DOI: 10.15199/17.2025.10.4

Natural Coagulants in Focus: Superior Performance over Iron-Based Agents in Cosmetic Wastewater Treatment

Naturalne koagulanty i ich większa efektywność w porównaniu ze środkami na bazie żelaza w oczyszczaniu ścieków kosmetycznych

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Keywords: *Cosmetic wastewater, wastewater treatment, iron-based coagulants, natural coagulants, flocculation, organic pollution*

Abstract

This study presents a comparative analysis of chemical and natural coagulants, focusing on the removal of Total Organic Carbon (TOC) from wastewater generated by the cosmetics industry. The novelty of this work lies in the use of bio-based materials, specifically wood powder and hazelnut shell powder, as alternative coagulants, and in evaluating their performance against conventional iron-based coagulants (PIX-110, PIX-111, PIX-112, PIX-113, and PIX-122) as well as the anionic flocculant AN 913 SH. Experimental results demonstrated that the natural coagulants significantly outperformed the most effective chemical coagulant (PIX-111), which achieved a TOC removal efficiency of 22.15%. In contrast, wood powder and hazelnut shells achieved TOC removal efficiencies of up to 80.3% and 82.16%, respectively. The use of natural coagulants also resulted in lower chemical consumption and reduced sludge production. Notably, iron-based coagulants substantially decreased the pH of the treated wastewater, necessitating post-treatment pH adjustment—a drawback not observed with natural coagulants. These findings underscore the potential of agricultural waste-derived materials as effective and environmentally sustainable alternatives for TOC removal in industrial wastewater treatment.

Słowa kluczowe: *Ścieki kosmetyczne, oczyszczanie ścieków, koagulanty na bazie żelaza, koagulanty naturalne, flokulacja, zanieczyszczenia organiczne*

Streszczenie

Praca przedstawia analizę porównawczą skuteczności koagulantów chemicznych i naturalnych, koncentrując się na usuwaniu Ogólnego Węgla Organicznego (OWO) ze ścieków przemysłu kosmetycznego. Nowość pracy polega na zastosowaniu organicznych materiałów odpadowych, w szczególności wiórów drzewnych i mielonych łupin orzecha laskowego, jako alternatywnych koagulantów, oraz na ocenie ich skuteczności w porównaniu z konwencjonalnymi koagulantami na bazie żelaza (PIX-110, PIX-111, PIX-112, PIX-113 i PIX-122) oraz anionowym flokulantem AN 913 SH. Wyniki eksperymentów wykazały, że naturalne koagulanty znacząco przewyższały skutecznością najefektywniejszy koagulant chemiczny (PIX-111), o skuteczności usuwania OWO 22,15%. Natomiast wióry drzewne i łupiny orzecha laskowego umożliwiły usunięcie OWO odpowiednio do 80,3% i 82,16%. Zastosowanie naturalnych koagulantów skutkowało również niższym zużyciem chemikaliów i mniejszą produkcją osadu. Warto zauważyć, że koagulanty na bazie żelaza istotnie obniżały pH oczyszczanych ścieków, co wymagało dodatkowej korekty pH — efekt ten nie występował w przypadku koagulantów naturalnych. Wyniki te podkreślają potencjał materiałów pochodzących z odpadów rolniczych jako skutecznych i ekologicznie zrównoważonych alternatyw do usuwania OWO w oczyszczaniu ścieków przemysłowych.

Introduction

One of the biggest environmental problems brought on by industrialization is water contamination. The main cause of water pollution is industrial effluents, which are defined by high concentrations of dyes, suspended particles, heavy metals, and organic and inorganic pollutant. Depending on the kind of raw materials and chemical processes used, these effluents' complicated composition differs among sectors. Untreated industrial wastewater discharge into aquatic systems causes significant ecological disruptions, decreased dissolved oxygen, and discolored water. Furthermore, a variety of health hazards, including as cardiovascular, respiratory, and dermatological conditions, have been connected to human exposure to tainted water [4]. Synthetic dyes and heavy metals are examples of persistent and non-biodegradable contaminants that are frequently difficult to remove using conventional wastewater treatment methods, particularly biological processes. Because of its high removal efficiency, cost-effectiveness, and ease of use, coagulation/flocculation (C/F) has become a popular physicochemical technique in response to these constraints. However, there is a trend toward more sustainable options as a result of worries about the health and environmental effects of utilizing chemical coagulants, especially those using iron and aluminum salts.Natural coagulants/flocculants (NC/Fs) made from renewable resources such plant seeds, peels, polysaccharides, and tannins have been

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the subject of more and more recent study. These materials are appealing alternatives to traditional chemicals in wastewater treatment because of their biodegradability, low toxicity, and possible economic benefits. Moringa oleifera (MO), for example, has shown significant effectiveness in eliminating oil, color, turbidity, and chemical oxygen demand (COD) from a variety of effluent types. Similarly, because of its cationic character and floc-forming capacity, chitosan—a naturally occurring polymer derived from chitin—has demonstrated encouraging outcomes in wastewater purification. In addition to conventional NC/Fs, magnetic-natural C/Fs (M-NC/Fs) and modified natural coagulants/flocculants (MN-C/Fs) have been investigated to improve therapeutic efficacy, recyclability, and selectivity. These cutting-edge materials assist the development of circular treatment technologies by integrating magnetic particles or functional groups to enhance separation and reuse . Nevertheless, a number of obstacles still need to be overcome, including dose optimization, stability under changing pH and temperature conditions, and production scalability. In order to maximize C/F efficiency, process parameters are essential. Particle charge and coagulant activity are strongly influenced by pH, with 6.5 to 7.5 usually being the ideal range[10]. Furthermore, careful optimization of coagulant dose, mixing intensity, and duration is required. The ideal treatment conditions, such as quick mixing (100–200 rpm), moderate mixing (20–50 rpm), and settling times of 20–30 minutes, are frequently ascertained using laboratory-scale jar experiments [16]. These parameters have been the subject of several investigations. According to significant turbidity and COD removal may be achieved by treating textile effluent with $FeCl_3$ at pH 9 under ideal circumstances, which include quick mixing at 150 rpm and slow mixing at 30 rpm. Similarly, [15] used MO at 2000 mg/L to remove over 90% of TSS and turbidity found that, under ideal mixing circumstances, a chitosan-based coagulant had COD and color removal efficiencies of 83% and 90%, respectively. Despite these developments, the commercialization of NC/Fs is still constrained by differences in process standardization, storage stability, and raw material characteristics. In order to overcome these constraints and enhance material performance, more investigation is required into chemical modification, immobilization on magnetic supports, and incorporation into hybrid treatment systems.

Chemical coagulants and flocculants are widely utilized in industrial wastewater treatment to eliminate suspended particles and other contaminants. Chemical coagulants, which are typically inorganic salts, function by neutralizing the electrostatic charges of suspended particles, leading to their destabilization and subsequent aggregation into larger, more easily removable clusters. Common examples of chemical coagulants include aluminum sulfate (alum), ferric sulfate, ferric chloride, and polyaluminum chloride (PAC). Conversely, chemical flocculants are generally high-molecular-weight organic polymers that facilitate particle aggregation, making them heavier and easier to separate from wastewater. These polymers possess a high electric charge density, enabling them to adsorb onto particle surfaces and form bridges between them, ultimately leading to the formation of larger flocs. Examples of commonly used chemical flocculants include polyacrylamide, polyethyleneimine, and polydiallyldimethylammonium chloride (polyDADMAC). Several studies have demonstrated the effectiveness of chemical coagulants in wastewater treatment. Investigated the application of alum for paper mill wastewater treatment, reporting reductions in COD and TSS by up to 78% and 81%, respectively, at a dosage of 40 mg/L [9]. Similarly, examined [24] the use of ferric chloride for treating petrochemical plant effluents and found it effective in reducing COD, oil and grease content, and heavy metal concentrations. Although chemical coagulants/flocculants are known for their efficiency in pollutant removal, research indicates potential long-term health risks associated with their prolonged exposure, including Alzheimer's disease and senile dementia. Additionally, their usage results in significant sludge generation, which poses challenges in terms of disposal and regeneration. For instance, a water treatment plant utilizing alum with a capacity of 190 million liters per day is estimated to generate at least three tonnes of solid waste daily, amounting to over 1,000 tonnes annually.The excessive sludge accumulation further exacerbates waste management challenges, as existing disposal sites are insufficient to handle the increasing sludge volume. To enhance coagulation/flocculation performance and minimize treatment duration, various materials such as carbon nanotubes [22], zeolites, bentonite [27], and silica have been incorporated into treatment processes. While these additions have contributed to improved efficiency, challenges remain regarding their separation and regeneration. Moreover, the high sludge volume produced by chemical coagulants increases disposal costs and raises concerns about potential environmental hazards. Given the adverse environmental and health impacts of chemical coagulants/flocculants, recent research has shifted towards exploring alternative, sustainable solutions for water treatment. Consequently, there is a growing emphasis on the development of natural coagulants/flocculants (NC/Fs) as eco-friendly and sustainable substitutes for conventional chemical treatment agents.

Plant-based coagulants and flocculants are organic compounds derived from natural sources such as seeds, roots, and leaves of various plants. These substances can be classified as both ionic and non-ionic polymers with different molecular weights [21]. Their coagulation and flocculation abilities stem from the presence of active compounds like proteins, polysaccharides, and tannins. Due to their natural origin, plant-based coagulants/flocculants are considered environmentally friendly and sustainable alternatives to synthetic chemical treatments. Some of the most commonly used plant-based coagulants/flocculants include Moringa oleifera (MO), chitosan, and tannins. Moringa oleifera, also known as the drumstick tree, contains cationic polyelectrolytes in its seeds, which can effectively bind with negatively charged particles such as dyes and heavy metals. When introduced into wastewater, these polyelectrolytes destabilize suspended particles, facilitating their aggregation and eventual removal. Additionally, tannins and lignin have demonstrated significant potential in eliminating dyes and heavy metals from industrial effluents. Tannins, which are naturally occurring polyphenolic compounds found in plants like tea, grapes, and oak, exhibit a strong affinity for heavy metals, forming insoluble complexes that can be easily removed from wastewater. Similarly, lignin, a complex aromatic polymer present in plant cell walls, has shown promise in heavy metal removal, making it a valuable candidate for industrial wastewater treatment. Several studies have evaluated the effectiveness of plant-based coagulants/flocculants in treating industrial wastewater, yielding promising results. For instance, tannin-based coagulants have been studied for textile industry wastewater treatment, achieving complete (100%) color removal at a concentration of 180 mg/L. This study also reported improved settleability and reduced sludge production compared to chemical coagulants. Moringa oleifera seeds were applied as a coagulant in dairy wastewater treatment, effectively reducing total solids by 94.6%, sulfate by 72.4%, and chloride by 64% [11].

Additionally, investigated the efficacy of a natural coagulant extracted from Cassia fistula seeds for treating wastewater from a textile dyeing industry. Their findings revealed a color removal efficiency of 93.8%. Another study explored the application of a natural coagulant derived from tamarind seeds for treating detergent wastewater, demonstrating a maximum turbidity and COD reduction of 97.7% and 39.6%, respectively [18].).

Materials and Methods

The cosmetic plant, located in Poland, is the source of the cosmetic wastewater (CW) sample. A large variety of cosmetics, such as lipsticks, shampoo, serum, liquid soap, and lotions, were produced in this factory. Wastewater is brought to the lab in a plastic container and kept a freezer at 4°C in the lab until the experiment is completed.

Every coagulation experiment involved putting 500 mL of wastewater into a beaker and mixing it at a steady 250 rpm using a magnetic stirrer. To guarantee proper dispersion and floc formation, the mixture was agitated 50 rpm for 15 minutes after the pH was adjusted to 6.0 with 3M NaOH after the coagulant was added. Following agitation, the wastewater was poured into a 500 mL cylinder and allowed to settle. The following coagulant therapies were used:

1. For iron-based coagulation, a selected iron-based coagulants—either PIX-110, PIX-111, PIX-112, PIX-115, or PIX-122—were added individually to the wastewater.
2. In the flocculant-only treatment, an anionic flocculant (AN 913 SH) was added without any metal-based coagulants.
3. In the combined treatment approach, both an iron-based coagulant (from the PIX group) and AN 913 SH were added to assess the synergistic effects of coagulant and flocculant use.
4. In the natural coagulant treatment, either hazelnut shell powder or wood powder was used as the sole natural, bio-based coagulant.

Reliable comparisons of coagulant efficiency were made possible by the uniformity of the experimental settings with regard to mixing, pH control, and settling time. Supernatant samples were gathered and examined to assess treatment effectiveness following a 24-hour sedimentation period. Chemical oxygen demand (COD), total suspended solids (TSS), anionic surfactants, total phosphorus (TP), and conductivity were among the characteristics assessed in both raw and treated wastewater. A TOC-L analyzer (Shimadzu, Kyoto, Japan) fitted with an OCT-L8-port sampler was used to measure total organic carbon (TOC). The evaluation of removal efficiency across various coagulant types and treatment approaches was made possible by these standardized analyses.

Result and Discussion

The cosmetic industry's wastewater treatment process involves several stages, including physical, chemical, and biological treatments, each targeting specific pollutants. The following table 1 summarizes the key parameters of the wastewater both before and after treatment, highlighting the impact of the coagulation process and other treatments used in the factory.

Table 1. Wastewater parameter
Tabela 1. Parametry ścieków

Parameter	Unit	Raw Wastewater	Coagulated Wastewater	Removal %
TOC	mg/L	1424	613.3	~56.9
COD	mg/L	3702	1644	~55.6
Anionic Surfactants	mg/L	850	800	~5.9
Total P	mg/L	12	11	~8.3
Conductivity	mS/cm	1.245	1.462	increase observed

The raw wastewater underwent coagulation treatment, which showed notable improvements in a number of important metrics, suggesting that the technique was successful in raising the quality of the water. TOC dropped from 1424 mg/L to 613.3 mg/L, a decrease of around 56.9%. In a similar vein, the COD decreased significantly, from 3702 mg/L to 1644 mg/L, by around 55.6%. These decreases demonstrate how well coagulation removes organic contaminants. Nevertheless, just 5.9% and 8.3% of TP and anionic surfactants were reduced, respectively, indicating the treatment's low efficacy. It's interesting to note that following coagulation, the wastewater's conductivity rose from 1.245 mS/cm to 1.462 mS/cm, indicating the presence of ionic species. The salts or coagulants that were left over after the chemical reactions might be the cause of this rise. Overall, while coagulation greatly enhanced organic pollutant removal, its influence on nutrient and surfactant levels was negligible, and further treatment may be necessary to address these elements.

Different quantities of iron-based coagulants were tested in 500 mL samples to see how they affected pH levels in order to evaluate them for wastewater treatment. The doses of PIX-110, PIX-122, PIX-112, PIX-111, and PIX-115 coagulants were 1 mL, 0.5 mL, and 0.25 mL, respectively. It was found that the pH decreased more significantly when the coagulant dosage was increased. All of the coagulants significantly reduced the pH at the maximum concentration (1 mL), but PIX-110 caused the most significant drop to 3.15, needing 5 mL of NaOH to get the pH back to 6. The minor pH drops at 0.5 mL still required significant neutralizing efforts; for example, PIX-110 caused the pH to drop to 3.36, which needed to be corrected with 8 mL of NaOH to reach 6.. pH decreases were slight but nevertheless detectable at the lowest dose (0.25 mL). For instance, PIX-112 lowered the pH to 3.0, necessitating the correction of 8.4 mL of NaOH. These pH decreases are caused by the hydrolysis of iron salts, which, when dissolved in water, release hydrogen ions (H^+), acidifying the solution. The amount of coagulant injected immediately correlates with the degree of hydrolysis and, in turn, the pH drop. This is a well-known occurrence in coagulation theory, where metal coagulants, such ferric salts, liberate H+ ions while forming hydroxide precipitates, particularly in low-alkalinity fluids. Overall, the findings are consistent with both actual observations and theoretical predictions, demonstrating that enhanced hydrolysis processes caused by larger dosages of iron-based coagulants amplify pH lowering. Process optimization requires an understanding of this connection, especially when choosing the right coagulant doses and making sure that pH is effectively controlled during large-scale wastewater treatment operations.

Following coagulant addition, particularly with PIX-110, PIX-111, PIX-112, PIX-113, PIX-122, and AN 913 SH, significant reductions in TOC were achieved (table 2). Notably, PIX-111 and PIX-122 demonstrated the most substantial reductions in TOC, with values of 517.2 mg/L and 525.4 mg/L, respectively. Conversely, AN 913 SH at 1ml exhibited a marginal decrease in TOC concentration compared to untreated wastewater, with a value of 518.2 mg/L. Additionally, comparisons between different dosages of AN 913 SH (1ml, 5ml, and 10ml) indicate varying impacts on TOC levels, with the highest dosage resulting in a TOC concentration of 509.8 mg/L. Interestingly, PIX-110 and PIX-113 displayed differing efficiencies at 0.5ml and 1ml dosages, suggesting dosage-dependent responses. Further analysis of TOC reduction based on different dosages of PIX-110, PIX-111, PIX-112, PIX-113, PIX-122, and AN 913 SH reveals nuanced variations in effectiveness. Notably, PIX-111 at both 0.25ml and 0.5ml dosages demonstrated consistent TOC reduction, indicating its reliability across different concentrations. PIX-110, PIX-112, and PIX-113 also exhibited significant TOC reduction, albeit to a lesser extent compared to PIX-111. Conversely, AN 913 SH displayed minimal impact on TOC levels, with values comparable to or slightly higher than untreated wastewater, indicating limited effectiveness in TOC removal..

Table 2. TOC removal using iron based coagulant and anionic flocculant AN913SH

Tabela 2. Usuniecie OWO przy użyciu koagulanta na bazie żelaza i anionowego flokulantu AN913SH

Coagulant	PIX-110	PIX-111	PIX-112	PIX-113	PIX-122	AN 913 SH	AN 913 SH	AN 913 SH	AN 913 SH
Volume (mL)	0.25	0.25	0.25	0.25	0.25	1	5	10	2.5
TOC (mg/L)		508.2	522.5	517.2	509.8	525.4	518.2	509.8	519.7
Coagulant	PIX-110	PIX-110	PIX-111	PIX-111	PIX-112	PIX-112	PIX-113	PIX-113	
Volume (mL)	0.5	1	0.5	1	0.5	1	0.5	1	
TOC (mg/L)	494.5	484	477.4	481.4	501.8	504.2	508.6	495.5	

Overall, PIX-111 emerges as the most effective coagulant for TOC reduction in wastewater treatment, consistently demonstrating significant reductions across different dosages. Compared to other iron-based coagulants and AN 913 SH, PIX-111 consistently achieved notable TOC reduction.

Following the application of wood powder and hazelnut shell coagulants, notable reductions in TOC were observed (Table 3). Specifically, TOC levels decreased to 122.5 mg/L, 120.8 mg/L, and 188.5 mg/L with wood powder dosages of 1g, 3g, and 5g respectively. Similarly, hazelnut shell coagulant dosages of 1g, 3g, and 5g resulted in TOC levels of 117.1 mg/L, 109.4 mg/L, and 113.1 mg/L, respectively. These findings highlight the efficacy of both wood powder and hazelnut shell coagulants in reducing TOC levels in wastewater. The varying dosages of each coagulant demonstrated nuanced effects on TOC reduction, with higher dosages generally resulting in more significant reductions. These results suggest the potential of natural coagulants derived from wood powder and hazelnut shells as sustainable alternatives for wastewater treatment, contributing to the optimization of purification processes and the mitigation of environmental pollution.

Table 3. TOC removal using wood powder and hazelnut shell

Tabela 3. Usunięcie OWO z wykorzystaniem wiórów drzewnych i skorup orzechów laskowych

Unit	Wood powder			Hazlenut Powder		
Dose	1g	3g	5g	1g	3g	5g
TOC (mg/L)	122.5	120.8	188.5	117.1	109.4	113.1

Table 4. Performance of chemical and natural coagulants for TOC removal

Tabela 4. Skuteczność koagulantów chemicznych i naturalnych w usuwaniu OWO

Cogulants	Volume (mL)	TOC (mg/L)	Removal (%)
PIX-110	0.25	507.5	17.25
pIX-111	0.25	508.2	17.13
PIX-112	0.25	522.5	14.80
PIX-113	0.25	517.2	15.66
PIX-110	0.5	494.5	19.37
PIX-111	1	484	21.08
PIX-112	0.5	477.4	22.15
PIX-113	1	481.4	21.50
PIX-112	0.5	501.8	18.18
PIX-112	1	504.2	17.78
PIX-113	0.5	508.6	17.07
pix-113	1	495.5	19.20
AN 913 SH	1	525.4	14.33
AN 913 SH	5	518.2	15.50
AN 913 SH	10	509.8	16.87
AN 913 SH	2.5	519.7	15.26
Wood powder	1	122.5	80.02
Wood powder	3	120.8	80.30
Wood powder	5	188.5	69.26
Hazlenut Powder	1	117.1	80.90
Hazlenut Powder	3	109.4	82.16
Hazlenut Powder	5	113.1	81.5

Table 5 reports the TOC removal efficiency for both natural and chemical coagulants in the treatment of wastewater from paper pulp mills. The natural coagulant chitosan removed 70% of TOC, while the artificial coagulants PEI and HE only managed 30%. This suggests that the removal of organic carbon from the wastewater was considerably more successful with chitosan. Because natural coagulants are polymeric and biodegradable, the performance gap indicates that they can interact with dissolved organic molecules more effectively. Despite the table's inadequate TOC data, the information that is now available clearly shows that natural coagulants function better at decreasing organic pollution. This is in line with the increased interest in bio-based products and sustainable water treatment methods.

Used alum and fruit peel coagulants[30]. Both coagulants exhibit increased clearance efficiency when the dosage is increased from 1 to 6 g/L. When compared to fruit peels, alum reliably removes more COD and TOC. Fruit peels remove 54.44% of COD and 36.3% of TOC at 6 g/L, whereas alum removes 84.41% of COD and 64.34% of TOC. Fruit peels show a consistent rising trend despite decreasing efficiency, suggesting room for improvement. The information emphasizes how both coagulants are dose-dependent Important information about the efficacy and environmental potential of different treatment agents is revealed by comparing chemical and natural coagulants for the removal TOC. Chemical coagulants, especially formulations based on alum and ferric, regularly outperform natural coagulants in terms of maximal removal efficiency, according to experimental results and supporting evidence from the literature. Natural coagulants still have a lot of potential, nevertheless, particularly when considering sustainability, less sludge generation, and less secondary pollution.Higher doses (6 g/L), alum showed TOC removal of up to 64.34%. However, depending on the source and circumstances, natural coagulants including chitosan, sunflower seed peels, and Moringa oleifera seeds were able to remove TOC with efficiencies ranging from 36 to 70%. This indicates a comparatively smaller but significant ability to eliminate organic contaminants, indicating that although natural coagulants might not be able to fully replace chemical agents just yet, they might be useful additions or substitutes, particularly in decentralized or inexpensive water treatment systems. These findings are further supported by the experimental data produced in this investigation. Depending on dose, coagulants such as PIX-110, PIX-111, PIX-112, and PIX-113, which constitute synthetic chemical coagulants, showed TOC removal efficiencies ranging from around 14.8% to 22.15%. For these compounds, 0.5–1 mL was the ideal clearance volume, with efficiency as high as 22.15%. The removal effectiveness of AN 913 SH, another chemical coagulant that was evaluated at various doses (1–10 mL), ranged from 14.33% to 16.87%, indicating a plateau effect and declining returns at increasing volumes. In this study, natural coagulants—like wood and hazelnut powders—performed noticeably better than their artificial equivalents. Wood powder achieved a maximum TOC clearance of 80.3% at a dose of 3 mL, whilst hazelnut powder achieved an astounding 82.16% at the same amount. Both natural coagulants shown good efficacy and consistency throughout testing volumes, surpassing 80% TOC elimination even at lower doses (1 mL). Natural substances including cacti, chitosan, rice starch, banana peel, and watermelon seed have also been shown to effectively remove TOC and turbidity, supporting this trend in the literature. For example, chitosan reduced TOC by 70% and removed color by up to 96%. These compounds have a number of environmental benefits, including being biodegradable, inexpensive, readily available locally, and producing less sludge than ferric

Table 5. Comparison of the Effectiveness of Natural and Synthetic Coagulants for Wastewater Treatment.
Tabela 5. Porównanie skuteczności koagulantów naturalnych i syntetycznych w oczyszczaniu ścieków.

Type of Wastewater	Chemical Coagulant	Removal Performance	Natural Coagulant	Removal Performance	Reference
Paper mill industry	Alum	Turbidity: 97.1% COD: 92.7%	Moringa oleifera	Turbidity: 96.0% COD: 97.3%	Boulaadjout et al., 2018
Concrete plant	Alum and $FeCl_3$	Turbidity: 99.9%	-	Turbidity: 99.9%	De Paula et al., 2018
River water	Alum	Turbidity: 75%	-	Turbidity: 62.5%	Alo et al., 2012
POME	Alum	Turbidity: 98.7% Color: 94% Oil: 95%	-	Turbidity: 88.3% Color: 90.2% Oil: 87.1%	Jagaba et al., 2020
POME	$FeCl_3$	Turbidity: 95.8% Color: 66.4% Oil: 95.7%	-	-	Jagaba et al., 2020
Paint industry	$FeCl_3$	Color: 89.4% COD: 83.4% Turbidity: 88.5%	Cactus	Color: 88.4% COD: 78.2% Turbidity: 82.6%	Vishali and Karthikeyan, 2015
Confectionary	PAM	TSS: 93.5% COD: 95.9%	-	TSS: 92.2% COD: 95.6%	Sellami et al., 2014
Glue	PAM	TSS: 90.7% COD: 86.3%	-	TSS: 90.3% COD: 82.1%	-
Paper and mill	PEI and HE	Color: 80% TOC: 30%	Chitosan	Color: 90% TOC: 70%	Ganjidoust et al., 1997
POME	Alum	Turbidity: 98.7% COD: 75% Oil: 95%	Chitosan	Turbidity: 98.4% COD: 68.3% Oil: 94.9%	Jagaba et al., 2020
POME	Alum	Turbidity: 82.2% COD: 49.1%	Rice starch	Turbidity: 92.5% COD: 30.9%	Teh et al., 2014
Leachate	PACl	Turbidity: 76% COD: 65% NH[illegible]-N: 25%	Diplazium esculen-tum leaf	Turbidity: 87% COD: 68% NH[illegible]-N: 34%	Zainol et al., 2017
Leachate	Alum	Color: 69% TSS: 45% Turbidity: 36%	Hibiscus rosa leaf	Color: 61% TSS: 72% Turbidity: 60%	Awang and Aziz 2012
Synthetic turbid water	Alum	Turbidity: 73.1%	Banana peel	Turbidity: 65.6%	Kian-Hen and Peck-Loo 2017
POME	Alum	COD: 59% BOD: 61% TSS: 71%	Jatropha curcas seed	COD: 70% BOD: 65% TSS: 88%	Abidin et al., 2017
Latex effluent	Ferric Sulfate	COD: 98% TSS: 98% Turbidity: 89%	Dragon fruit foliage	COD: 94.7% TSS: 85.9% Turbidity: 99.7%	Idris et al., 2013
Artificial turbid water	Alum	Turbidity: 97.9%	Mango seed	Turbidity: 92%	Seghosime et al., 2017
Dam water	Alum	Turbidity: 98.5%	Watermelon seed	Turbidity: 89.3%	Muhammad et al., 2015
Cassava effluent	Alum	Color: 49% Turbidity: 56%	Watermelon seed	Turbidity: 99.3% Color: 100%	Dos Santos et al., 2020
Synthetic wastewater	Alum	Turbidity: 99.6% Sludge: 58 mL/L	Acacia negara	Turbidity: 99.6% Sludge: 40 mL/L	Abidin et al., 2011
Paint effluent	$FeCl_3$	COD: 82% Color: 89%	Based on tannin	COD: 87% Color: 99%	Aboulhassan et al., 2015

salts or alum. However, in some situations, the somewhat lower effectiveness of natural coagulants emphasizes the necessity for further optimization. This covers pH modifications, dose-response studies, and hybrid applications that mix chemical and natural agents for mutually beneficial effects. For instance, it has been demonstrated that coagulant aids like rice starch or watermelon seed greatly increase the effectiveness of main agents like alum. The operational context is a crucial factor. Chemical coagulants could still be the best option for treating wastewater on an industrial scale, when reliability and efficiency are crucial. However, natural coagulants offer a great substitute for small-scale, rural, or environmentally sensitive applications. Their application can lessen treatment facilities' reliance on chemicals, cut operating expenses, and lessen their environmental impact.

Conclusion

With removal efficiencies typically ranging from 14% to 22%, chemical coagulants such as AN 913 SH and the PIX series (PIX-110, PIX-111, PIX-112, PIX-113, PIX-122) lower TOC in wastewater. Among chemical coagulants, PIX-111 typically outperforms the others, yielding TOC reductions of around 17–21%. Though there is a limit to efficacy and some chemical coagulants exhibit decreasing returns at larger dosages, increasing the coagulant dosage enhances TOC removal. At ideal dosages, the TOC removal efficiency of natural coagulants—wood powder and hazelnut shells in particular—exceed 80%. Compared to the chemical coagulants examined in the study, this clearance rate is significantly higher. Even at lesser dosages, natural coagulants exhibit reliable effectiveness, indicating a great deal of promise for environmentally friendly wastewater treatment. At ideal dosages, the TOC removal efficiency of natural coagulants—wood powder and hazelnut shells in particular—exceed 80%. Compared to the chemical coagulants examined in the study, this clearance rate is significantly higher. Even at lesser dosages, natural coagulants exhibit reliable effectiveness, indicating a great deal of promise for environmentally friendly wastewater treatment.

Superior TOC removal efficiency, reduced sludge production, economic effectiveness, and environmental friendliness make natural coagulants great options for decentralized and sustainable wastewater treatment systems. However, depending on the scope and objectives of the treatment, natural coagulants could need to have their dose and conditions optimized to enhance their effectiveness.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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