Develop an integrating coagulation and RO systems to treat highly turbid water using synthesized coagulants

Yogendra Singh Solankia, Madhu Agarwala,* and A. B. Gupta b

a Department of Chemical Engineering, Malaviya National Institute of Technology, Jaipur 302017, India
b Department of Civil Engineering, Malaviya National Institute of Technology, Jaipur 302017, India
*Corresponding author. E-mail: madhunaresh@gmail.com

ABSTRACT

In the present study coagulation process was used as pretreatment for the RO membrane with turbid raw water collected from Bisalpur Dam, Rajasthan, India. To optimize coagulation performance, three kinds of coagulants, namely, Alum (commercially available), synthesized inorganic polymeric coagulant-medium basicity (IPC-M), and inorganic polymeric coagulant-ultra high basicity (IPC-UH) were examined for turbidity removal with varying operating parameters. It was observed that in the optimum pH range of 6–7, the IPC-UH resulted as the best performing coagulant with 0.99 mg/L equivalent Al₂O₃ dose revealing 2 NTU residual turbidity and residual aluminium of 0.001 mg/L. Moreover, Langelier saturation index and Ryznar stability index values were evaluated at optimum conditions of all the three coagulants proclaiming negligible scaling potential. Furthermore, the coagulant-treated water (100 L) was fed to the RO membrane, and the performance was noted in terms of flux, pressure, and TDS. It was observed that IPC-UH has the lowest reduction in permeate flux of 0.78 L/min/m² compared to commercially available coagulant alum (0.90 L/min/m²). Also, the increased feed pressure was observed for all the coagulants treated water with the lowest value of 2.3 kg/cm² for IPC-UH, which was 2.5 kg/cm² for Alum (commercially available coagulant). Henceforth, integration of coagulation before the RO system resulted in effective pretreatment of turbid water with very minute scaling.

Key words: Alum, coagulation, IPC-M, IPC-UH, RO membrane

HIGHLIGHTS

• The hybrid treatment process for highly turbid water collected from Bisalpur Dam, Rajasthan was proposed.
• IPC-UH coagulant was found to be effective for turbidity removal in comparison to commercially available coagulant alum.
• The scaling potential of coagulant treated water were evaluated feeding coagulant treated water to RO membrane.
• IPC-UH treated water when fed to RO membrane resulted in negligible scaling.
1. INTRODUCTION

Impurities in surface water are undesirable due to their negative impact on the health of living organisms (Birhanu & Leta 2021). The contamination by these impurities could be in the form of dissolved or colloidal particles. The presence of colloidal particles makes water turbid. Majorly, species responsible for turbidity in water include suspended particles, clay, silt, bacteria, algae, and undissolved solid particles (Soros et al. 2019). These adhering species in groundwater are challenging to remove because of their microscopic size and static nature (Zand & Hoveidi 2015). These particles have very small dimensions and are electro negatively charged, resulting in inter-colloidal repulsions and interactions between the ionic species, are generally named as colloids by investigators and reported that colloids have a very slow sedimentation rate due to very small diameter (Mazloomi et al. 2018; Ozbey-Unal et al. 2018). According to the World health organization (WHO) norms and Bureau of Indian Standard (IS:10500) guidelines, the acceptable limit of turbidity in drinking water should be less than 2 NTU (World Health Organization 2011; Standards 2012). Therefore, raw water with high turbidity is not acceptable for drinking purposes, and for the same efficient treatment approaches need to be explored.

However, investigations were performed for removing such elements responsible for causing turbidity in water using techniques like coagulation, flocculation, settling, and filtering (Yang & Kim 2009; Dubey et al. 2018b; Solanki et al. 2019, 2020b).
As reported by earlier reports for turbidity removal, the coagulation was revealed to be feasible due to its ease in operation, cost-effective, appropriate for rural areas, and negligible energy requirement (Gaikwad & Munavalli 2019). Coagulation comprises two stages, namely, floc formation and agglomeration, followed by sedimentation (Umar et al. 2016). The fundamental mechanism behind coagulation is the interaction between destabilized particles supported by the slant of a slow mixture (Moussa et al. 2017; Samrat et al. 2018). These destabilized particles clump together to create a floc that can be easily removed by precipitation. There are many commercially available coagulants like alum, PACl, Ferric chloride, ferric sulfate that have been employed for turbidity removal. However still, there is scope for improving their performances in terms of sludge generation, sedimentation rate, and percent turbidity removal efficiency. Malik et al. (2018) used alum for turbidity removal and found 92% turbidity removal with a dose of 250 mg/L at 250 NTU initial turbidity (Malik 2018). However, alum faces issues like a sharp drop in pH when it is added to the water. Hence, it requires equivalent alkalinity doses to neutralize the water resulting increment in TDS of treated water and a higher amount of sludge generation (Kaggwa et al. 2001). Other limitations include high maintenance cost, large space requirements, and residual aluminum concentrations in the treated water. High aluminum concentrations in water have been associated with Alzheimer’s disease and other carcinogenic effects in humans (Halder et al. 2019; Singh Solanki et al. 2019). Furthermore, Poly aluminum chloride was used to treat the turbid water to overcome alum-associated challenges. Kanika et al. (2019) used PACl and found 60% removal efficiency with a dose of 5 mg/L at 10 NTU initial turbidity. These investigations suggested that PACl shows better turbidity removal performances than alum, such as low dose requirements, increased sedimentation rates, high efficiency at a lower temperature, low sludge generation, and residual aluminum concentration (Saxena et al. 2019).

In surface turbid water treatment, ferric chloride-based coagulant was used. The coagulant is associated with a series of problems like creating color in the water that causes yellowish-brown spots on the object. Moreover, if its quantity in the treated water is more than one mg/L, it can lead to opacity and not pleasing taste in water because of the conversion of Fe²⁺ to Fe³⁺ in the air vicinity (Standards 2012). Furthermore, new coagulants that can perform better in turbidity removal, lower dose, low residual Al and colloids, liquid form instead of solid for better mixing need to be developed. In addition, drinking water purification involves RO treatment to remove excess dissolved salts and microbes harmful to human health. The pre-treatment of feed water before RO is necessary to prevent membrane fouling by colloidal particles expressed as turbidity. However, in the case of coagulant pretreatment, it is also essential to evaluate the impact of residual coagulants on the life of the membrane, its operational performance, and morphology. Therefore, the present article proposes integrating coagulation and RO systems to treat highly turbid water using synthesized coagulants. The coagulants synthesized in the previous research work (Solani et al. 2020a) were implemented in the present article for removing turbidity of water collected from the Bisalpur dam, which is the major source of drinking water in Jaipur Rajasthan (India). All the physicochemical properties were determined for the collected dam water sample and coagulant treated water stream and outlet stream of the RO system. The scaling potential of coagulant-treated water was determined in terms of LSI and RSI. Moreover, the parameters like flow rate, flux, TDS, and pressure drop for RO membrane were evaluated to analyze the integrated system performance.

2. MATERIALS AND METHODS

2.1. Chemicals

All of the chemicals utilized in the investigation, including aluminium sulphate (Al₂(SO₄)₃·16H₂O), calcium carbonate (CaCO₃), and hydrochloric acid (HCl), were purchased from Merck which were of analytical grade. Inorganic Polymeric Coagulants were synthesized using polymerization of aluminium tri-hydrate (Al₂O₃·3H₂O) with an aqueous solution of 32% hydrochloric acid as per our earlier publication (Solani et al. 2020a). Same coagulants were used in this study for a removal of turbidity.

2.2. Optimization of coagulation parameter

In order to evaluate the turbidity removal efficacy of different coagulants (alum, IPC-M, and IPC-UH), batch coagulation/floculation studies were carried out in a jar test apparatus at various operating conditions such as coagulants dose and pH (4–8). The dose of coagulants was optimized for particular initial turbidity and pH was optimized to find the maximum efficiency of coagulant with particular pH. Lime and dilute HCl was used to maintain the process pH at the desired value. To optimize the process parameters, 1,000 mL jars and paddle mixers were used in the experiments. First, the coagulants were added to the turbid water in the set doses and pH. After adding the coagulant, the contents in the jar were mixed for 5 minutes at a speed of
180 rpm, followed by 15 minutes of slow mixing at 20 rpm. The mixture in the jar was then allowed to settle for 30 minutes to separate solids from the liquid.

2.3. Evaluation of scaling tendency of coagulant treated water on RO membrane

Langelier Saturation Index (LSI) and Ryznar Stability Index (RSI) are two parameters that predict the scaling tendency of water based on its physicochemical properties. To calculate the LSI, the parameter like water’s alkalinity (mg L$^{-1}$ as CaCO$_3$ or calcite), calcium hardness (mg L$^{-1}$ Ca$^{2+}$ as CaCO$_3$), total dissolved solids (mg L$^{-1}$), actual pH, and temperature ($^oC$) were measured. pH as a master variable, LSI denotes the driving force for scale development and growth. The RSI algorithm is based on a correlation between an empirical database of scale thickness seen in water sources and associated water chemistry data. As indicated in Table 1, the LSI and RSI equations were used to calculate the scaling tendency of coagulant-treated water in the present study.

2.4. Impact of coagulant treated water on RO membrane

To specify the impact of coagulant treated water on RO membrane, experiments were carried out using the experimental setup shown in Figure 1. The coagulant-treated water was fed from the storage tank to the domestic spiral bound RO membrane (Vontron ULP1812-75) in dead-end mode using a booster pump, and the permeate flux, feed pressure, and TDS were measured, respectively. The RO membrane with the active membrane area of 4.2 ft$^2$ (0.38 m$^2$) and porosity of 0.0001 microns was used in all runs.

2.5. Analysis method

The turbidity of raw and treated water was measured using a Digital turbid meter (NAINA). The pH, TDS were measured using the Hanna multimeter (HANNA HI-5522), and the fluoride concentration was measured using fluoride ions selective electrode (Thermo-Orion Versastar). For analyzing the residual aluminum and sulphate concentration in the water samples UV-vis spectrophotometer (UV-1800, Shimadzu, Japan) was used (Siriangkhawut et al. 2013). Alkalinity, Hardness, magnesium concentration was measured by titration method (Manivasakam 2005). A flame photo meter was used to measure the concentration of calcium, Potassium, Sodium ions. Total organic carbon (TOC) was measured using a TOC analyzer (Shimadzu TOC-L). Membrane characterization was done to understand the morphology of both virgin and used RO membranes using scanning electron microscopy (SEM) operating with energy-dispersive X-ray spectroscopy (EDS) detector (Nova Nano SEM 450) under vacuum pressure of 15 kV. For detecting the functional group of RO membrane, Fourier-transform infrared spectroscopy (FTIR) was used in the scan range of 4,000–400 cm$^{-1}$.

3. RESULTS AND DISCUSSION

3.1. Physicochemical property of coagulant

The specific gravity, percent amount of relative basicity, chloride, and Al$_2$O$_3$ were examined by titration methods to get the physicochemical characteristics of the synthesized IPC samples (Tang et al. 2015), and the findings are reported in Table 2.
3.2. Physicochemical property of raw water

Bisalpur dam, Rajasthan, India water samples having turbidity 5–6 NTU was used for all the experiments. In order to find the seasonal effect on turbidity, water sample were collected in different year (2019, 2020, and 2021) in the month of June. The physicochemical property of collected raw water is listed in Table 3.

3.3. Turbidity removal by coagulation

3.3.1. PH optimization

Coagulation is pH dependent process, and its effect on turbidity removal was examined in the present investigation. Experiments were carried out by varying the pH (4–8) of water keeping all other parameters constant like coagulant dose (2 mg/L Al₂O₃ for IPC-M, IPC-UH, and 4 mg/L Al₂O₃ for alum), contact time, initial turbidity (5.8 NTU) as illustrated in Figure 2. It was noticed that maximum 67.24, 85.3, and 86.2% removal of turbidity was observed at pH 6.5, 6.7, and 6.6 with alum, IPC-M, and IPC-UH, respectively. The variation in turbidity removal with pH may be due to the minor formation of aluminium’s monomer, oligomer, and polymer species (Pommerenk & Schafran 2005; Zhao et al. 2008; Tang et al. 2015). Most of the aluminium species present in coagulant are in dissolve form below pH 6 and above pH 7 and not accountable for precipitation of hydroxyl ions with simultaneous co-precipitation of turbidity. This may be the reason for coagulants showing maximum efficacy for fluoride removal around pH 6.5.

3.3.2. Dose optimization

The effects of varying coagulant doses on residual turbidity and aluminum of water samples were shown in Figure 3, revealing that with an increase in the dose of each coagulant (2 to 5 mg/L for Alum, 0.75 to 2 mg/L for IPC-M, and 0.70 to 2 mg/L for IPC-UH in term of Al₂O₃), the residual turbidity decreases but the residual aluminum increases. The dose required in the case of both the IPC is 1/3 to that of the dose required in the case of Alum. This may be due to the formation of more polymeric ([Al₈O₈(OH)₆]²⁺) and oligomeric aluminum species ([Al₃(OH)₇]²⁺) and [Al₂(OH)₄.5H₂O]²⁺) having a positive charge relative
Table 3 | Physicochemical property of dam water with respective collected date (Standards, 2012; World Health Organization, 2011).

| Physicochemical property | Permissible limit |
|--------------------------|-------------------|
|                          | IS:10500 | WHO | 2019 | 2020 | 2021 |
| TDS (mg/l)               | 500      | 600 | 219  | 226  | 218  |
| Alkalinity (mg/l) as CaCO₃ | 200     | 600 | 154  | 151  | 152  |
| Hardness (mg/l) as CaCO₃ | 180      | 300 | 120  | 124  | 122  |
| Turbidity (NTU)          | <2       | <2  | 5.3  | 5.8  | 6.0  |
| Calcium (mg/l)           | 75       | 75  | 23.1 | 22.6 | 22.2 |
| Sodium (mg/l)            | 60       | 200 | 27.6 | 26.3 | 29.4 |
| Magnesium (mg/L)         | –        | 50  | 12.1 | 12.0 | 12.2 |
| Potassium (mg/l)         | No limit display | 12 | 3.4  | 3.4  | 4.2  |
| TOC (mg/l)               | No limit display | –  | 5.04 | 5.00 | 6.3  |
| Fluoride (mg/l)          | 1.0      | 1.5 | 0.30 | 0.31 | 0.37 |
| pH                       | 6.5–8.5  | 6.5–8.5 | 8.2 | 8.1  | 8.0  |
| Chloride (mg/l)          | 250      | 250 | 21.1 | 19.2 | 21.5 |
| Nitrate (mg/l)           | 45       | 10  | 2.31 | 2.40 | 2.29 |
| Aluminium (mg/l)         | 0.2      | 0.2 | BDL  | BDL  | BDL  |
| Sulphate (mg/l)          | 200      | 250 | 32   | 31   | 33   |

Figure 2 | Effect of process pH on residual turbidity with constant initial turbidity (5.8 NTU), constant coagulant dose of 2 mg/L Al₂O₃ for IPC-M, UH and 4 mg/L Al₂O₃ for alum.

to the monomeric species (Al₂(OH)₆·2H₂O) in case of IPC-UH (Solanki et al. 2020a). Moreover, polymeric species present in IPC show the net structure and bridging flocs formation during the coagulation process. To achieve the permissible turbidity (2 NTU), the optimized dose of the coagulants was 3.90, 1.04, and 0.99 mg/L for Alum, IPC-M, and IPC-UH, respectively (Table 4). On the other hand, the residual aluminum concentration in treated water was 74, 19, and 10 μg/L with Alum, IPC-M, and IPC-UH, respectively. This might be due to polymeric aluminum species with low charge density and a higher degree of polymerization present in IPC-M and IPC-UH (Bi et al. 2004). The outcome of the optimization in the process resulted in 0.99 mg/L to be the optimized dose of IPC-UH to achieve the desired turbidity (<2 NTU) and residual aluminum concentration (0.01 mg/L) of treated water.
Figure 3 | Impact on residual turbidity with varying dose of coagulants (Alum, IPC-M, and IPC-UH). The physicochemical property of coagulants (alum, IPC-M, and IPC-UH) treated water to achieve residual turbidity (<2 NTU) shown in Table 4.
3.4. Plausible mechanism for turbidity removal

The mechanism for turbidity removal by inorganic polymeric coagulants and alum was explored, revealing two prominent factors, including charge neutralization and precipitation, governing the process. There are three major Al species formed in the coagulation process: monomeric, oligomeric, and polymeric species (Dubey et al. 2018a). The monomeric, oligomeric, and polymeric Al species are dominant in the case of alum, IPC-M, and IPC-UH, respectively (Solanki et al. 2020a). The monomeric species lead to sweeping flocculation, resulting in various sized flocs, both big and small (Dubey et al. 2018b, 2018a). The bigger flocs settle fast, helping smaller ones settle through sweep flocculation, but very fine flocs are difficult to settle. However, polymeric species results in only bigger flocs through bridging mechanism leads to better separation of turbidity. Also, the ability of polymeric species to form a bridge between the particle leads to the formation of a net structure which may cause colloidal particles (turbidity) to be adsorbed on the inner and external regions of the structure (Lin et al. 2008). This might be a justification for IPC-UH to result in higher removal efficiency, and IPC-M followed a similar pattern. It was found that the electrical double layer formed by cationic species present in both IPC lead to the accumulation of polymeric compounds and amorphous hydroxyl groups to be precipitated with turbidity in the treated water. The mechanism is represented in Figure 4 for alum (sweep flocculation) and IPC (bridging flocculation).

3.5. Mathematical model to predict the scaling tendency of coagulants treated water

The LSI and RSI measurements derived from water quality parameters for the coagulants treated water and also used as indicators of the possible scaling conditions of the water. By utilizing pH, TDS, calcium and alkalinity concentrations from the coagulants treated water, the LSI and RSI were determined. The impact of coagulants dosage on LSI and RSI values of treated water were calculated and represent in Table 4. In case of all coagulants, the value of LSI is decrease with increment of coagulants dosage reveal that the scaling potential was decrease suggesting that scaling element may be precipitated with sludge during coagulation process. At coagulant dose of 2 mg/L, the LSI values are $-0.27$, $-0.17$, $-0.21$ for coagulant Alum, IPC-M, and UH respectively. The negative LSI value demonstrates negligible scaling impact of treated water on RO membrane (Taghavi et al. 2019). The RSI values were calculated for the same and plotted in Figure 5. An increase in RSI
Figure 4 | Plausible mechanism for turbidity removal by alum and IPC’S.

Figure 5 | LSI and RSI value of coagulants (Alum, IPC-M, and IPC-UH) treated feed with varying coagulant dose.
value has been observed with coagulant dose. At coagulant dose of 2 mg/L in term of Al₂O₃, the RSI values are 8.09, 7.94, and 8.01 for coagulant Alum, IPC-M, and UH respectively. In the RSI values for all coagulants are higher than 6 demonstrate negligible scaling impact of treated water on RO membrane (Ozbey-Unal et al. 2018).

3.6. Evaluation of RO membrane performance after coagulation

3.6.1. Alum treated feed

Alum treated water was fed to the RO membrane set up and the measured operating parameters (feed pressure, permeate flux, and TDS) with respect to time were shown in Figure 6(a) and 6(b). From the Figure it can be observed that feed pressure increased from 5.1 to 7.6 kg/cm² and permeate flow flux was decreased from 1.05 to 0.15 L/min/m². The permeate TDS was increased from 40 to 420 mg/L with increase in feed TDS from 229 to 2,771 mg/L. Figure 6(a) also reveals that more than 50% permeate flux was decrease in initial 4 hour due to the presence of fine flocs formed during coagulation process. The fine flocs may form a layer of solid and dissolved monomeric aluminium species on the surface of membrane leading to reduction in flux and increase in feed pressure (60% increase in initial 4 hour).

3.6.2. IPC-M treated feed

IPC-M treated water was passed through RO membrane, change in feed pressure, permeate flux, and TDS with respect to time were measured and present in Figure 7(a) and 7(b). The change in feed pressure from 4.9 to 7.2 kg/cm², decrease in permeate flow from 0.98 to 0.16 L/min/m², and increase in permeate TDS from 20 to 405 mg/L with increase in feed TDS from 220 to 3,687 mg/L were observed as depicted in Figure 7. From the pattern shown in Figure 7(a), gradual increase in feed pressure and decrease in permeate flux was observed due to gradually increase in feed TDS as shown in Figure 7(b).

3.6.3. IPC-UH treated feed

IPC-UH treated water was fed to the RO membrane and the resulting variations were presented in the Figure 8(a) and 8(b). It can be seen that during the operation the feed pressure was 2.5 kg/cm² reporting the decrease flux from 0.92 to 0.14 L/min/m². The study states that there was 51% reduction in permeate flux for 7.30 h and 34% reduction reported for last 2 h of operation. It can be evaluated that the overall reduction in permeate flux was 85%. The outcome pattern reveals that maximum variations in flux was due to gradual increase feed concentration when the system was operated at dead end mode. This may be observed from Figure 8(b) the feed TDS was increased from 225 to 5,820 mg/L indicating that most of the salts were discharged in the reject stream rather than deposit on RO membrane. In case of alum treated feed, the TDS increases from 245 to 2,720 mg/L indicating that the salts were deposited on the membrane. This was also justified by SEM image as shown in Figure 9.
3.7. Used membrane characterization

3.7.1. Fourier transform infrared spectroscopy (FTIR) characterization of RO membrane

Figure 9 shows the FTIR spectra of virgin and used RO membrane with different coagulants treated feed. The pattern was noted with sharp changes from alum to IPC-M and IPC-UH. The strong peak at 3,330–3,360 cm$^{-1}$ signifies the presence of OH bonds (He et al. 2015). Peaks near 3,312 cm$^{-1}$ was due to N-H stretching (Amines), and near 1,650 cm$^{-1}$ and 1,150 cm$^{-1}$ are of poly Sulfone support layer, present on the surface of the virgin membrane (Sagle & Freeman 2004). Disappearance of these peak in case of alum treated feed may be evidence that membrane surface was covered by deposition of salts on it as shown in Figure 9(b). The appearance of peak near 866 and 610 cm$^{-1}$ may be assigned to some stretching vibrations of a lattice of interlinked Al-O, with tetrahedral structure may be due to aluminium interlink species present on membrane surface (Saxena et al. 2019). The peaks near 1,398, 1,404, and 1,560 cm$^{-1}$ represents the finger print region for NH$_2$ Amide-II group, nitro group (N = O bend), and N-H bend (amines primary) in case of virgin membrane shown in Figure 9(a). Also, the same peaks were reported in the spectral scan of used membrane with IPC treated feed revealing the negligible scaling on used RO membrane surface (Figure 9(c) and 9(d)).

3.7.2. SEM with EDS analysis of membrane

SEM is often used as a combined characterization technique to provide detailed information on the size, shape, and structure of membrane material and foulants (Sagle & Freeman 2004). The surface morphology of virgin and used membranes is
located in Figure 10(a)–10(d). The SEM analysis of the virgin membrane shows the interconnected pores, and the microporous structure is often prepared from rigid polymeric materials with large voids, as shown in Figure 10(a) (Jamaly et al. 2014). SEM image of the used membrane with alum treated feed is shown in Figure 10(b). The membrane pores are not visible, and it might be due to scaling arising by the deposition of salts on the membrane surface (Gao et al. 2017; Ozbey-Unal et al. 2018). The outcome of scaling is the decrease in permeate flux and increase in membrane feed pressure, and the data obtained from RO membrane justify the fact. In the case of IPC-UH treated water feed shows negligible change on membrane surface as microporous structure and interlink pores are completely visible on the surface of the membrane as shown in Figure 10(d). This is a clear indication to recommend IPC-UH for pretreatment of RO membrane compared to alum as it is a well-known coagulant for turbidity removal. IPC-M closely follows this phenomenon through SEM characterization.

Energy Dispersive X-ray Spectroscopy (EDS) provide information about the elemental composition of a sample. The spectral patterns were recorded in Figure 10(e)–10(h), revealing that calcium-based scaling is in the majority for all the coagulants. The prominent deposition of calcium over the RO membrane was due to the reverse behavior of solubility of CaCO3 with respect to water leading to high hardness comprises carbonate alkalinity (Rahman et al. 2018). Apart from this, there were other peaks of aluminium and oxygen with high intensity in the case of alum as depicted in 10 (F), indicating residual aluminum and residual turbidity. However, these peaks were not dominating in case of IPC-M and UPC-UH proposing that IPC-M and IPC-UH treated water was less likely to cause deposition over the membrane surface as compared to alum treated water. The fact was supported by physio-chemical property analysis that there was negligible residual aluminum for IPC-M and IPC-UH treated water, leading to lesser scaling tendency. Therefore, IPC-M and IPC-UH could be suggested for treating high turbid water and suitable for improving the scaling potentials when used as pretreatment for the RO membrane system.
Figure 10 | SEM image and EDS analysis of (a and e) virgin membrane, (b and f) alum treated feed, (c and g) IPC-M treated feed, (d and h) IPC-UH treated feed.
4. COST ANALYSIS

4.1. Cost analysis for synthesis of coagulant (IPC)

Coat estimation for synthesis of IPC divided in two sections, (A) raw material cost, and (B) operational cost:

(A) Raw material cost:
- Aluminium trihydrate cost = Rs. 60/Kg
- Hydrochloric acid cost = Rs 500/L
- Aluminium metal cost = 143/kg

(B) Operational cost:
- Electricity consumption for 1 kg IPC synthesis: 2kW × 2 hr. × Rs. 6 = Rs. 24.0

Material cost for synthesis of 1 kg IPC-M = Rs. 324/kg
Material cost for synthesis of 1 kg IPC-UH = Rs. 324 + 5 = 329/kg
Total cost (material + operational) for synthesis of 1 kg IPC-M = Rs. 348/kg
Total cost (material + operational) for synthesis of 1 kg IPC-UH = Rs. 353/kg
Total Cost of Aluminium sulphate (Alum) Merck grade = Rs. 12,878/kg

Cost to treat 100 L water with initial turbidity of 5.8 NTU

(A) Material cost:
- IPC-M dose = 0.104 g @ Rs. 348/kg = Rs. 0.036
- IPC-UH dose = 0.099 g @ Rs. 353/kg = Rs. 0.034
- Alum dose = 0.390 g @ Rs. 12,878/kg = Rs. 5.022

(B) Operational cost:
- Electricity consumption in coagulation to treat 100 L water = 0.5kW × 2 hr. × Rs. 6 = Rs. 6

Total cost with IPC-M = Rs. 0.036 + Rs. 6 = Rs. 6.04/100 L
Total cost with IPC-UH = Rs. 0.034 + Rs. 6 = Rs. 6.03/100 L
Total cost with Commercially available Alum = Rs. 5.022 + Rs. 6 = Rs. 11.02/100 L

5. CONCLUSIONS

This study evaluated the efficiency of coagulants toward removing turbidity and the effect of coagulant-treated water on the performance of RO membrane with three kinds of coagulants. The turbid water sample was collected from Bisalpur dam, Rajasthan, India, with 5–6 NTU turbidity. The dose of coagulants was optimized in batch mode and found the amount required of IPC-UH is 0.99 mg/L Al₂O₃ to achieve set residual turbidity of 2 NTU, which was closely followed by IPC-M with a dose of 1.04 mg/L Al₂O₃. To achieve the same goal, the amount of commercially available coagulant (alum) was 3.99 mg/L Al₂O₃, which was four times more than the IPC-UH. The LSI and RSI values are -0.27, -0.17, -0.21 and 8.09, 7.94, 8.01 for alum, IPC-M, and UH treated water.

Moreover, the effect of coagulation on the performance of RO membrane as a pretreatment has been evaluated. In the case of alum treated feed, the feed pressure increased by 2.5 kg/cm² as well as permeate flux decreased by 0.9 L/min/m² for 100 L permeate at dead-end mode but in the case of IPC-M, IPC-UH feed pressure increased by 2.3 kg/cm² and permeate flow flux decreased by 0.78, 0.82 L/min/m². These phenomena conclude that most salts were discharged in the reject stream rather than deposit on the RO membrane in the case of IPC-UH treated feed. Furthermore, the lowest increment in reject stream TDS in the case of alum treated feed compared to IPC’s treated feed, indicating that more salts were deposited on the membrane in the case of alum treated feed. SEM with EDS characterization supported the finding, and obtained results suggest that IPC-UH and IPC-M are suitable for turbidity removal.

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DATA AVAILABILITY STATEMENT

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