

Enhanced Coagulation: Promising Findings and Challenges

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Abstract

The coagulation process remains one of the fundamental treatment techniques for treating water and wastewater. Enhancing the coagulation process is more and more a popular research topic. This work focuses on the implementation of chemical oxidation-enhanced coagulation (EC). It also discusses distinguished findings and innovations of EC and its main dares and trends. Pre-oxidation remains widely employed in dealing with water carrying algae and ameliorates coagulation by breaking the organic coating and modifying the surface potential of particles, even if precautions should be adopted to avoid algal organic matter release. EC remains importantly influenced by practical variables such as mixing conditions and coagulation process control. As a perspective, modeling mathematically EC is more than requested. Employing ozonation with GAC could also be adopted and estimated in situations where EC is utilized.

Subject Areas

Chemical Engineering & Technology

Keywords

Enhanced Coagulation (EC), Dissolved Organic Matter (DOM), Algae, Disinfection By-Products (DBPs), Charge Neutralization

1. Introduction

The coagulation process remains one of the most frequent phenomena in nature and industrially applied water treatment techniques [1]. During coagulation, colloids are merged into bigger flocs [2]. On such aggregates, dissolved organic matter (DOM) is adsorbed [3] [4]. Therefore, such pollutants could be eliminated during the next solid/liquid separation techniques (especially, decantation and sand filtration) [5]. The pathway for eliminating organic matter (OM) by coagulation possesses three major manifestations [6]. During the first one, positively charged metal ions (Fe³⁺, Al³⁺) and negatively charged particulate organic matter (POM) are electrically neutralized and aggregated [7]. During the second one, metal ions and DOM molecules constitute insoluble complexes and precipitates and finally, throughout the last one, physicochemical adsorption of DOM takes place on the surface of metallic hydroxide (*i.e.*, $Fe(OH)_{3(s)}$ or $Al(OH)_{3(s)}$) [3] [8]. Ecological contamination issues are worsening and water quality standards are beginning to be stricter; thus, traditional coagulation technique becomes inapt to remove DOM [9]. Therefore, enhanced coagulation (EC) and optimized coagulation were suggested founded on present water treatment plants and via taking into account the working circumstances of preceding and following stages to attain the target of advanced water treatment [10] [11] [12] [13]. EC adopts maximized total organic carbon (TOC) elimination as its unique aim, which is comparable with optimized coagulation (maximize turbidity, particulate TOC and DBPs precursor reductions, and minimize residual coagulant, sludge production and operating costs) in drinking water treatment practice [14] [15].

In fact, the idea of EC is suggested by the American Hydraulic Association in the 1990s in order to ameliorate the OM reduction via augmenting the injection of coagulant in the traditional coagulation method while assuring the elimination of colloids [16] [17]. Increasing the coagulant dosage is ensured by the coagulation pH circumstances [18]. Further, optimized coagulation is suggested founded on EC [19] [20] [21].

Lately, there is a growing interest in the study of EC [22] [23] [24]. Special focus was accorded to (1) comprehend the properties of OM in water supplies [25] [26], (2) define OM reduction rules to determine an OM reduction strategy [27] [28] and, (3) define the pathways of EC elimination of OM. Elevating OM removal performance is related not only to the coagulant injection and water pH, but also to the nature and distribution of the OM and solid matter in the water, implying the temperature, hydraulic condition, and coagulant morphology [29]. Since the idea of contaminants in water supplies is more and more extended and their removal is progressively more and more difficult [30], procedures to support coagulation are becoming more varied [31]. As an illustration, permanganate oxidation-assisted coagulation has been largely adopted to ameliorate turbidity, NOM, and algae removal during the coagulation method [32] [33]. Ballast microsand and magnetic powder could be viewed as fully developed techniques, comprising "Actiflo" technique and "CoMag" technique [13] [34] [35] [36]. Utilizing ballast technology is as well more ameliorated in dealing with wastewater. Researchers investigated the effect of introducing powdered activated carbon (PAC) or organoclay (OC) adsorbent and ferric chloride (FeCl₃) coagulant jointly on the coagulation efficiency [3] [37] [38]. They found that the turbidity of the clarified water was smaller if OC was injected throughout the coagulation stage and PAC reduced more than half or almost all of the dissolved aromatic compounds. Scientists employed synthetic hydroxyapatite in integration with chitosan and illustrated that it could efficiently eliminate 88% - 95% of copper and zinc ions. One more common research trend is suggesting and employing novel coagulants, like inorganic polymer flocculants, biopolymer flocculants and natural coagulants [39]. However, several issues appear below implementing EC [17] [40]. As an illustration, pre-oxidation risks to harm the cell membrane, conducting to toxin liberation and augmented taste and odor [41]. Further, introducing microsand will negatively influence the pump maintenance. Consequently, it is indispensable to investigate the running pathway, dares and novel revelation related to boosting the coagulation phenomena to decrease its drawbacks.

This work focuses on the implementation of chemical oxidation-EC. It also discusses distinguished findings and innovations of EC and its main dares and trends.

2. Chemical Oxidation-Enhanced Coagulation (EC)

Investigating chemical oxidization-EC remains one of the problem areas in the water treatment study [40] [42]. The major driving forces stay to decrease the poisoning of conventional oxidation and ameliorate the coagulation performance. In numerous water treatment plants, potassium permanganate (KMnO₄) pre-oxidation as an easy EC technique has been efficiently implemented [43]. Further, several pre-oxidants (like ferrate [44] [45] [46], ozone [47] [48], permanganate complex agents, persulfate, Fenton reagents (Fe²⁺ + H₂O₂) [49] [50] [51], and sodium hypochlorite [52] [53] [54]) have been suggested [13] [40].

2.1. Practical Concepts

Even if the route of pre-oxidation for ameliorating coagulation efficiency is not identical to other oxidants, the expansion of pre-oxidation is commonly pointed at varying the zeta potential via destroying the organic coating on the surface of the particles [55]. This will leads to formation of aggregates [13] [56].

2.2. Chlorine (Cl₂) and Chlorine Dioxide (ClO₂)

It is well known that chlorine is a disinfectant [57] [58]. Chlorine could be injected as an oxidant of a little polluted water (*i.e.*, surface water) to reduce color and taste. Chlorine has not been largely employed to ameliorate coagulation; however, chlorine as pre-oxidant has the potential to ameliorate coagulation and increase the reduction of algae cells [59] [60] [61]. For treating drinking water, chlorine dioxide is frequently produced from sodium chlorite reacting with Cl₂, hypochlorous acid, or hydrochloric acid. Identically to chlorine, ClO₂ pretreatment possesses a favorable influence on algae reduction. Scientists [13] proved that ClO₂ injection possesses an interesting capacity to decrease algae viability and oxidize ionic and complexed soluble manganese. Researchers [13] estab-

lished that the optimal injection of 0.5 mg/L of Cl_2 could avoid the eruption of *Pseudomonas aeruginosa*. Chlorine dioxide pre-oxidizing could demolish the cell walls of algae, conducting to the grave decomposition of membrane glycoproteins or some amino acids. Decreasing cell integrity using ClO_2 pre-oxidation considerably ameliorates the reduction of algae via the coagulation precipitation technique. Nevertheless, ClO_2 pre-oxidizing only possesses a restricted impact when dealing with surface water that carries little or no algae. Scientists [13] introduced 0.6 and 1.0 mg/L of ClO_2 for pre-oxidizing the potable water and noted no crucial amelioration in potable water quality. Further, NaOCl has the potential to infiltrate the cell membrane of *Microcystis aeruginosa* inducing the liberation of intracellular organic matter (IOM) and potassium ions (K⁺) from the cells, because of that demolishing cell chemosphere and increasing the reduction of the algae via coagulation.

2.3. 0₃

Ozone is a strong disinfectant and oxidant [47] [48]. Since 1906, it has been utilized in water treatment plants in Europe [13]. Ozone has several applications as it is employed to kill pathogens, decolorize, demobilize algae, and decrease inorganic substances [47]. In the water treatment industry, O_3 has numerous merits: (a) it neutralizes chlorine-resistant viruses and spores [27] [28] [30] [62]; (b) it is rarely influenced by sewage pH and temperature; (c) it eliminates color, odor, and phenols from sewage, augments the dissolved oxygen level, and ameliorates water quality; (d) it could increase the biodegradability of contaminants; and (e) it is hard to decompose and will not form side contamination due to residues. Consequently, it has been largely tested and utilized. Researches established that reasonable injections of O_3 ameliorate coagulation yield. Some interpretations have been suggested [13]: (1) O₃ oxidation could augment the level of oxygenated functional groups on solid surfaces (like carboxylic acids), conducting to complexation with cations (e.g., Ca²⁺, Mg²⁺, Al³⁺, etc.) and generation of metal humic acid complex precipitates [63]; (2) O₃ could transform high-molecular-weight compounds into low-molecular-weight compounds, decreasing space and electrostatic repulsion, and ozonation decreases the stabilization of organic chemicals that cover the surface of particles, which leads to their desorption; (3) ozonation polymerizes metastable organic compounds, which leads to particle aggregation via bridging reactions; (4) ozonation modifies the surface chemistry of organic chemicals and augments coagulation via charge neutralization.

As a pre-oxidant, O_3 has been largely utilized to ameliorate coagulation. Further, O_3 remains frequently employed to remove NOM, algae, heavy metal ions, humus, and dye wastewater. NOM is adsorbed on the colloids and minerals' surface [3]. Researchers [13] established that ozone could cause the aggregation of NOM. Other researchers [13] found that O_3 as a pre-oxidant possesses a more considerable influence on coagulating colloids in the water of moderate hardness than on coagulating colloids in soft water. Scientists [13] focused on the pathway of O_3 reduction of NOM and discovered that O_3 could induce colloidal instability only in the occurrence of calcium. They suggested a hypothesis founded on electrostatic complexation/charge neutralization and calcium oxalate precipitation: (i) the components of ozonated NOM could complex with calcium and, (ii) the ozonation of NOM augments the number of coordination sites on the surface and the complexation of NOM with calcium is comparatively easy. Numerous investigations [13] focused on the most important variables that touch the O_3 performance in coagulating NOM: the properties of the surface water (hardness, pH, alkalinity, and kind and level of NOM), O_3 injection, and coagulation parameters (*i.e.*, coagulant's injection and kind). As a pre-oxidant, O_3 could be employed in integration with additional oxidants (Fenton, permanganate, etc.). Applying O_3 as a pre-oxidant stays so promising to improve coagulation yield.

As a rule, only small quantities of O_3 could increase the coagulation performance, and, however, elevated injections of O_3 can augment the turbidity of the definitive water. The best injection of O_3 is at all times intimately linked to the NOM charge density. The higher the charge density of NOM is, the higher the needed injection of O_3 [13].

2.4. Permanganate

Permanganate illustrates elevated reactivity in oxidizing a large set of organic and inorganic compounds. Permanganate is mostly introduced to deal with odor and taste, reduce iron, manganese, and algae and work as a killing agent. The concept of permanganate pre-oxidation to ameliorate coagulation performance may be explained by the fact that permanganate is oxidized to form manganese dioxide (MnO₂), which is a powerful adsorbent and could elevate the flocculation dynamics via elevating the particle concentration. As a pre-oxidant, permanganate could efficiently reduce heavy metals and OM [13].

During the last thirty years, permanganate as pre-oxidant for enhancing coagulation efficiency has caught growing interest. In the water treatment plant, cyanobacteria could generate metabolites or toxins that are hard to eliminate via classical water treatment technology [2] [4] [41]. As a result, pre-oxidation techniques are largely employed (e.g., Cl₂, O₃, ClO₂, and KMnO₄). Since Cl₂ and ClO₂ could generate DBPs, KMnO₄ usage as pre-oxidant becomes largely employed. Indeed, scientists [13] noted that KMnO₄ could considerably ameliorate the coagulation of water via the production of the powerful adsorbent MnO₂, which adsorbs onto colloids' surfaces. Further, researchers [13] discovered that MnO₂ adsorbs humus only when Ca²⁺ is existing. Scientists [13] found that augmenting Ca^{2+} level, the settling velocity was importantly augmented and Ca^{2+} enhanced permanganate contribution via electrically neutralizing surface bridging. In addition to permanganate integration of algae flocs to augment settling velocity, the introduction of KMnO₄ could also cause algal cells to liberate OM. Scientists [13] proved that the flocculating performance of roughly destroyed algae is so minimal. Indeed, maters with extremely elevated molecular weight (MW) will bond to the coagulant, inducing its failure, which may also decrease the coagulation performance. Further, KMnO₄ is utilized at a usual injection (0 - 2 mg/L). Therefore, there is a small deterioration of algal cells. Researchers [13] examined the harm of the KMnO₄ injection to algae (KMnO₄ dosages were 1 mg/L, 2 mg/L, and 6 mg/L). A suitable injection of KMnO₄ (e.g., 2 mg/L) contributed to extracellular organic matter (EOM) secretion via algae. Researchers [13] illustrated that EOM could ameliorate the integration of algae flocs and MnO₂ and attain the aim of EC. Further, immoderate manganese (>2 mg/L) will touch the effluent water standard. As a rule, excess MnO₂ is reduced via a decantation tank throughout the water treatment, even if it augments the load on the sand filter and reduces the backwash cycle. The properties of the raw water require to be examined to guarantee the total transformation of the peracid salt into MnO₂. The drawbacks of KMnO₄ pre-oxidation are controlled to enhance coagulation to the highest level.

2.5. Ferrate

As an interesting chemical agent, ferrate could be viewed as coagulant and oxidant in dealing with water and wastewater [44] [45] [46]. It possesses a powerful redox potential (from 2.2 V in acidic pH to 0.7 V in alkaline conditions) [46]. Throughout the reduction of ferrate, with the formation of $Fe(OH)_{3(s)}$, hydrolyzed substances with an elevated positive charge could be formed [46]. Such hydrolysates will conduct to colloids, push the particles to be electrically neutralized, and adsorb water molecules and fine particles, therefore augmenting the settling velocity of the coagulation [44]. In only 1 min, ferrate could destabilize colloids, whilst iron salts require 30 min to reach stable findings [13]. Moreover, ferrate may be viewed as an emerging multifunctional oxidant, disinfectant, and coagulant. Ferrate does not form any DBPs in water treatment. It is a green water and wastewater treatment product [44] [45] [46]. It is well accepted that ferrate could efficiently reduce several organic and inorganic contaminants (e.g., nitrogenous organics, drugs, antibiotics, algae, etc.) and different metals (like Mn²⁺, Cu²⁺, Pb²⁺, Cd²⁺, Hg²⁺, Fe^{2+/3+}, Cr³⁺, etc.). Ferrate was found better than Fe(SO₄) below low-dose circumstances when dealing with colored solution. Ferrate has the potential to efficaciously decrease the UV₂₅₄ and turbidity of water. As a pre-oxidant, ferrate was successfully employed to ameliorate coagulation and deal with water carrying algae. Using electrochemical technology, scientists [13] fabricated potassium ferrate (K₂FeO₄) and proved that 1 mg/L K₂FeO₄ and 10 mg/L iron salt reached an identical treatment impact. The degradation velocity of ferrate is a function of the pH degree, water temperature, initial K₂FeO₄ dosage, and coexisting ions.

3. Enhanced Coagulation (EC): Distinguished Findings and Innovations

To satisfy requirements for water quality and algal control, Hu et al. [64] em-

ployed micro-ozone, KMnO₄, ferrate, and chlorine dioxide as pre-oxidants. Throughout chlorination and chloramination, the generation of usual carbonaceous disinfection by-products (C-DBPs) and emerging nitrogenous disinfection by-products (N-DBPs) was examined integrating numerous techniques: (i) coagulation-sedimentation-filtration (CSF), (ii) pre-KMnO₄/O₃/K₂FeO₄/ClO₂ matched with CSF, and (iii) pre-KMnO₄/O₃/K₂FeO₄/ClO₂ merged with CSF and pursued by granular activated carbon (GAC)/O₃-GAC advanced treatment. Micro-ozone pre-treatment integrated with CSF and O3-GAC illustrated the best efficiency in reducing chloroform (CF) and dichloracetonitrile (DCAN) precursors. Pre-oxidation had an unfavorable influence on chloropicrin (TCNM) and chloral hydrate generation, but a favorable influence on DCAN. Pre-oxidation $(KMnO_4, O_3, K_2FeO_4, and ClO_2)$ had a favorable impact on reducing overall cytotoxicity, and O₃ pre-oxidation merged with CSF pursued by O₃-GAC performed the best. Nevertheless, for reducing overall genotoxicity, the ClO₂ pretreatment illustrated the best findings, whether or not GAC or O3-GAC was implied. Such findings remain useful for regulating the design of the treatment processes in drinking water treatment plants.

Zhang *et al.* [65] assessed the possibility of combining high-basicity polyaluminum chloride (PACl) and high-viscosity chitosan coagulating low-temperature and low-turbidity water. Higher-basicity PACl with a larger fraction of Al_c (colloidal Al species in PACl) and smaller portion of Al_a (monomeric Al species in PACl) was useful in reducing turbidity and NOM, as well as controlling the remaining Al content. Moreover, combining PACl with high basicity (90.3%) and chitosan with high viscosity (500 mPa·s) achieved the efficient reduction of turbidity and NOM, with reduction performances of about 87%, 63%, and 82% for turbidity, DOM and UV₂₅₄, respectively (**Figure 1**). Larger and more settleable flocs tended to produce via the synergistic effect of charge neutralization by Al_b (polymeric Al species in PACl) and interparticle bridging by both the Al_c species and chitosan, as a result conducting to excellent coagulation efficiency. Such an investigation could give a helpful solution for dealing with low-temperature and low-turbidity water.

Besides EOM, IOM is also well removed by coagulation. IOM is also liberated from algae and is a significant precursor to DBPs in drinking water treatment [66]. Liu *et al.* [67] studied the coagulation efficacy of two Al salts: aluminum chloride (AlCl₃) and PACl (carrying 81.2% Al₁₃) focusing on the influence of Al species distribution on reducing IOM. PACl illustrated better performance than AlCl₃ in terms of eliminating turbidity and DOM, thanks to the higher charge neutralization impact and greater stability of pre-formed Al₁₃ species [68] [69]. The superiority of PACl in eliminating DOM can be attributed to the higher binding affinity between Al₁₃ polymer and the low and medium MW fractions of IOM [70]. There is a more important production of complexes between AlCl₃ and IOM, which benefits the reduction of tryptophan-like proteins thereafter. Moreover, PACl illustrated more important superiority juxtaposed to AlCl₃ in



Figure 1. Schematic diagram for proposed mechanisms of applying high-basicity PAC combined with chitosan with high viscosity for removing turbidity, DOC, UV₂₅₄ and simultaneously controlling residual Al content [65].

the reduction of <5 kDa and hydrophilic fractions, which are considered as the hardest to eliminate by coagulation.

In some countries like China, *M. aeruginosa* frequently blooms in summer whilst Cyclotella meneghiniana outbreaks in fall. As mentioned above, pre-oxidation can improve algae reduction before the coagulation stage. Nevertheless, the immoderate injection of pre-oxidant could augment the DBPs formation potential. Shi et al. [71] focused on the trichloromethane (TCM) formation, the changes of water quality indexes, and the morphology changes of algae from M. aeruginosa or C. meneghiniana contaminated water during $KMnO_4$ or Cl_2 pre-oxidation-coagulation-chlorination disinfection (Figure 2). TCM yield for the two algal species decreased with the injection augmentation of KMnO₄ pre-oxidation, but increased with the injection augmentation of pre-chlorination. Consequently, the 2.0 mg/L KMnO₄ or 0.5 mg/L Cl₂ was suggested as the best injection for preventing both M. aeruginosa blooms in summer and for C. meneghiniana outbreaks in fall. M. aeruginosa showed a slightly higher TCM yield than C. meneghiniana in such techniques. Taking into account the liberation of K⁺, KMnO₄ had less damage to cell integrity than Cl₂ at the injection \leq 2.0 mg/L. Further, *C. meneghiniana* was easier to be disrupted by both pre-oxidants than M. aeruginosa, combining with subsequent coagulation led to different value of DOM, UV-visible absorbance (UV₂₅₄) and turbidity.



Figure 2. Scanning electron microscopy (SEM) of *M. aeruginosa* before pre-oxidation (a); after 2.0 mg/L KMnO₄ pre-oxidation (b); after 2.0 mg/L pre-chlorination (c); and SEM of *C. meneghiniana* before pre-oxidation (d); after 2.0 mg/L KMnO₄ pre-oxidation (e); after 2.0 mg/L pre-chlorination (f). The experimental conditions are as follows: the concentration of *M. aeruginosa* and *C. meneghiniana* at 7.3×10^7 cells/L and 2.1×10^7 cells/L, respectively, pH at 7.0 ± 0.1 , and reaction time for 72 h.

Hussain *et al.* [72] investigated the efficiency of titanium trichloride (TiCl₃) as a coagulant for surface water treatment and juxtaposed it with traditionally utilized aluminum sulfate (alum). TiCl₃ illustrated a considerably bigger potential for reducing DOM at pH ~3 at which charge neutralization was observed to be the governing pathway for the flocculation. Such a phenomenon was more obvious from the relatively bigger floc sizes obtained with TiCl₃ application (**Figure 3**). Nevertheless, the destabilization of Ti-flocs took place at pH 4.5 via an adsorption-enmeshment route because of highly negative zeta potential. Moreover, TiCl₃ was more efficacious than alum in reducing humic substances. Combining alum and TiCl₃, either as the same chemical or both, illustrated better effectiveness than a single injection implementation. TiCl₃ can be an efficient solution for a water of low alkalinity and high DOM level and low pH wastewaters for the removal of hydrophobic compounds and particulate matter.

Several poisonous cyanobacteria manifest naturally with a filamentous, stacked cell arrangement named trichomes. Even if water treatment could be regulated to save cyanobacterial cells intact and avert the liberation of hazardous compounds, numerous physicochemical stresses encountered throughout the treatment technologies could lead to trichome truncation, reducing treatment efficacy by allowing single cells or short trichomes to reach the product water. This makes it easy for toxic compounds as well as OM to reach the distribution system. Pestana *et al.* [73] noted that genera (*Pseudanabaena, Planktolyngbya*) with short trichomes (<10 - 12 cells per trichome) are hardly influenced by the unit processes (loss of one to four cells respectively). However, genera (*Planktoltrix, Geitlerinema, Dolichospermum*) with longer trichomes (30+ cells per trichome) suffer from high degrees of truncation (up to 63, 30, and 56 cells per trichome, respectively). The occurrence of a rigid sheath and/or mucilaginous layer seems to provide some protection from truncation. Some unit processes



Figure 3. Micromorphology of alum (graphs (a), (c) and (e)) and TiCl₃ (graphs (b), (d) and (f)) flocs formed at optimum pH (3 for TiCl₃ and 6 for alum) and at coagulant dose of 16 mg/L, observed under SEM at various magnification levels (graphs a & b, 2500×; c & d, 30,00×; e & f, 300,000×) [72].

change the sensitivity or resilience of trichomes to disruption by physical stress. Some genera (*Planktothrix, Geitlerinema*) were sensitive to pre-oxidation making them more susceptible to shear stress, whilst *Dolichospermum* sp. seems more robust after pre-oxidation. Whilst the possibility of toxicogenic genera breaking through into the product water remains a real danger, in their research, Pestana *et al.* [73] did not note toxicogenic cyanobacteria. There is a necessity for plant operators to study the incoming cyanobacterial composition in the raw water in order to adjust treatment parameters and thus limit the potential of hazardous compound breakthrough.

Thanks to its physicochemical impacts that are not identical to those of chemical applications, the ultrasonic technology is becoming more interesting [74] [75]. Indeed, high-frequency ultrasound is recognized as an efficient technique since the theoretical resonance frequency of the gas vesicles in *M. aeruginosa* is in the high-frequency range (>100 kHz), which gives rise to gas vesicles collapse and alters the settleability of the algal cells. Li *et al.* [75] focused on the impacts of the ultrasonic frequency, acoustic power density, and duration on enhancing coagulation to reduce turbidity in algae-laden water. They examined

the morphology of algae cells, the modifications in EOMs, the zeta potential, and the formation of hydroxyl radicals. The frequency showed fewer influences than power and duration on coagulation. More severe cellular damages took place at 430 and 740 kHz than other frequencies. Sonication can induce the collapse of gas vesicles inside the cell (Figure 4). Such influence was attributed to the instantaneous high-pressure produced by the ultrasonic cavitation instead of the resonance. In addition, sonication would conduct to an elevation in proteins in EOM with continuous ultrasonic irradiation, showing that a small quantity of proteins can promote coagulation and that the accumulation of proteins would inhibit coagulation. Free radical content testing illustrated that the generation of excessive free radicals was frequently accompanied by a decrease in coagulation efficacy. The suitable mechanical impacts were the major pathway of ultrasonic EC. Consequently, the suitable ultrasonic condition was the one that conducted to a small amount of protein leakage and little formation of free radicals, which took place at 740 kHz and 0.02 W/mL in around 5 min, and would significantly enhance the turbidity removal rate in algae-containing water from approximately 80% - 90%.

4. Enhanced Coagulation (EC): Dares and Tendencies

As seen above, EC stays a more technical tool to remove OM, algae, and turbidity. With the continuous contamination of surface water, harder targets have been adopted for EC [40] [76].



Figure 4. Flocs photos after coagulation: (a) flocs without sonication (\times 6.00 k), (b) flocs without sonication (\times 20.00 k), (c) flocs with sonication of 740 kHz and 0.02 W/mL for 5 min (\times 6.00 k), (d) flocs with sonication of 740 kHz and 0.02 W/mL for 5 min (\times 20.00 k) [75].

Juxtaposed to the traditional coagulation, EC possesses considerable merits in increasing the elimination yield of DBPs and their precursors [77]. In addition, experimental optimization design employing orthogonal experimental design, response surface optimization design, uniform design and neural network system are employed [40] [76]. Such procedures could regulate the circumstances of EC dosage, pH, etc., thus ameliorating the target of coagulation and decreasing the formation of coagulated sludge.

Saxena *et al.* [78] found that the pH at optimum doses was comprised between 6.5 and 8. Such finding proposed that reduction was mostly affected by sweep coagulation [7] and the full charge neutralization [7] was not probable (**Figure 5**). In the same context, eliminating DOM by coagulation correlated well with the hydrophobicity of the algal organic matter [79]. As a result, future researches have to focus on the sweep coagulation and charge neutralization mechanisms contributions [68] [76]. In this context, a sweep coagulation/charge neutralization ratio could be suggested similarly to the hydrophilic/hydrophobic ratio [39] proposed few years ago for better DOM removal monitoring. A coagulant-dose adjustment procedure founded on UV_{254} monitoring was applied at a full-scale plant [80]. For the large span of waters experimented, an alum/ UV_{254} stoichiometric injection of 180 ± 25 mg alum cm/L shows a point of diminishing return (*i.e.*, it maximizes DBP precursor removal).



(c) Charge Neutralization

(d) Adsorption and entrapment

Figure 5. Schematic representation of possible mechanisms for mixed humic acid and kaolin removal [78].

5. Conclusion

Thanks to their easy functioning, high versatility, low energy consumption, and high-cost efficiency, coagulation and flocculation remain fundamental stages in the water treatment industry. This work discussed the usage of the EC method and focused on the performance of the EC technique from the point of view of various EC procedures. Pre-oxidation is largely utilized in dealing with water carrying algae. Pre-oxidation ameliorates coagulation by breaking the organic coating and modifying the surface potential of particles. Nevertheless, the pathway of pre-oxidative and coagulation stays totally unlike for numerous oxidants and pollutants. The present knowledge shows that EC remains founded on the pathway and dynamics of conventional coagulation. As long as the coagulation impact is considerably ameliorated, it could be adopted as EC. As a perspective, modeling mathematically EC is more than requested [81] [82]. Pre-oxidation techniques could be adopted to ameliorate raw water flocculation features, even if precautions should be adopted to avoid EOM release. Employing ozonation with GAC could also be adopted and estimated in situations where EC is utilized [13] [83] [84].

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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