International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 50 No. 2 May 2025, pp. 256-266

Turbidity Removal Efficiency Of Different Inorganic Coagulants During Water Treatment - A Review

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Abstract: Accessible drinking water sources, including ground and surface waters, are being polluted because of changing climates and other human activities. Turbidity is a critical factor in water treatment processes because it significantly impacts water quality, as it is a measure of the transparency of water, with turbidity increasing as the concentration of suspended particulates increases. This process removes turbidity from the surface water and converts dissolved organic matter into suspended colloidal material. Conventional iron and aluminum salts and synthetic polymers are commonly used as chemical coagulants for surface water treatment. Coagulation-flocculation is also the most conventional treatment process in water treatment plants.

The turbidity removal for Alum varies from 94.14% to 99%. The turbidity removal for PACl ranges from 88% to 99% and 77% to 99% for Ferric chloride coagulant. The alum and ferric chloride are among the most extensively used chemical coagulants in many countries.

Keywords: Coagulant, Water, Turbidity, Efficiency, Coagulation, Flocculation

1. Introduction

Drinking water demand around the world has increased enormously alongside rapid population growth. Accessible drinking water sources, including ground and surface waters, are being polluted because of changing climate and other human activities. Turbidity is a critical factor in water treatment processes because it significantly impacts water quality, as it is a measure of the transparency of water, with turbidity increasing as the concentration of suspended particulates increases(Dayarathne, Angove et al. 2022).

Producing drinking water from surface water sources involves various treatment steps, including flocculation/coagulation. This process removes turbidity from the surface water and converts dissolved organic matter into suspended colloidal material. Conventional iron and aluminum salts and synthetic polymers are commonly used as chemical coagulants for surface water treatment (Al-Wasify, Hamed et al. 2023).

Coagulation-flocculation is also the most conventional treatment process in water treatment plants. A large amount of residue or waste is produced during this process, called water treatment sludge. The constituents of this inescapable by-product vary depending on the characteristics of raw water, type and dosage of the used coagulants and the water treatment plant's operating conditions. (Yaghoobian, Zonoozi et al. 2022).

While water treatment plants produce safe drinking water, they inevitably produce waste products, as well. In the treatment process of drinking water resources, the contaminants that are unhealthy or undesirable for consumption are removed in water treatment plants.

The majority of drinking water treatment plants rely on coagulation and flocculation for the removal of turbidity, colour, natural organic matter and pathogens from raw water. Amongst the various coagulants used, the most

International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
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commonly used are aluminum sulfate and ferric salts (Salehin, kumar Kulandaivelu et al. 2020).

2. Water turbidity

Water turbidity is due to the presence of suspended material including algae, clay, silt, metal oxides resulting from soil erosion, silt, viruses, bacteria, minerals matters such as asbestos, silicate, fine particles of organic matter and soluble material.
Turbidity is also due to the presence of colloidal particles, which are characterized by a very low size (in the range 1 nm–1 µm): because of that, their removal by free settling or filtration is hindered. Furthermore, they also possess an electrical (mostly negative) charge on the surface which determines a repellent force between similar particles(Chiavola, Di Marcantonio et al. 2023).
Turbidity describes the cloudiness of water caused by suspended particles such as clay and silts, chemical precipitates such as manganese and iron, and organic particles such as plant debris and organisms. As turbidity increases, it reduces the clarity of water to transmitted light by causing light to be scattered and adsorbed. The turbidity can also indicate the presence of hazardous chemical and microbial contaminants, and have significant implications for water quality.

2.1. Source of turbidity

Sources of turbidity (river runoff, dredging) can be broadly classified as natural or anthropogenic. Natural turbid reefs have established and continue to grow under high turbidity conditions where particulate matter is continuously resuspended by wind-driven waves. In contrast, anthropogenic turbid reefs have experienced recent increases in sediment delivery due to changes in land use (coastal development, dredging, catchment deforestation, agriculture) and in sediment resuspension rates due to human activities (ship traffic, fishing trawlers), alongside climate change-driven increases in rainfall, resulting in greater land runoff (Zweifler, O'leary et al. 2021).

Human activities have resulted in higher levels of turbidity in aquatic systems due to increased sediment runoff from agriculture, urbanization, and mining activities into nearby water bodies. Previous research has suggested that as turbidity increases, fish may increase their mobility to counteract the reduction in low visual acuity and maintain prey consumption similar to those in clear water(Rodrigues, Ortega et al. 2023).

The main cause of turbidity in water is human activities. Some industries, such as mining and agriculture that

causes movement of particles and gets mixed up with water. It's caused by suspended or dissolved matter like

clay and silt fine organic and inorganic matter, soluble colored organic compound, algae etc (Singh and Kishor 2020).

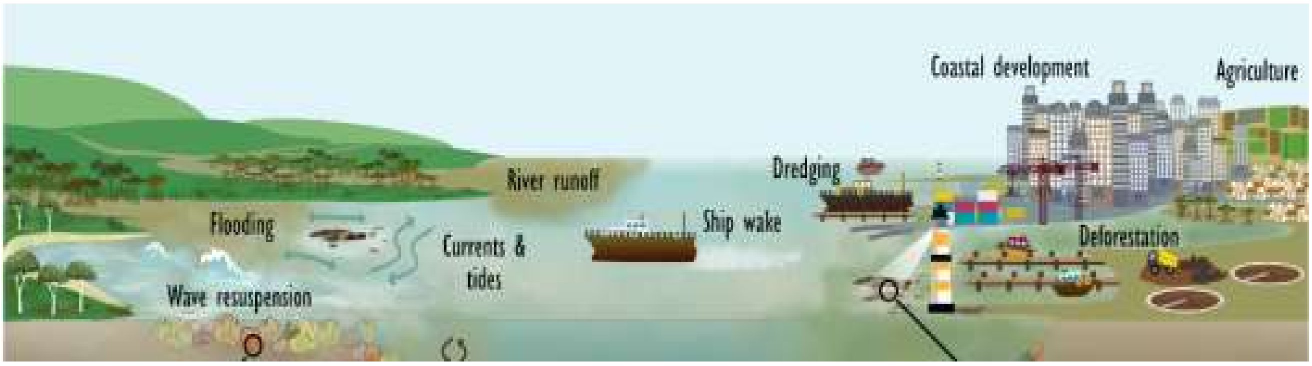

Figure 2.1. Sources of turbidity (Zweifler, O'leary et al. 2021)

2.2. Limits of turbidity according to different standards

Turbidity is a result of invisible particles measured in nephelometric turbidity units (NTU). The United States EPA and the WHO standards require turbidity to remain below 5 NTU, while the European standards limit turbidity to 4 NTU. Mean turbidity (NTU) for the following countries: Australia, Canada, German, Iceland, Ireland, Qatar, New Zealand, Singapore, United Arab Emirates, United Kingdom and United States varies from 0.1 to 2. The United Arab Emirates had the most turbid drinking water, while the United States, the United Kingdom, Ireland, Canada, and Singapore had the least turbid water (Karim, Guha et al. 2020).

Table 2.1. Limits of turbidity in the Drinking Water Regulations for the various countries

Countries	Regulatory Agencies	Turbidity (NTU)
All (WHO)	World Health Organization (WHO)	5
United States	Environmental Protection Agency	5
European Union	EU Drinking Water Directive	4
United Kingdom	Drinking Water Inspectorate	4
Canada	Health Canada	0.1
Germany	Federal Ministry of Health	1
Australia	National Health and Medical Research Council	5
United Arab Emirates	Environment Agency Abu Dhabi	4
Qatar	Qatar Electricity and Water Corporation	4
China	Ministry of ecology and Environment	1

2.3. Measuring turbidity

Turbidity is typically measured using a turbidimeter, which quantifies the amount of light scattered by particles in the water. The unit of measurement is called a 'nephelometric turbidity unit' (NTU). Lower NTU values indicate clearer water, while higher values indicate cloudier water (de Camargo, Spanhol et al. 2023).

2.4. Turbidity health issues

High turbidity levels can indicate the presence of harmful microorganisms and pollutants. Consuming water with high turbidity can lead to gastrointestinal issues and other health problems(de Camargo, Spanhol et al. 2023). Turbidity is problematic in drinking water treatment processes, causing issues such as high chemical demand in the coagulation process, head loss in sand filters, and membrane fouling. Natural organic matter (NOM) and clay particles are contributors to turbidity in most drinking water sources (Dayarathne, Angove et al. 2022). If the water has higher turbidity level it affects the human health. In water bodies such as lakes, rivers and reservoirs high turbidity levels can reduce the amount of light reaching to the lower depth of submerged aquatic plants spices. It also affects the ability of fish, shell fish gill to absorb the DO (dissolve oxygen) (Karim, Guha et al. 2020).

3.Water treatment process

3.1 Unities involved in water treatment

Raw Surface water undergoes several appropriate treatments after its capture. These treatments include pre-oxidation, clarification by coagulation/flocculation, sedimentation, filtration, and disinfection before being

distributed in drinking water pipelines. The coagulation/flocculation stage is the basic treatment to

remove suspended and colloidal matters. Hydrolysable metal salts based on aluminum or iron are frequently used to promote particle collision by neutralizing charge to ensure their destabilization, and their agglomeration into large aggregates, which are then separated by sedimentation and filtration.

Water treatment plants are facilities designed to correct the characteristics of influent water to the plant and make it suitable for its final use. Different treatments are therefore needed as both influent water and final uses vary widely(Benalia, Derbal et al. 2021).

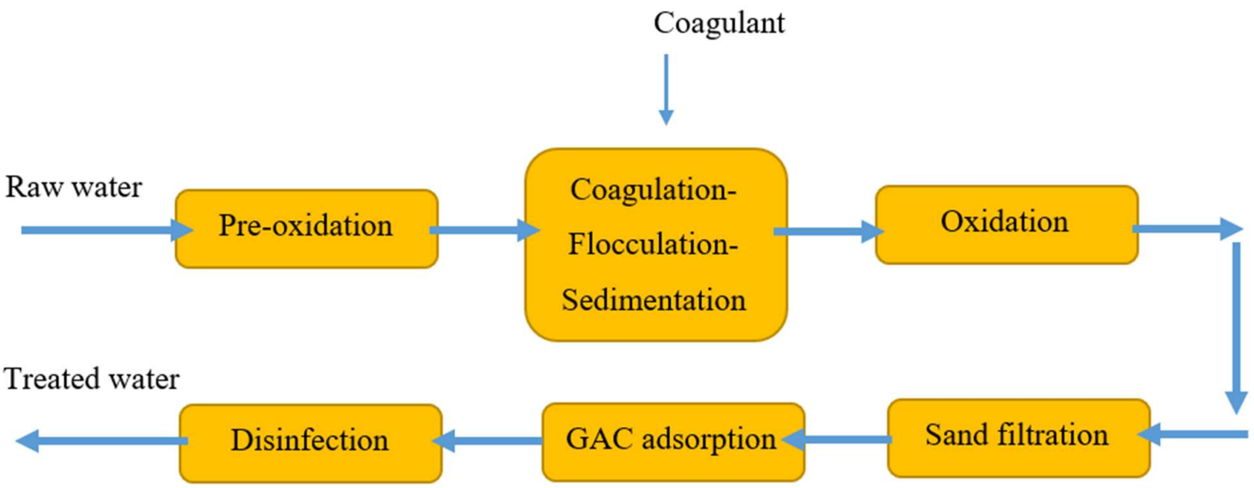

Figure 3.1. Layout of the drinking water treatment plant

Coagulation–flocculation is widely present in the water treatment plants with the aim to reduce the turbidity content. By adding positively charged coagulants under rapid mixing and pH-controlled conditions, the neutralization of the negative charges on the colloids is achieved and consequently the electric destabilization of the suspension takes place. After the addition of the coagulants under rapid mixing conditions, the particles can bind with the chemicals and each other to form larger particles (flocs); gentle mixing allows aggregation of insoluble flocs and their progressive size increase (flocculation). Finally, settling of flocs to the bottom of the unit leads to the accumulation of a chemical sludge, whereas a clear supernatant, being rid of turbidity, is formed above (Chiavola, Di Marcantonio et al. 2023).

3.2. Coagulation

The coagulation process involves adding iron or aluminum salts, such as aluminum sulphate, ferric sulphate, ferric chloride or polymers, to the water. These chemicals are called coagulants, and have a positive charge. The positive charge of the coagulant neutralizes the negative charge of dissolved and suspended particles in the water. When this reaction occurs, the particles bind together (this process is sometimes also called flocculation). The larger particles, or floc, are heavy and quickly settle to the bottom of the water supply. This settling process is called sedimentation (SDWF, 2023).

The mechanism for the removal of organics via coagulation has three main aspects: (1) positively charged metal ions and negatively charged organic colloids are electrically neutralized, destabilized and aggregated; (2) metal ions and soluble organic matter molecules form insoluble complexes and precipitates; and (3) physical and chemical adsorption of organics occurs on the surface of alum (Cui, Huang et al. 2020).

3.2.1. Factors affecting coagulation

Many factors can affect the efficiency, nature, amount of coagulant, pH, mixing speed, timing, mixing, time and temperature of the flocculation process (Zaki, Hadoudi et al. 2023).

As coagulation is often used as the first unit process in treating water to separate the suspended solids portion from the water, a precise application of coagulation process depends upon the understanding of the factors that affect the coagulation process and interaction between those factors. The pH and coagulant dosage are the significant factors affecting the removal efficiency of colloidal particles.

Coagulant dose

Coagulant dose affecting the agglomeration of colloidal particles through the amount of ionic species that is added into the system which can be absorbed by negatively charged colloidal particles and neutralize their charge.

The coagulant doses are determined by the operators for the coagulation process at water treatment plants which is a multi-factor approach based on raw and treated water quality(Shi, Chow et al. 2022). Proper coagulation ensures high removal efficiency of colloids and non-sedimenting suspension, as well as associated micropollutants (Rosińska, Dąbrowska et al. 2021).

pH

The predominance of a particular hydrolysis species during destabilization is greatly dependent on the pH value. At extremely acidic region such as pH 2, destabilization is significantly influenced by adsorption where excessive dosage of coagulant may lead to surface charge reversal and restabilization. While at higher pH around 5, the predominant species is negatively charged and from this phenomenon, it can be postulated that bridging mechanism might take place due to excessive surface charge covering which turns in restabilization of suspended particles. For the neutral pH values of 6 and higher, it is seen that restabilization does not occur(Asharuddin, Othman et al. 2021).

Besides the identification of optimal coagulation conditions that could be recommended for the corresponding water treatment plant, the importance of the solution pH is one of aspects of coagulation, which usually governs the coagulation behaviour of both pollutants and coagulants. In general, most colloidal impurities are negatively charged in the pH range common for natural waters (approximately pH 5–9) and are therefore colloidally stable and prevented from agglomeration as a result of electrical repulsions (Pivokonsky, Novotna et al. 2024).

Temperature

Temperature plays a critical role in turbidity removal by coagulation- a widely used method for removing suspended charged particles. Many factors involved in the coagulation/flocculation/sedimentation processes are site-specific, including temperature, pH, turbidity, NOM composition, and coagulant type. pH plays a significant role in coagulation as it changes the surface charge of suspended colloids which can have a large impact on coagulant use and dose (Dayarathne, Angove et al. 2022).

3.2.2. Types of coagulants

Aluminum and iron salts are the chemicals commonly used in the coagulation /flocculation process. However, these mineral coagulants can be costly and negatively alter the quality of the drinking water (Chiavola, Di Marcantonio et al. 2023).

The conventional approach is therefore to use prepolymerized coagulants. There are various types of prepolymerized coagulants, such as polyaluminum chloride (PAC), polysilicic acid (PSi), polyferric sulfate (PFS), etc. Among them, polyaluminum chloride is the most widely used in water purification in the world due to its fast flocculation speed and large floc size (Zhang, Yu et al. 2023).

Coagulant can be classified into natural, and chemical coagulants that were investigated as an agent through the coagulation process. Natural coagulants are classified as plant-based coagulants. Moreover, animal-based coagulants such as chitosan, and Micro-organisms-based coagulants.

Whereas applied chemical coagulants were categorized into three different classes; Hydrolyzing metallic salts as Alum, Ferric chloride, Ferric sulfate, and Magnesium chloride. The second class is Prehydrolyzing metallic salts that were represented in Polyaluminium sulfate, Polyaluminium chloride, Polyferric chloride, Polyaluminium ferric chloride, and Polyferrous sulfate. Meanwhile, the third class is synthetic cationic polymers such as aminoethyl polyacry-lamide, Polyamine Polyalkylene, Polyethylenimine, Polydiallyldimethyl ammo-nium chloride (El-taweel, Mohamed et al. 2023).

Coagulant chemicals come in two main types such as primary coagulants and coagulant aids. Primary coagulants neutralize the electrical charges of particles in the water which causes the particles to clump together. Chemically, coagulant chemicals are either metallic salts (such as alum) or polymers.

International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
Vol. 50 No. 2 May 2025, pp. 256-266

Alum is the aluminum salt considered the most economical. Polyaluminum (PACl) is used in drinking water treatment due to its cost and efficiency. PaCl has recently been recognized as an alternative coagulant because it is less sensitive to pH. Ferric salts are good but dangerous coagulants and should be handled with care. $FeCl_3$ is a coagulant that has proven effective in raw and industrial water treatment by removing organics and decolorizing(Zaki, Hadoudi et al. 2023).

Ferric Chloride works as a flocculant and coagulant. It is versatile in the water treatment industry and is an alternative to ferric sulfate. It generally promotes faster sedimentation, especially in cold water.

Ferric Chloride removes organics mainly through charge neutralization and adsorption-bridging, resulting in a good purification performance (Guo, Zhang et al. 2023).

In the water treatment process, alum and ferric chloride are amongst the extensively used chemical coagulants in many countries. They quickly react with water to give a variety of products containing cationic species, which can neutralize negatively charged particles. Although most of the coagulant used is retained in sludge during the sedimentation process, a part of it remains in finished water when important coagulation parameters such as pH, dose coagulant, and raw water turbidity were poorly controlled (Gobena, Adela et al. 2020).

Coagulation is responsible for particle destabilization which occurs through the addition of a chemical coagulant under rapid velocity gradient. It can be defined as a physical-chemical process that neutralizes electrical charges on particles surfaces, and also reduces colloids electrical double-layer repulsion forces. This allows microparticles to arrange into larger particles through collisions. Chemicals such as ferric chloride, aluminum chloride, aluminum sulfate and ferric sulfate are widely used as coagulants in coagulation processes (de Oliveira Anício, dos Santos Lopes et al. 2021).

3.3. Flocculation

The flocculation process is a solid-liquid separation process that can destroy the stability of dissolved impurities and colloidal impurities and produce large floc aggregates, which can be removed from the water in the subsequent filtration process (Wang, Chang et al. 2022).

The flocculation causes unstable particles to collide and

typically lasts from thirty to forty-five minutes. Flocculation is a step that follows coagulation and allows the size of the macromolecules to be agglomerated by the coagulants and adjuvants added to facilitate the aggregation phenomenon.

The efficiency of the flocculation process is impacted by several factors, such as the properties of the flocs formed, the dosage of coagulants and flocculants added, pH, temperature, and mixing rate (Zaki, Hadoudi et al. 2023).

3.4. Sedimentation

Gravitational sedimentation alone without coagulation can only remove coarse suspended solids such as sand and silt. Finer particles, however, will not settle in any reasonable time. Thus coagulants and flocculants must be added for these particles to get flocculated and produce larger particles that are settleable. Therefore, this condition indicates settling time plays a crucial role in the removal of turbidity (Asharuddin, Othman et al. 2021)

Several products, called coagulation aids, can increase the settling velocity, which improves sedimentation and separation of suspended particles in the treated water (Zaki, Hadoudi et al. 2023).

4. Turbidity removal by coagulants

4.1. Modal of turbidity removal from water

Turbidity is one of the most important parameter which governs the efficiency of coagulation-flocculation process. In this paper, different removal efficiencies of turbidity were discussed based on initial and final turbidities and different doses of coagulants used in water treatment processes. The turbidity removal can be calculated by the following formula below.

$$\text{Turbidity removal from water}(\%) = \frac{\text{Tui}-\text{Tuf}}{\text{Tui}} * 100$$

where T_{ui} and T_{uf} (NTU) are the initial and final turbidity in water, respectively(Salem, Almansoory et al. 2023).

4.2. Recent turbidity removal efficiencies

The finished water residual turbidity of 3.82 NTU (97.45% removal efficiency) was achieved upon the use of 25mg/L of alum. Whereas upon the use of 15 mg/L ferric chloride, the residual turbidity, 2.82NTU (98.12% removal efficiency) was observed(Gobena, Adela et al. 2020). Several coagulants such as Ferric chloride ($FeCl_3$), Titanium chloride ($TiCl_4$), and Aluminum chloride ($AlCl_3$), Nonionic polyacrylamide (PAM) and anionic polyacrylamide (aPAM), the turbidity removal efficiencies can range from 83% to 99% (Dayarathne, Angove et al. 2022).

The flocculation experiments results showed that the maximum turbidity removal rate for polymer-flooding wastewater could reached 98.3% at dosage of 120mg/L of PAC (Wu, Deng et al. 2023).

The removal efficiency of turbidity by PAC and polymeric ferric sulfate (PFS) were both above 90 % (Tang, Gao et al. 2023). Among the different chemicals tested, Polyaluminum chloride (PAC) provided the highest removal at the lowest dosage (90% at 3.5 mg/L PAC, 88% at 18.9 mg/L PACS and 77% at 30 mg/L $FeCl_3$)(Chiavola, Di Marcantonio et al. 2023).

The alum showed good efficiency towards turbidity removal (94.14%) compared to the other used coagulants i.e. $FeCl_3$ and MNPs (Magnetic nanoparticles). The efficiency was further improved (99.12%) when alum was used in combination with MNPs. (Kumari and Gupta 2020).

At a constant $FeCl_3$ dosage of 50 mg/L, it can be seen that effluent turbidity decreased as the reaction pH was increased from 5 to 7. Turbidity level dropped to 5.7 NTU (Saththasivam, Ogunbiyi et al. 2022).

Turbidity was reduced significantly from 6550 NTU in the raw dairy soiled water to a minimum of 6, 10, and 67 NTU for PACl, $FeCl_3$ and alum, respectively, at their highest doses (representing a reduction 99 %in turbidity)(Mohamed, Siggins et al. 2020). The effective

combination (catalytic ozonation of coagulated/ flocculated sample using PACl as coagulant) showed higher removal efficiency of turbidity 84% (Rizvi, Ikhlaq et al. 2022).

The optimal condition for the removal of turbidity was a coagulant dose of 12 mg/L at pH 13. For the optimal values, the $FeCl_3$ presented a maximum removal of 94.63 ± 0.98% for turbidity (Otálora, Wilches-Torres et al. 2022).

Coagulation using alum at concentrations between 5 and 10 mg/L Al produced water with turbidity less than 1.0 NTU from solutions containing 5 mg/L microspheres with an initial turbidity of 16 NTU (Skaf, Punzi et al. 2020).

The performance of CFAS was evaluated by domestic sewage, and the results indicated the best removal efficiency of turbidity of 93.8% (He, Shen et al. 2024).

With the dosage increasing from 1 g/L to 3.5 g/ L, the turbidity removal rate increased slowly and then gradually leveled off. PAFS achieved highest turbidity removal rate of 99 % at the dosage of 2 g/ L, PFS and PAC performed with 81.3 % and 68 % for, respectively(Shi, Wang et al. 2023).

The surface water samples had the turbidity of 9.3-11.2 NTU. For the coagulation process, pre-hydrolyzed polyaluminium chloride (PACl) coagulants was used. At the dose of 3 mg Al per litre used, the removal efficiency of turbidity was 80%. With regard to turbidity, the removal efficiencies were 88% and 94% for doses of 4 and 5 mg/L, respectively(Rosińska, Dąbrowska et al. 2021).

For three coagulants named Aluminum sulphate, Ferric chloride and Ferric sulphate were used for the treatment and it was found that a dose of around 450 ppm of Ferric chloride performed the best compared to the other two coagulants tested for the wastewater since it can achieve a 95.72 % turbidity removal (Dhrubo, Jannat et al. 2023).

International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

https://ijpsat.org/
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By using the ferric chloride ($FeCl_3$,40% as a coagulant, and Himoloc polyacrylamide, a cationic polymer, as a flocculant at an initial turbidity of 1559 ± 3.47 NTU, the results showed that the optimal pH was 6.87, the optimal coagulant dose was 7.89 g/L, the optimal flocculant dose was 12 ml/L, and the optimal stirring time was 22.8 min. In these optimal conditions, turbidity was reduced by 90.38 %(Bouyakhsass, Souabi et al. 2023).

Table 4.1. Summary of turbidity removal rate of different inorganic coagulants

Coagulants	Optimum dose (mg/L)	Initial turbidity(NTU)	Final turbidity(NTU)	Turbidity removal efficiency	Year	References
Alum	25	-	3.82	97.45%	2020	Gobena, Adela et al.
Ferric chloride	15	-	2.82	98.12%	2020	Gobena, Adela et al.
PAC	120	523 ± 1	-	91.3-99.3%	2023	Lingmin
PAC	50	60 ± 2	-	>90%	2023	Tang, Gao et al.
Polyacrylamide(PAM)	14.5	60 ± 2	-	>90%	2023	Tang, Gao et al.
Polyaluminum-ferric chloride (PCFA)	25	-	-	81.3%	2023	Yongjun Sun
PAC	3.5	15 -17	-	90%	2023	Chiavola, Di Marcantonio et al.
PACS	18.9	15-17	-	88%	2023	Chiavola, Di Marcantonio et al.
Ferric chloride	30	15-17	-	77%	2023	Chiavola, Di Marcantonio et al.
Alum	10-70	34	1.8	94.14%	2020	Kumari and Gupta
Ferric Chloride	50	66 ± 3	5.7	-	2022	Saththasivam, Ogunbiyi et al.
PAC	250	6550	6	99%	2020	Mohamed, Siggins et al.
Ferric Chloride	470	6550	10	99%	2020	Mohamed, Siggins et al.
Alum	168	6550	67	99%	2020	Mohamed, Siggins et al.
PAC	263.4	346	-	77.3%	2022	Rizvi, Ikhlaq et al.
Ferric Chloride	12	54.33± 1.51	-	94.63%	2022	Otálora, Wilches-Torres et al.
Alum	5-10	16	1	-	2020	Skaf, Punzi et al.
CFAS (Composite Ferric Aluminum Silicate)	150	105	8.51	91.90%	2024	Shaocang He

In this research, three of the most commonly considered coagulants in the process of turbid water treatment for their efficiency in reducing turbidity are aluminum sulfate (alum), ferric chloride, and polyaluminum chloride (PACl).

Coagulation–flocculation, sedimentation, and filtration units are commonly used in conventional treatment. The removal efficiency of all of these activities is highly reliant on particle size, which may normally be improved by aggregation of tiny particles in the coagulation flocculation sequence. The nature and quantity of colloidal pollutants, the kind and dosage of chemical coagulant, the usage of coagulant aids, and chemical features of the water, such as pH, temperature, and ionic character, all influence turbidity removal by coagulation. (Jasim, Azeez et al. 2022).

5. Conclusion

Conventional iron and aluminum salts and synthetic polymers are commonly used as chemical coagulants for surface water treatment. Coagulation-flocculation is also the most conventional treatment process in water treatment plants. Turbidity is one of the most important parameter which governs the efficiency of coagulation-flocculation process. The turbidity removal for Alum varies from 94.14% to 99%. The turbidity removal for PACl ranges from 88% to 99% and 77% to 99% for Ferric chloride coagulant. Alum and ferric chloride are among the most extensively used chemical coagulants in many countries. They quickly react with water to give a variety of products containing cationic species, which can neutralize negatively charged particles.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of Acronyms

NTU: Nephelometric Turbidity Units

WHO: World Health Organization

CFAS: Composite Ferric Aluminum Silicate

PCFA: Polyaluminum-ferric chloride

PAM: Polyacrylamide

PAC: Polyaluminium chloride

EPA: Environmental Protection Agency

EU: European Union

GAC: Granular activated carbon