OPEN ACCESS

Volume: 4

Issue: 2

Month: May

Year: 2025

ISSN: 2583-7117

Published: 02.04.2025

Citation:

Prabhat Kumar Tiwari, Rajesh Kumar Misra, Vijay Kumar Meshram "A Review on Wastewater Treatment Using Adsorption and Coagulation /Flocculation Methods" International Journal of Innovations in Science Engineering and Management, vol. 4, no. 2, 2025, pp. 130–136.

DOI:

10.69968/ijisem.2025v4i2130-136

A Review on Wastewater Treatment Using Adsorption and Coagulation/Flocculation Methods

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Abstract

The global community found wastewater issues to be a complex challenge. In the remediation of effluent, there are numerous methods, including physical, chemical, biological, and combinations of these methods. Adsorption and coagulation are two examples of the physicochemical techniques that are often used in wastewater treatment. This article reviews the literature on wastewater treatment utilising coagulation/flocculation and adsorption techniques. It concluded that adsorption and coagulation/flocculation are effective, low-cost, and widely adopted methods for wastewater treatment. Their efficiency is influenced by key parameters such as pH, dosage, and contact or settling time. Adsorption, especially with modified clays and biochars, offers high capacity for removing diverse pollutants. Coagulation using both conventional and bio-based coagulants also shows promising results. Though each method has limitations, their adaptability and effectiveness make them suitable for various real-world applications. Integrating these technologies can enhance treatment efficiency and support sustainable wastewater management, particularly in resource-limited settings.

Keywords; Wastewater treatment, Adsorption, Coagulation/Flocculation, Adsorbent, Coagulant, Water pollution, Heavy metals, Synthetic wastewater, etc.

INTRODUCTION

One may argue that every material, in one form or another, can turn into a contaminant if it is discovered outside of its typical habitat or in higher proportions than usual. However, when concentrations of chemical contaminants are high enough to have a negative impact on the environment or endanger living things, they are considered pollutants [1]. There are hundreds of industrial chemicals on the market today that may harm both people and the environment. It is fortunate that the production of a significant number of these chemicals is not sufficient to pose a hazard to the environment or human health. However, a large number of other natural and man-made compounds are hazardous and generated in large enough amounts to pose a risk to human health or the environment. Therefore, government organisations control the manufacture, handling, transportation, and disposal of these compounds. Chemical pollutants discharged into the environment come from a wide variety of sources, although they usually fall into a few broad categories [2].

All life and human existence depend on water, which is also crucial for the provision of drinking water and the economy. Every year, the amount of water required for domestic and commercial operations continues to rise. Due to industrial globalisation, growing residential and commercial regions, and agricultural lands that produce massive amounts of wastewater, the globe is now experiencing a water crisis [3]. Eighty percent of the world's wastewater enters our environment every day without any treatment, endangering both human health and the ecosystem. This has far-reaching effects on aquatic biodiversity, climate resilience, and the security and accessibility of food and water.

The hazardous mixture of pollutants that wastewater brings endangers marine life as well as our food and water supplies [4]. Water pollution refers to the discharge of compounds into subsurface groundwater, rivers, streams, estuaries, and lakes until they obstruct the normal operation of ecosystems or the beneficial use of water. Water pollution may involve the discharge of energy, such as heat or radioactivity, into bodies of water in addition to the discharge of materials, such as chemicals, debris, or germs [5].

Wastewater treatment

The removal and elimination of contaminants from effluent is the process of wastewater treatment. This means that it may be recycled back into the water cycle as an effluent. The wastewater has an acceptable environmental effect once it is back in the water cycle. It may also be used again [6]. We refer to this procedure as water reclamation. This procedure is carried out at a wastewater treatment facility. At the appropriate wastewater treatment facility, a variety of wastewater types are processed. A sewage treatment facility is used to treat wastewater from homes [7]. Domestic wastewater is sometimes known as sewage or municipal wastewater. Sewage treatment plants or distinct industrial wastewater treatment facilities handle the treatment of industrial wastewater. It often comes after pre-treatment in the latter scenario. Leachate treatment plants and agricultural wastewater treatment plants are additional kinds of wastewater treatment facilities [8].

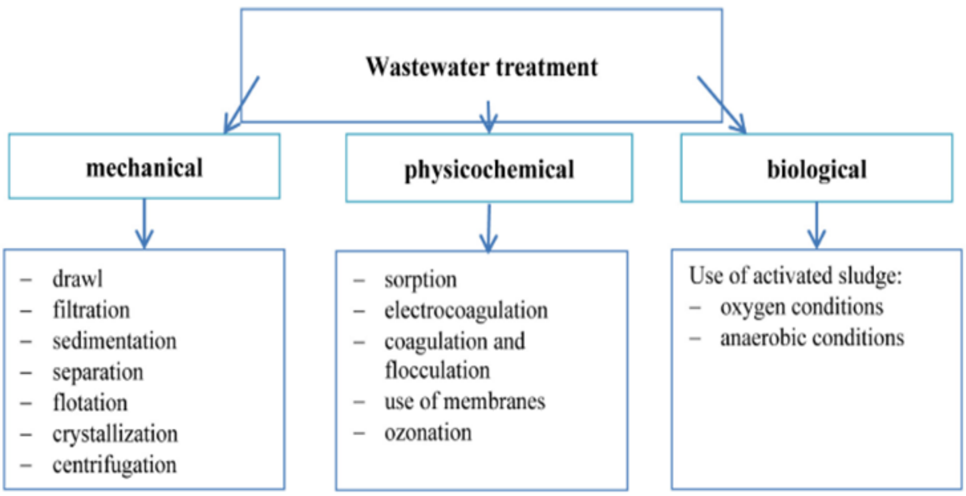
Table 1 Technologies of wastewater treatment [8]

Type of treatment	Advantages	Disadvantages
Biological	Potential for removing metals	Technology is still under development
Photocatalysis	High degradation rate	Potential to harmful due to exposure to carcinogenic UV light
Membrane technology	Membrane properties could be adjusted small occupation area high processing efficiency	Membrane fouling
Ultrasonication	Compact environmentally friendly	Require high energy
Adsorption	simple design cost-effectiveness excellent approach for removing organic pollutants	require regeneration of the adsorbent
Coagulation/ flocculation	simple process good for reclamation or removed pollutants	require high dosage produce massive sludge and large particles

Wastewater Treatment Methods

Each of the four wastewater treatment techniques has an own treatment procedure. However, before beginning any medical operation, an examination and assessment should be conducted [9]. Four distinct industrial water treatment systems are described below:

Figure 1 Wastewater treatment methods [9]



Physical Technologies for Waste Water Treatment: Physical water treatment is the process of purifying wastewater using physical methods. Screening, sifting, and sedimentation are employed in this technology to eliminate particles from effluent. This method doesn't involve the use of any chemicals.

Mechanical techniques for treating wastewater: Mechanical filtration, one of the conventional techniques for wastewater treatment, may be carried out in one of two ways:

- **Ceramic Membrane Technology:** Ceramic membrane filtration is the process of filtering wastewater using ceramic membranes that are placed in homes. The filtering process will start as soon as the wastewater starts to flow through the membranes. A feed pump provides the pressure needed to move water through the ceramic membrane.
- **Sand Filter Technology:** We have been using this technique for more than 200 years. It works better in circumstances when gravity or pressure pushes fluids downhill. Among its drawbacks is the possibility of insufficient disinfection from this method. The sand filter is a large tank filled with special-grade sand.

Biological Method of Wastewater Treatment: It is the use of biological processes for wastewater treatment. At this stage, organic materials present in wastewater, including "food, soap, oil, and human waste, decompose".

Chemical Methods of Wastewater Treatment: Despite the fact that there are numerous chemical treatment methods, the most frequently employed are ion exchange, disinfection, precipitation, adsorption, and chemical neutralisation. The material is impacted by shifting environmental factors, even if the chemical treatment techniques described above vary.

Importance of wastewater treatment

In order to safeguard both human and animal health as well as our environment, wastewater treatment is essential. Untreated wastewater may harm natural ecosystems, contaminate our water supplies, and result in dangerous diseases. Essentially, wastewater treatment facilities perform the function described; they cleanse the water that flows down our sewers prior to its discharge into the environment. No matter how hard these plants are being planted throughout the globe, more has to be done [10]. One of our most valuable resources, water, is being wasted. Wastewater may be treated in a variety of ways, and the more effective the method, the more of it can be recycled before being released into the ocean. Concerns over fracking and wastewater have prompted the public to confront oil firms, and regulations are gradually evolving, particularly with regard to environmental impacts and transparency. The sector is being scrutinised, which is a good thing since the more openness mandated by legislation, the better. For too long, large-scale enterprises like mines, oil firms, and others have been left uncontrolled and offered to the highest bidder; thus, we need to raise the bar for them [11], [12].

LITERATURE REVIEW

(El Mouhri et al., 2024) [13] A thorough analysis of the different elements influencing the coagulation/flocculation process used to treat tannery effluent was then carried out. This was achieved by adjusting the target components and monitoring how they affected the elimination of certain physicochemical characteristics, including total chromium (Cr), electrical conductivity (EC), chemical oxygen demand (COD), and optical density (OD). "Approximately 100% for TSS, 98.71% for BOD5, 99.93% for COD, 98.88% for NH_4^+, 98.21% for NO_3^-, 90.32% for NO_2^-, 93.13% for SO_4^{2-}, 95.44% for PO_4^{3-}, 96.08% for OD", and 60% for total chromium are the removal rates obtained after treating tannery wastewater using the PA-HE coagulant-flocculant combination. These findings show that the PA-HE treatment technology effectively removes a variety of contaminants from tannery effluent. PCA has been implemented to anticipate "the CF treatment approach" by preprocessing the input data and identifying the critical variables that influence the process.

(Sinharoy & Chung, 2024) [11] This section emphasises "the advantages, drawbacks, methods, and efficiency" of the various methods used to remove fluoride from water, including adsorption, fluidised bed crystallisation, coagulation, electrocoagulation, ion exchange resin, and membrane-based procedures (such as nanofiltration, reverse osmosis, electrodialysis, and pervaporation). Each method is evaluated based on its efficiency in removal, operational complexity, cost-effectiveness, and suitability for different water treatment application sizes. To provide insights into potential research directions, the latest advancements and emerging trends in fluoride removal technology are also evaluated. In order to inform decision-makers, researchers, and water treatment practitioners on the latest developments and best methods for lowering fluoride contamination in water sources, this study aims to compile the body of existing knowledge.

(Khan et al., 2023) [14] For the purpose of water remediation, this review offers a thorough examination of the surface adsorption properties of various clay varieties. In the following section, the adsorption process on clay surfaces are investigated, elucidating the complex relationships among contaminants and active areas on clay surfaces. The review also emphasises the effectiveness and adsorption ability of various clay kinds for detoxifying water of different pollutants. These pollutants include dyes, organic pollutants, heavy metals, and newly discovered toxins. The paper also discusses the drawbacks and restrictions of clay-based adsorbents, such as problems with cost-effectiveness, regeneration, and disposal. There are suggestions on how to overcome these obstacles as well as possible future paths in the area of clay-based water treatment.

(Panwar et al., 2022) [15] Such contaminants might be cleaned up using coagulation, an efficient basic chemical treatment method. Due to the expensive cost of chemical coagulant-treated water, most rural residents are forced to depend on readily available sources, which are usually of poor quality and expose them to waterborne infections. Throughout "the coagulation and flocculation stages" of wastewater treatment, a natural coagulant, which is a plant-based coagulant that occurs naturally, can be employed to reduce turbidity. Natural coagulants may be used in place of chemical coagulants. It serves a dual function by lowering turbidity and having positive ecological effects. The goals of this research were to optimise the coagulation process and assess the feasibility and effectiveness of substituting natural coagulants with widely used synthetic coagulants like aluminium sulphate.

(Sultana et al., 2022) [16] This study is an innovative investigation to find substitute ingredients that may be used as a natural coagulant, taking into account the effects of chemical coagulation. Two distinct regional clays that were gathered from the Patuakhali coastline region of Bangladesh and Portugal were used as coagulants in the current investigation. Clay coagulant treatments were used to examine the effectiveness of removing "heavy metals (Cr, Cd, Ni, and Pb)", chemical qualities (pH and COD), and physical characteristics (turbidity) from wastewater. In comparison, the Patuakhali coastal clay was shown to have the greatest removal effectiveness. In addition to being readily accessible locally, this soil has the potential to be profitable.

(Precious Sibiya et al., 2021) [17] Ferromagnetite (F), alum (A), and eggshells (E) are the three coagulants and their hybrids (FA, FE, and FEA) that were examined in this research as potential economical coagulants for the processing of industrial wastewater. Turbidity, colour, and total suspended solids were examined in relation to the effects of coagulant dose "(10–60 mg/L) and settling time". The characterised supernatant's results indicated that the pollutants had been removed to a degree of roughly 80%. The ternary hybridised (FEA) and binary (FA > FE) coagulants were shown to be less efficacious than the possibilities of F. F's treatment performance was definitively demonstrated to be effective for wastewater treatment at an optimal dosage of 20 mg/L and a settling duration of 30 minutes.

Table 2 different coagulants used in wastewater treatment [17]

Coagulant type	Dosage (mg/L)	Turbidity removal (%)	Color removal (%)	TSS removal (%)
Eggshells (E)	20	98.89	98.88	98.52
Alum (A)	20	99.58	99.66	100
Ferromagnetite (F)	20	99.17	94.62	95.19
FEA	20	99.76	99.59	100
FA	20	99.51	99.66	99.75

(Sukmana et al., 2021) [8] Adsorption and coagulation are two examples of the physicochemical techniques that are often used in wastewater treatment. Coagulation and adsorption are two great ways to get rid of contaminants. Adsorbent dosage, temperature, contact duration, and pH all have a significant impact on the adsorption process. The primary determinants of the coagulation process are pH, settling time, and coagulant dosage. Previous studies have examined chemical materials as adsorbents and coagulants; however, substituting chemical materials has become a difficult topic in recent years. Natural materials have gained popularity because of their effectiveness and environmentally benign qualities, making them promising new materials for wastewater treatment. The use of natural materials as adsorbents and coagulants, as well as the function of "adsorption and coagulation in wastewater treatment", were examined in this paper.

(El-Baz et al., 2020) [18] One of the most difficult issues that people face is water contamination. Many methods, including "flotation, coagulation, ion exchange, biological treatment, adsorption, membrane, etc.", were presented to get treated water and wastewater. Of these, the adsorption approach has shown itself to be a cost-effective and efficient way to remove synthetic colours, inorganic pollutants (like heavy metals), and organic pollutants "(like phenols, methylene blue, methyl orange, benzene, etc.)" from contaminated water. "Activated Carbon (AC), nanomaterials, natural adsorbents, industrial by-products, agricultural residues", and bio-sorbents are among the most frequently employed adsorbents. This review provides a summary of their efficacy, cost, and regeneration studies.

(Gautam & Saini, 2020) [19] The effluents produced by numerous industries have been effectively and cost-effectively managed through the use of synthetic compounds for coagulation. The synthetic chemicals themselves, however, are problematic since they are not native, they do not decompose, and their residual residues might create health problems. The current study offers a cutting-edge analysis of the use of natural coagulants in the treatment of industrial wastewaters, along with a comparison of their respective benefits and drawbacks to those of chemical coagulants. Future research directions that might eventually result in the widespread commercial use of natural coagulants have also been identified. These areas will provide a sustainable and environmentally friendly solution to the issues caused by synthetic chemical coagulants and industrial effluents.

(Saravanan et al., 2020) [20] In order to investigate Zn (II) ion adsorption, the current work concentrated on creating a mixed biosorbent utilising fungal biomass (Aspergillus tamarii) and "agricultural waste (Borassus flabellifer male inflorescence)". To improve the Zn (II) ion elimination procedure, the biomass from synthesised agricultural waste was chemically altered. A higher level of zinc removal was achieved at a zinc concentration of 25 mg/L, a contact time of 40 minutes, a pH of 6.0, a biomass dose of 2.5 g/L, and a temperature of 30°C. The maximal monolayer adsorption capacity (qm) for RBFM-Aspergillus tamarii and SMBFM-Aspergillus tamarii was determined to be 49.79 mg/g and 54.74 mg/g, respectively, based on adsorption studies, which indicated that "the Langmuir isotherm and pseudo-first order are the best suited models".

(Nabbou et al., 2019) [21] Because large amounts of fluoride ions have been found in drinkable water, this article focusses on using clay, specifically kaolinite, to remove fluoride ions from Saharan groundwater in the Tindouf area of Algeria. When the pH ranges from 4.5 to 6, adsorption experiments demonstrate that fluoride ion removal was effective. 0.442 and 0.448 mg/g were the adsorption capacities under these conditions, respectively. The analysis of fluoride removal from simulated potable water reveals that fluoride absorption was unaffected by the presence of nitrate and chloride ions. Nevertheless, the adsorption capacity is reduced by sulphate and carbonate ions. This research indicates that kaolinite is a cost-effective and efficient material for groundwater fluoride ion removal.

(Singh et al., 2018) [22] This article also examines the elimination of Fluoride, Phosphate, Nitrate, and Radionuclides from effluent. There has also been discussion of adsorption mechanism, thermodynamic parameters, kinetic models, and adsorption isotherm models. This article discusses the state-of-the-art in water pollution removal techniques and enumerates several adsorbent types. The causes of pollution and the toxicities of pollutants have been discussed. A review has been conducted of the adsorption mechanisms that are responsible for the removal of pollutants by various adsorbents. In addition, efforts have been made to identify the benefits and disadvantages of adsorbents, as well as the future research requirements in the field of water purification through the use of adsorbents.

CONCLUSION

This review highlights the effectiveness of adsorption and coagulation/flocculation as prominent methods for wastewater treatment. Adsorption is influenced by key parameters such as pH, adsorbent dose, temperature, and contact time, while coagulation depends on coagulant dose, pH, and settling time. Among various materials, kaolinite clay and sweet lemon peel biochar have demonstrated exceptional adsorption capacities, particularly for heavy metals and fluoride. Surface modification techniques like cation exchange and functionalization further enhance adsorption performance. Although batch mode is ideal for preliminary adsorption studies, it lacks scalability for continuous systems. In contrast, coagulation using alternative coagulants like ferromagnetite and eggshells, along with emerging bio-coagulants, offers sustainable and cost-effective solutions, especially in rural settings. Isotherm models such as Langmuir and Freundlich continue to be reliable for predicting adsorption behavior. Thermodynamic data supports improved fluoride adsorption at elevated temperatures, and the presence of competing anions like nitrate or chloride does not significantly impact adsorption efficiency. Overall, both methods offer low-cost, practical, and efficient treatment options, with their applicability tailored to specific wastewater characteristics and regional resource availability. Their integration or hybrid application can further enhance pollutant removal and support compliance with environmental discharge standards.

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