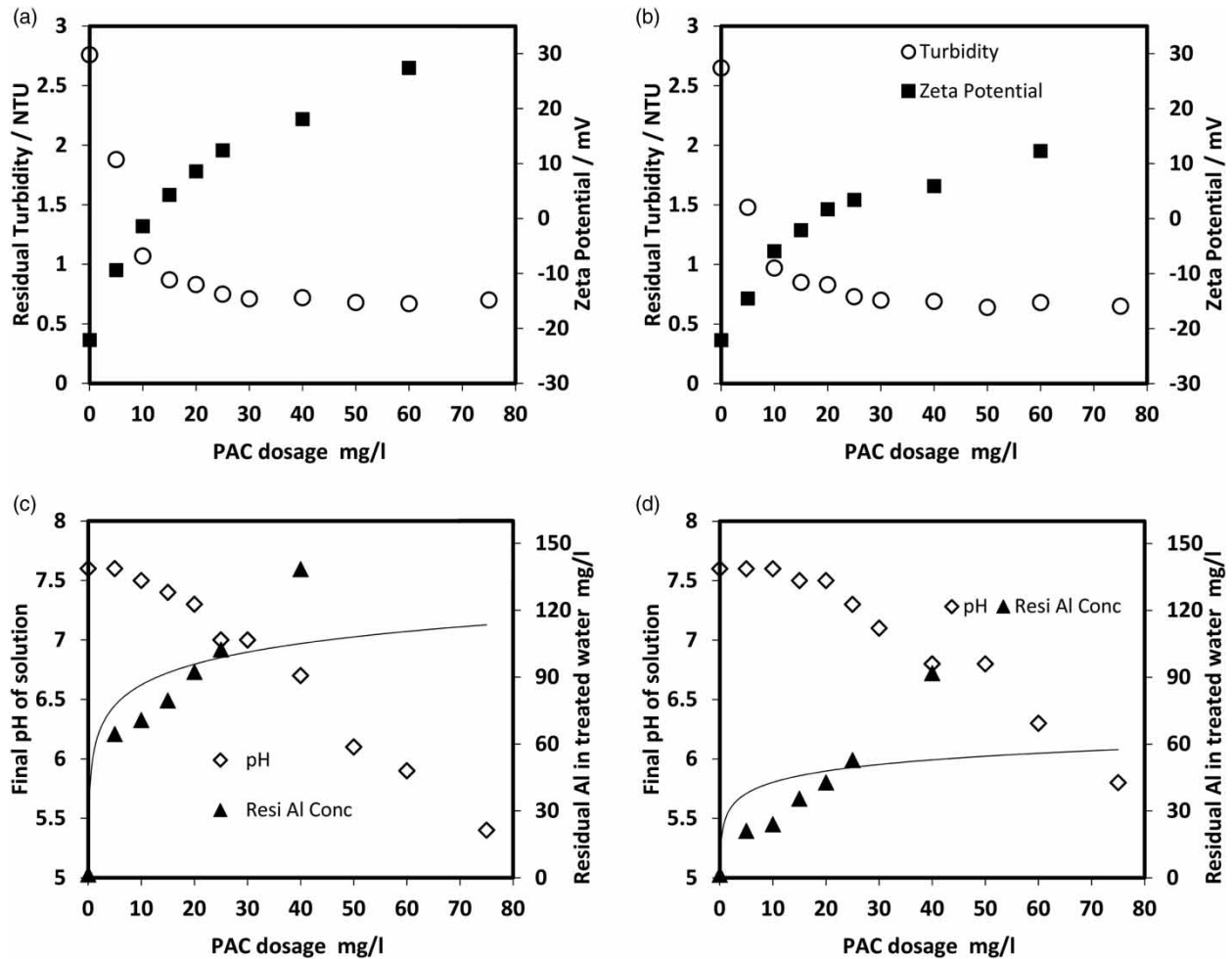


Figure 2 | Effect of PACI dosage on the residual turbidity (\blacksquare), zeta potential (\circ), final pH of solution (\diamond) and residual aluminium concentration (\blacktriangle) in the treated water for PAC-HB (a,c) and PAC-MB (b,d).

The zeta potential of water after adding the coagulant increases continuously and nearly reaches zero at optimum doses of 10–15 mg/L. An increase in zeta potential with dose concentration occurs as the hydrolysis product of PAC is positively charged. Indirectly, a change in zeta potential also gives inside of coagulant's optimum dose based on the charge neutralisation mechanism. As per ASTM the zeta potential of the solution should be (± 5) for strong coagulation-flocculation (Letterman 1999). Over and above the optimum coagulant dose, charge neutralisation occurs, and turbidity does not alter much as precipitated coagulant floc combines through the mosaic effect similar to the polymeric bridging (Dentel 1991). Gradual increase in zeta potential after the optimum dosage is mainly because of charge reversal of developed floc due to the restabilization mechanism (Yao 1987).

Comparatively, both HB-PAC and MB-PAC do not show much difference in turbidity removal behavior. In both cases, zeta potential crosses its limit of (± 5) at PAC doses of 10–15 mg/L, as shown in Figure 2(a) and (b). This indicates the optimum dose concentration for both PACs is 10–15 mg/L; above that the mosaic effect dominated the precipitates which start combining. At the same time, the charge neutralization occurs slightly earlier for HB than that of MB PAC. Ye *et al.* (2007) also found that the zeta potential for high basic PAC increases quicker than less basic PAC. This may be linked to the change in the solution pH after PAC addition at the same dosage, as shown in Figure 3.

The mechanism of turbidity removal by the PAC is influenced by various factors, including the pH of the solution, concentration PAC dosing, temperature of solution, and other water quality parameters. The pH of the solution decreases with the addition of PAC, mainly due to PAC hydrolysis, Figure 2(c) and (d). The high basic PAC (HB-PAC) lowers the pH of water to a

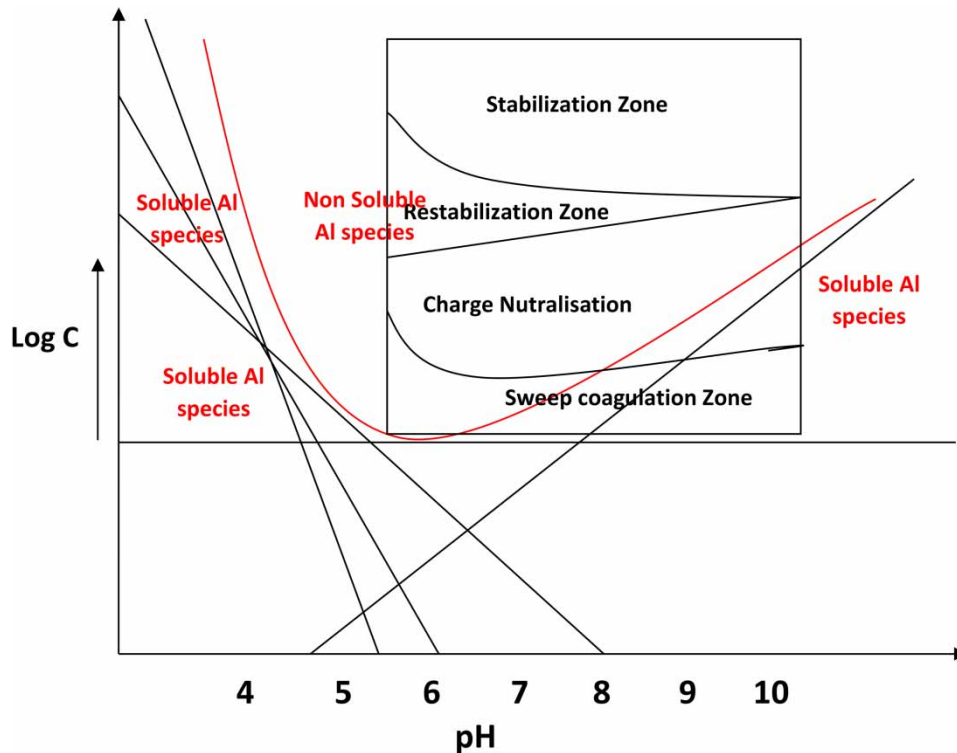


Figure 3 | Coagulation zones and different types of aluminium species formed at different solution pH.

greater extent than the lower basic PAC (MB-PAC). This could be one of the significant factors for the quicker increase in the zeta potential in the case of HB-PAC compared to MB-PAC. The solution's pH plays a vital role in the coagulation mechanism and ultimately in the coagulant's performance. The optimum PAC precipitation occurs at pH 7–9, and it gets affected below and above the optimum pH.

The residual Al concentration in the treated water increases over and above the optimized PAC dose concentration. Comparatively, more residual Al concentration is observed in the case of HB-PAC than MB-PAC (Figure 2). The enhanced residual Al is well explained by pH reduction of the solution with PAC dosing and the change in coagulation mechanism at lower pH. This is well defined by the PC-pH diagram of Al, as shown in Figure 4. Over and above the circumneutral pH, the solubilisation of Al in treated water increases due to the formation of different Al phases. Al forms various monomeric ($\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})_3$, $\text{Al}(\text{OH})_4^-$), polymeric ($\text{Al}_2(\text{OH})_2^{4+}$, $\text{Al}_2(\text{OH})_3^+$) and amorphous species. All species formed have different solubility constants at specified solution pH.

At circumneutral solution pH, the polymeric form of $\text{Al}(\text{OH})_3$ is the most stable and dominating species, whereas with decreasing pH of $\text{Al}(\text{OH})_2^+$, $\text{Al}(\text{OH})^+$, and Al^{3+} initiated the dominating the speciation. The formed $\text{Al}(\text{OH})_3$ is the most stable species and it has low solubility constant and is responsible for neutralizing the negative charge and stabilizing non-settleable turbidity particles by the coagulation-flocculation mechanism (Holt *et al.* 2005; Bendsdoka *et al.* 2008).

The mechanism at optimum pH is charge neutralisation. In the pH range of 6–8 four main coagulation zones occurred, i.e. stabilisation, charge neutralisation, destabilization, restabilization and sweep, as shown in Figure 3. At pH 10, restabilisation step gets missed, whereas below pH 6, the typical sweep zone gets missed (Wei *et al.* 2015). Out of all the mechanisms, PAC's best coagulation efficiency occurred mainly by charge neutralisation or the sweep coagulation mechanism. The type and concentration of the specified species is the function of the final solution pH. At low pH of around 6.0, charge neutralisation of PACl generally starts at an Al concentration of around 2.2 mg/L, whereas with increasing pH in the range of 8–10 it will require Al concentrations as low as 0.8 mg/L. Al concentration in treated water depending on the kind of species formed, as shown in Figure 3.

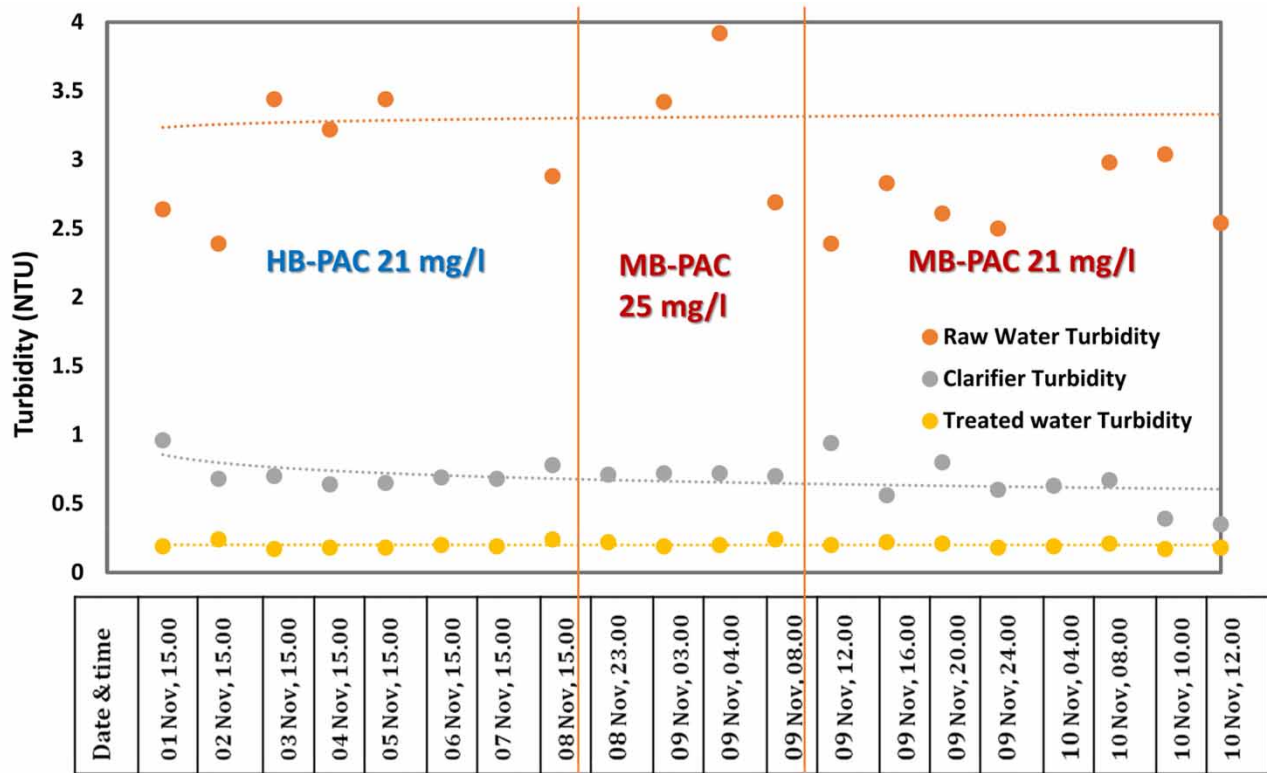


Figure 4 | Effect of changing PAC type and dose on the various parameters of Surajpura WTP.

3.2. Effect of different coagulation technology in WTP

To understand the effect of different sedimentation technology use in the Kekri and Surajpura WTPs on its turbidity removal, efficiency was studied in detail. In the present study, the raw water source and water collection point for both the WTPs is the same. The only difference is that water is transported 42 km for Kekdi WTP and 10 km for Surajpura WTP from the dam through separate pipelines. The turbidity and pH variations of Bisalpur dam water over the year is given in Table 2. The turbidity and pH of the water do not show much variation with seasonal change.

The raw water collected from the Kekri and Surajpura WTPs show a similar kind of activity towards the added PAC coagulants in terms of turbidity removal during laboratory experiments. The 10–15 mg/L PAC coagulant dosing is required to reduce the turbidity of treated water below the acceptable limit of 1 NTU.

During the actual working, the Kekdi WTP was found to be operational at the MB-PAC dose 5–10 mg/L to remove turbidity below the acceptable limit, whereas at Surajpura WTP the HB-PAC dose of 21 mg/L was in use to remove the turbidity below the acceptable limit of 1 NTU (Table 3).

Table 2 | Change in the turbidity and pH of raw water from Bisalpur dam over the year

Sr. No.	Month	Turbidity (NTU)	pH	Color (Hazen Unit)	Sr. No.	Month	Turbidity (NTU)	pH	Color (Hazen Unit)
1	Sep	12.3	7.6		8	Apr	4	7.6	
2	Oct	6.4	7.8		9	May	3.3	7.7	
3	Nov	4.3	7.6	3.4	10	Jun	3.3	7.7	
4	Dec	2.9	7.6		11	July	3.2	7.7	
5	Jan	4.1	7.7		12	Aug	3.6	7.4	
6	Feb	4.2	7.8		13	Sep	2	7.4	15
7	Mar	4.2	7.7		14	Oct	2.5	7.5	12.8

Table 3 | Physico-chemical parameters of samples collected from Kekri and Surajpura WTP

WTP	Dose of PAC	Sampling location	Turbidity (NTU)	Color (Pt-Co unit)	Total Hardness (mg/L)	Alkalinity (mg/L)	Chloride (mg/L)
KekriNew WTP	5 mg/L (MB-PAC)	Clarifloculator outlet	1.23	13.7	126	119	50
		Treated	0.77	10.9	126	121	52
KekriOld WTP	5 mg/L (MB-PAC)	Clarifloculator outlet	0.94	11.8	126	122	53
		Treated	0.46	9.7	122	124	50
Surajpura WTP	21 mg/L (HB-PAC)	Pulsator outlet	0.8	6.8	126	123	56
		Treated	0.47	5.5	122	119	58
Surajpura WTP	25 mg/L (MB-PAC)	Pulsator outlet	0.91	8	128	111	54
		Treated	0.42	6.7	126	102	56
Surajpura WTP	21 mg/L (MB-PAC)	Pulsator outlet	0.91	8.7	128	114	57
		Treated	0.41	4.8	124	110	58

The PAC dose in use at Surajpura WTP was around 3–4 times more than that of Kekri WTP. For the same raw water, both WTPs were using different PAC dosing. This difference in the PAC dose requirement may be attributable to the different types of sedimentation technology used at both the WTPs. The only difference is the type of PAC, at Kekri WTP the medium basicity PAC (MB-PAC) was in use whereas at Surajpura it was high basicity (HB-PAC)

To compare both the WTPs it was decided to change the PAC type from HB-PAC to MB-PAC at Surajpura WTP. The shifting of around 600 MLD working WTP from HB-PAC to MB-PAC was a large and challenging task. Looking towards the sensitivity of the situation and the intention of not disturbing the WTP much, initially on the safer side, a dose of 25 mg/L MB-PAC was incorporated by keeping all other WTP parameters constant. Pulsator-based WTP shifting makes it more complicated due to the highly sensitive floc blanket at the clarifier, which can get disturbed with small changes in water chemistry. During this transaction, changes occurring in the entire WTP and treated water were closely monitored with the time interval of 1 hr. Even after 12 hours of changing PAC type, the changes in the WTP, including pulsator outlet and treated water turbidity, were not seen, as depicted in [Figure 4](#). The floc size and its movements in the pulsator and at the pulsator outlet was not altered by changing the PAC type.

Assuming the WTP was stable at 25 mg/L, the dose of MB-PAC was reduced from 25 to 21 mg/L and the WTP was monitored for any changes in the floc size, quantity, its appearance and settling behavior in the pulsator for 30 hrs post-dose changes. After reducing the MB-PAC dose from 25 to 21 mg/L the slight variation and fluctuation in the pulsator outlet's turbidity were observed. The small-sized flocs were seen moving in the pulsator's outer surface and in the launders. These flocs were continuously in motion and coming towards the water's surface and in small quantities entered into the launders along with water in almost all chambers. It shows that the pulsator's sludge blanket gets disturbed due to PAC type and dose concentration changes. This concludes that the pulsator based clarifier is highly sensitive towards the small change in operating conditions and water chemistry. These small-sized flocs from launders were further arrested in the sand filtration media, and ultimately the treated water turbidity was unaltered ([Figure 4](#)). The overall study reveals that the Surajpura WTP was functioning well at the the HB-PAC dose of 21 mg/L. A small change in the PAC dose and chemistry leads to disturbances in

Table 4 | Coagulant cost comparison for different PAC types at Surajpura WTP

WTP treatment capacity (MLD)	PAC Type	PAC dosing (mg/Liter)	Total PAC (kg/Day)	Price per kg of coagulant ^a (Rs.)	Coagulant cost per Day (Rs. in Lacs)	Coagulant cost per Year (Rs. in Lacs)	Annual coagulant cost saving (%)
600	HB	21	12600	35	4.41	1609.7	–
600	MB	21	12600	24	3.02	1103.8	31.4
600	MB	10	6000	24	1.44	525.6	67.3

^aPrices were taken from online selling sites.

the sludge blanket in the pulsator. It is concluded that the pulsator based clarifier is more sensitive compared to the conventional clariflocculator.

The higher coagulant dose usage leads to more operation and maintenance costs of water treatment. The shifting from HB-PAC to MB-PAC at the same dose of 21 mg/L leads to a reduced 31.4% coagulant cost reduction whereas the further decrease in MB-PAC dose to 10 mg/L leads to 67.3% coagulant cost reduction, as shown in Table 4.

4. CONCLUSION

Different sedimentation technologies on the efficiency of conventional water treatment plants (WTP) have been investigated in detail. The well-known and popularly accepted and installed clariflocculator and pulsator-based sedimentation technologies have been chosen for comparative study. The effect of different basicity of polyaluminium chloride (PAC) coagulant to remove turbidity from surface water was evaluated by laboratory experiments and in two different working WTPs of various capacities. The overall conclusion is that the PAC's different basicities do not impart much effect on the turbidity removal efficiency, especially at low turbidity of around 3–5 NTU. Most of the turbidity gets removed at the dose concentration of 10–15 mg/L. The concentration of soluble Al and zeta potential increases with increasing the dose of PAC in treated water. The sedimentation is the most crucial part to decide the economic feasibility of conventional WTPs. The different sedimentation technologies behave differently with an added coagulant and require dissimilar amounts of coagulant to reduce the turbidity below an acceptable limit. The clariflocculator based WTP requires only 5 mg/L of PAC dose to remove turbidity below the acceptable limit of 1 NTU. In contrast, the pulsator-based WTP requires a PAC dose of 21–25 mg/L to comply with the purpose. The floc blanket in the pulsator-based WTP gets disturbed with slight variation in the coagulant dose and type. It shows that the clariflocculator based WTP is quite robust and economically viable, whereas the pulsator based WTPs are more sensitive towards the slight change in working parameters and water chemistry.

DATA AVAILABILITY STATEMENT

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

REFERENCES

- Aguilar, M., Saez, J., Llorens, M., Soler, A. & Ortuno, J. 2002 Nutrient removal and sludge production in the coagulation–flocculation process. *Water Research* **36**, 2910–2919.
- Bensdoka, K., Benammara, S., Lopicqueb, F. L. & Nezzala, G. 2008 Electro-coagulation of cutting oil emulsions using aluminium plate electrodes. *Journal of Hazardous Materials* **152** (1), 423–430.
- Camp, T. R. 1946 Sedimentation and the design of settling tanks. *Transactions of ASCE* **111** (6), 895–952.
- Cripps, S. J. & Bergheim, A. 2000 Solid management and removal for intensive land based aquaculture production system. *Aqua-cultural Engineering* **22** (1–2), 33–56.
- Dentel, S. K. 1991 Coagulant control in water treatment. *Critical Reviews in Environmental Control* **21** (1), 41–135.
- Edzwald, J. K. & Haarhoff, J. 2011 Seawater pretreatment for reverse osmosis: chemistry, contaminants, and coagulation. *Water Research* **45**, 5428–5440.
- Gregory, J. & Dupont, V. 2001 Properties of flocs produced by water treatment coagulants. *Water Science and Technology* **44**, 231–236.
- Heikal, H., El-Hafiz, A., EL-Baz, A. & Farghaly, S. 2017 Study the performance of circular clarifier in existing potable water treatment plant by using computational fluid dynamics. In: *XVI World Water Congress, International Water Resources Association, Mexico*, pp. 1–19. Available from: https://en.wikipedia.org/wiki/Bisalpur_Dam
- Holt, P. K., Barton, G. W. & Mitchell, C. A. 2005 The future for electrocoagulation as a localised water treatment technology. *Chemosphere* **59**, 355–367.
- Kawakami, T., Motoyama, A., Serikawa, Y., Amarasooriya, A. & Weragoda, S. K. 2016 The comparison of two water treatment plants operating with different processes in Kandy City, Sri Lanka. *Journal of Ecotechnology Research* **18** (1), 1–6.
- Kumar, N. & Balasundaram, N. 2017 Efficiency of PAC in water treatment plant & disposal of Its sludge. *International Journal of Applied Engineering Research* **12** (12), 3253–3262.
- Letterman, R. D. 1999 *Water Quality and Treatment: A Handbook of Community Water Supplies*. McGraw-Hill, New York.
- Lin, J., Huang, C., Chin, C. M. & Pan, J. R. 2008 Coagulation dynamics of fractal flocs induced by enmeshment and electrostatic patch mechanisms. *Water Research* **42**, 4457–4466.
- Packham, R. F. 1965 Some studies of the coagulation of dispersed clays with hydrolyzed salts. *Journal of Colloid Science* **20** (1), 81–92.
- Popa, I., Papastavrou, G. & Borkovec, M. 2010 Charge regulation effects on electrostatic patch-charge attraction induced by adsorbed dendrimers. *Physical Chemistry Chemical Physics* **12**, 4863–4871.

- Rice, E. W., Baird, R. B., Eaton, A. D. & Clesceri, L. S. 2012 *Standard methods for the examination of water and wastewater*. 22nd edn. American Public Health Association. Washington, DC.
- Salopek, B., Krasic, D. & Filipovic, S. 1992 Measurement and application of Zeta-Potential. *Rudarsko-geolosko-naftnizbornik* **4**, 147–151.
- Standard Practice for Coagulation-Flocculation Jar Test of Water ASTM D2035 – 80. 2003.
- Swamee, P. K. & Tyagi, A. 1996 *Design of class-I sedimentation tanks*. *Journal of Environmental Engineering* **122** (1), 71–73.
- Van Benschoten, J. E. & Edzwald, J. K. 1990 *Chemical aspects of coagulation using aluminum salts – I. Hydrolytic reactions of alum and polyaluminum chloride*. *Water Research* **24**, 1519–1526.
- Vepsalainen, M., Pulliainen, M. & Sillanpaa, M. 2012 *Effect of electrochemical cell structure on natural organic matter (NOM) removal from surface water through electrocoagulation (EC)*. *Separation and Purification Technology* **99**, 20–27.
- Wang, D. S., Tang, H. X. & Gregory, J. 2002 *Relative importance of charge neutralization and precipitation on coagulation of kaolin with PACl: effect of sulfate ion*. *Environmental Science and Technology* **36**, 1815–1820.
- Wang, H., Qi, J., Keller, A. A., Zhu, M. & Li, F. 2014 *Effects of pH, ionic strength and humic acid on the removal of TiO₂ nanoparticles from aqueous phase by coagulation*. *Colloids and Surfaces A; Physicochemical and Engineering Aspects* **450**, 161–165.
- Wei, N., Zhang, Z., Liu, D., Wu, Y., Wang, J. & Wang, Q. 2015 *Coagulation behavior of polyaluminum chloride: effects of pH and coagulant dosage*. *Chinese Journal of Chemical Engineering* **23**, 1041–1046.
- Wu, X., Ge, X., Wang, D. & Tang, H. 2007 *Distinct coagulation mechanism and model between alum and high al13-PACl*. *Colloids and Surfaces A; Physicochemical and Engineering Aspects* **305** (1–3), 89–96.
- Yang, Z., Gao, B., Cao, B., Xu, W. & Yue, Q. 2011 *Effect of OH⁻/Al³⁺ ratio on the coagulation behavior and residual aluminum speciation of polyaluminum chloride (PAC) in surface water treatment*. *Separation and Purification Technology* **80**, 59–66.
- Yao, C. H. 1987 *The Preparation of Polymeric Aluminum Chloride(PACl) and its Application in Water Treatment*. Johns Hopkins University Press, Baltimore, Maryland.
- Ye, C. Q., Wang, D. S., Shi, B. Y., Yu, J. F., Qu, J. H., Edwards, M. & Tang, H. X. 2007 *Alkalinity effect of coagulation with polyaluminumchlorides: role of electrostatic patch*. *Colloids and Surfaces A; Physicochemical and Engineering Aspects* **294** (1–3), 163–173.
- Yu, J., Wang, D., Yan, M., Ye, C., Yang, M. & Ge, X. 2007 *Optimized coagulation of high alkalinity, low temperature and particle water: pH adjustment and polyelectrolytes as coagulant aids*. *Environmental Monitoring and Assessment* **131**, 377–386.
- Yu, W. Z., Gregory, J. & Campos, L. C. 2010 *Breakage and re-growth of flocs formed by charge neutralization using alum and polyDADMAC*. *Water Research* **44**, 3959–3965.
- Zhao, Y. X., Gao, B. Y., Shon, H. K., Wang, Y., Kim, J. H. & Yue, Q. Y. 2011 *The effect of second coagulant dose on the regrowth of flocs formed by charge neutralization and sweep coagulation using titanium tetrachloride (TiCl₄)*. *Journal of Hazardous Materials* **198**, 70–77.

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