

# Application of Circular Economy to Natural Coagulation / Flocculation of Surface Water: A Review

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**Abstract.** Water treatment is one of the most researched areas due to water resources' importance for humans and the environment. Surface water pollution seems unavoidable because of increasing industrialization, which results in wastewater discharge into surface water bodies. Coagulation/flocculation is one of the practical approaches used in surface water treatment. However, the drawbacks of conventional chemical coagulants have been the main challenges that prompted research towards finding greener and sustainable alternatives such as natural coagulants. This review was intended to briefly glance at the natural coagulation/flocculation of surface water, the components of plant-based materials responsible for their coagulation activities and the circular economy of water. The review results showed that phytochemicals responsible for various coagulating activities include tannin, saponin, d-galactose, d-rhamnose, d-xylose, l-arabinose and galacturonic acid. In addition, these compounds function through different mechanisms. Also, the function of the active coagulants is related to the presence of specific functional groups. The review also indicates that the research on applying natural coagulants for surface water treatment is rapidly increasing globally. However, very few pieces of work were reported from Africa. Thus, more work needs to be done in this region. Furthermore, the circular economy of surface water related to natural coagulation/flocculation needs the attention of researchers as this approach can help manage surface water resources sustainably.

**Keywords:** Surface water pollution; coagulation/flocculation; Plant-based coagulants; active coagulant function; circular economy.

## INTRODUCTION

The increasing world population, industrialization, and globalization have increased water requirements, which put more pressure on natural resources. Though industrialization brings about improved social and economic lives, it has negative impacts on the environment in terms of wastewater disposal. The effluent with different pollutants, including turbidity and recalcitrant chemicals [1], is usually discharged in large volumes to the ecological system without proper treatment [2]. Consequently, raw surface water entering water treatment plants contains many pollutants, making them unfit for consumption

and other domestic uses. Raw surface water is made to pass through specific treatments intended to remove suspended particles, dissolved solids, and chemical substances such as metal ions, which are believed to have detrimental effects on humans if consumed in water. These treatment steps include filtration, coagulation/flocculation, clarification, and reverse osmosis. Also used in potable water production are emerging membrane processes like nanofiltration and ultrafiltration.

Conventionally, surface water treatment plants use four processes, namely coagulation, flocculation, sedimentation, filtration, and disinfection, to

make potable water available to the end users. These methods are usually applied in the surface water treatment rule. Coagulation is an essential step in water treatment, including surface water. This process involves causing organic and inorganic pollutants to agglomerate by applying a coagulant under rapid mixing. When larger flocs are formed by adding chemicals under slow agitation, the unit operation involved is flocculation. Sometimes, we call the process coagulation/flocculation when a single unit achieves both operations. This chemical process is known for its high efficiency in treating several pollutants. However, there are concerns about some of the chemicals used as coagulants and/or flocculants. For instance, the use of some inorganic salts has been linked to [3, 4]:

- a) Generation of significant amounts of potentially toxic inorganic waste,
- b) High level of residual aluminium salts in treated water, which has been said to be a factor in Alzheimer's disease and other neurological illnesses, and
- c) Additional chemicals are required for stabilization and corrosion control. Consequently, research has intensified to find alternatives to these chemicals.

Research on applying natural coagulants for surface water treatment is growing steadily. These nature-based materials are considered suitable substitutes for chemical coagulants due to characteristics such as non-toxicity, environmental sustainability, high effectiveness in treating pollutants and generation of less amount of sludge [5]; high efficiency at a wide range of pH [6, 7], and non-requirement for adjustment of treated water pH [8]. In addition, the natural coagulating materials are biodegradable and potentially decrease treatment-associated carbon emission footprints [9]. Natural coagulants offer additional advantages, especially in developing countries, because these materials are readily available at low or no cost. In contrast, chemical types are mostly imported at high prices due to forex policies.

Many plant-based materials have been used successfully for water and wastewater treatment, as reported in many scientific reviews and empirical research reports. However, researchers have identified some challenges that impede their application in large-scale water treatment. These include the availability of primarily bench-scale research on coagulation and concerns about waste

generation from the preliminary, secondary, and residuals in treated water that can threaten the population and environment. Recently, ease of waste handling and volume have been famous among the parameters used to evaluate the efficiency of the water treatment process; this aligns with the circular economy and United Nations Sustainable Development Goal 6 concerning Clean Water and Sanitation. As limited data can be found in the literature, this review work is intended to briefly look into plant-based materials used in surface water treatment in conformity with the circular economy.

## METHOD

To achieve the aim of this review, publications, including research articles and conference papers published in the last decade (2014-2024), were obtained from Google Scholar, Scopus, and Springer databases and reviewed thus.

## RESULTS AND DISCUSSION

*Surface Water Pollution.* Increasing human needs have led to heavy industrial activities, which produce targeted and unwanted products. These waste substances of various forms find their way into the environment via different means, including direct disposal. Though there are stringent standards and guidelines that the treated wastewater must meet before disposal into water bodies, enforcement and implementation of these laws in developing countries remains a challenge. Consequently, some industries discharge their wastewater to the receiving water bodies with no or improper treatment, thereby increasing the pollutant loads of the host surface water. Also, rivers and streams are sinks for wastewater generated from domestic activities, especially in areas without municipal wastewater treatment plants. Urban storm runoff is another primary source of surface water pollution [10]. This non-point source can also pollute the groundwater due to water flow. Agricultural activities can also contribute to surface water pollution. Dead plants, pesticides, and herbicides can indirectly contact the water body. Also, mining activities can expose our surface water to toxic metals and other chemicals.

Consequently, polluted surface water can contain a variety of pollutants, including humic acid, which can contribute to the yellow or brown colouration of the surface water [11, 12], turbidity,

dissolved solids, herbicides, antibiotics, heavy metals, pathogens, and pesticides. The types and loads of pollutants in the surface water depend on the location of the surface water, the kinds of dominant activities in the nearby surface water area, and the season. Figure 1 depicts various sources of surface water pollution.

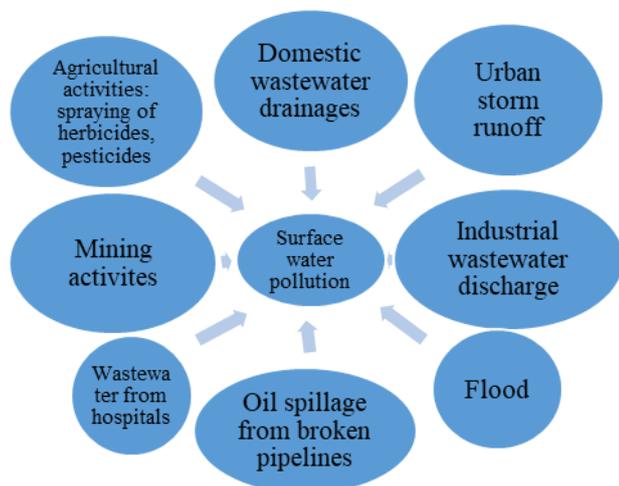


Figure 1 – Some Sources Of Surface Water Pollution

Since surface water can vary in pollutant load, selecting an effective method can help obtain treated water that is safe and fit for drinking.

**Coagulation/flocculation overview.** Coagulation is a process by which the addition of coagulant causes the destabilization of pollutants, including colloidal particles in the aqueous medium under fast mixing; these substances then agglomerate to form flocs, which can separate by gravitational sedimentation [13, 14] or filtration. Flocculation occurs at a lower mixing rate compared to coagulation. Figure 2 illustrates the process of coagulation and flocculation with the associated processes. Coagulation and flocculation are carried out in the same unit in some applications. In this case, the process is called coagulation/flocculation, as mentioned before. What differentiates the two is the agitation speed and time. Thus, coagulation/flocculation experiments are usually carried out in two mixing stages, with the coagulant added to the raw water in the first stage. Choosing adequate mixing time is critical for the accumulation of particles and proper settling [14, 15]. Coagulation/flocculation involves the formation of some clots of destabilized pollutants and the accumulation of the clots to form flocs by adding coagulants (figure 3). The process is very efficient in treating many pollutants. However, its efficiency

depends on factors like the pH of the raw water, mixing speed and time, settling time, and coagulant dosage [13].

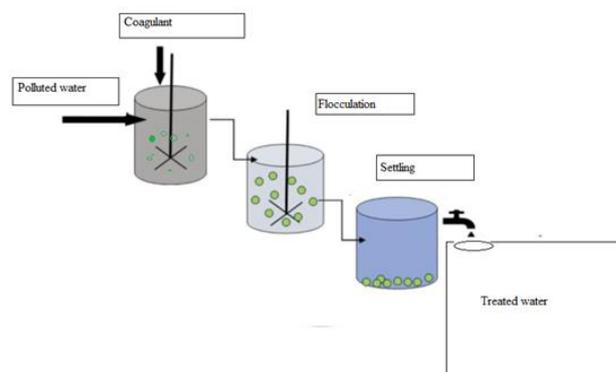


Figure 2 – Coagulation and flocculation of water to produce clean water [14]

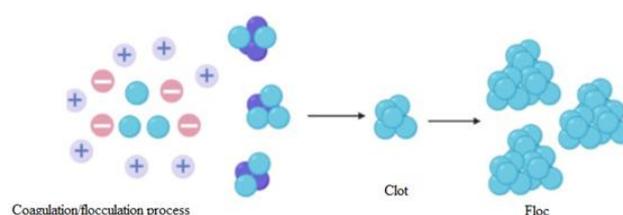


Figure 3 – The principle of coagulation/flocculation [14]

Conventionally, ferric- and aluminium-based coagulants are used for water treatment. The use of these chemicals has been associated with some drawbacks. These include generating a large volume of sludge, which can increase the cost of water treatment. Also, using alum and polyaluminum chloride as a chemical coagulant for water treatment has been linked to health concerns due to health-damaging residual chemical ions in the treated water [2, 16, 17].

Consequently, research on finding eco-friendly substitutes for chemical coagulants has increased recently. Figure 4 depicts the search analysis results on Scopus to determine the number of documents from various sources between 2014 and 2024. On July 3, 2024, 536 documents had 443 research articles, 35 reviews, 34 conference papers, 22 book chapters, and two books. Figure 5 shows that authors published the maximum number of documents on the subject matter in 2020, while the minimum number of publications occurred in 2014.

Documents by type

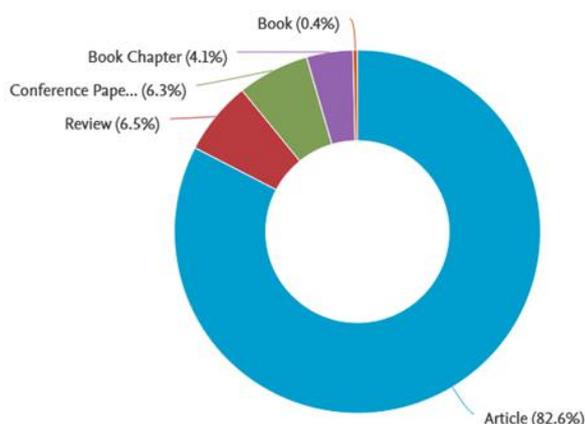


Figure 4 – Various sources of documents found on Scopus when treatment of surface water using natural coagulation was searched with "AND" and "AND NOT" soil and water treatment criteria

Documents by year

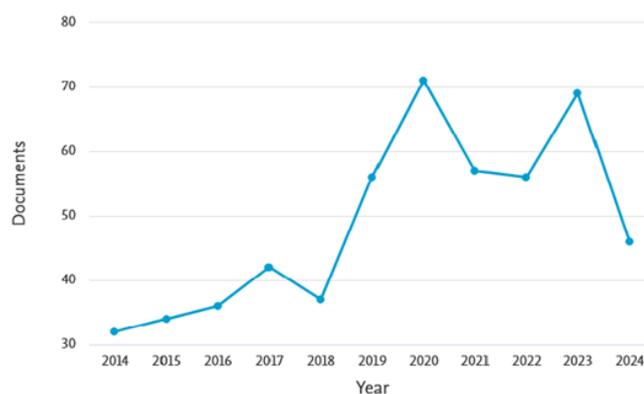


Figure 5 – Number of documents published per each year under review

Research can be instrumental to a country's economic and infrastructural growth. Figure 6 shows the number of documents published by the government, with China having a maximum of 117 publications and Egypt having a minimum of 20 publications; this indicates that more research outputs published in the leading region can positively impact the country's economy and infrastructural growth. Only one African country is noticed in the figure, with Nigeria absent in the year under review.

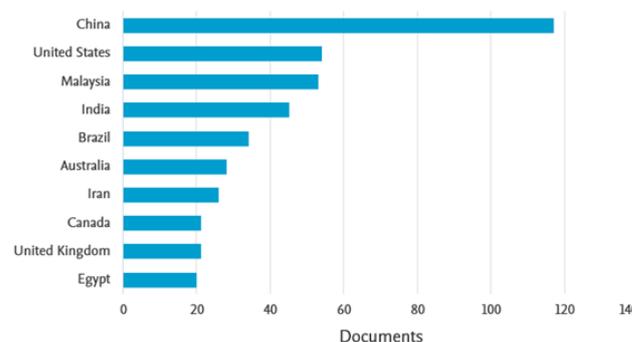


Figure 6 – Documents by country/territory

The chemicals responsible for the coagulating activities of plant-based materials are used in coagulation/flocculation. The reports on using coagulants produced from plants for water have increased in recent years, even though these materials have been used for water clarification as far back as 2000 bc [18]. The historical use of natural coagulants for water treatment has been briefly explained by authors [9]. Also, the review work carried out by this duo author resulted in the documentation of 57 coagulants obtained from different plants, most of which were seeds. The effectiveness of plant-based coagulants is associated with anionic polyelectrolytes, which indicates that they contain carboxylic and hydroxyl groups. Tanin is another component of plant-based materials that helps remove contaminants. Also, the bridging action mechanism of natural coagulants is related to their possession of some compounds, such as d-galactose, d-rhamnose, d-xylose, l-arabinose, and galacturonic acid. These compounds are present in *Opuntia latifolia* L., which is also anionic. Moringa seed is one of the notable natural coagulants in literature with dimeric, cationic protein as an active coagulant having an iso-electric point ranging from 10 and 11 and a molecular weight between 12 and 14 kDa, and this coagulant exhibits charge neutralization and adsorption mechanism as summarized from the review work of author [19]. In addition, some of these coagulants possess antimicrobial properties associated with the availability of saponins, phenols, and flavonoids [19].

*Circular economy in surface water treatment.* The traditional way of converting materials to new products and disposing of the waste generated from the activities or the one way of disposing of a thing bought after use, known as a linear economy, is no longer sustainable due to environmental issues and inefficient use of resources. A circular economy entails the efficient utilization of

resources and waste generation reduction via recycling and reuse. The circular economy is not a new approach, but its application to many sectors has been increasing recently while applying this principle to water treatment is rapidly emerging. [20]. The circular economy is about the 3rs, which means reduce, reuse, and recycle [21]. The 3r of water helps reduce the demand for freshwater and minimizes wastewater generation via recycling and reusing wastewater.

Consequently, water reuse, rainwater harvesting, and greywater recycling typically contribute to the circular economy of water, which can help address water scarcity and pollution challenges [20]. Authors [22] define a circular water economy with nine strategies: rethink, avoid, reduce, replace, reuse, recycle, cascade, store, and recover. In their review, the authors classified these strategies to decrease water use and the optimum and efficient water use and retaining water, as depicted in Figure 7. In addition, the work looked into the legislation needed, the implementation, and the challenges to be addressed to aid the transition to water circulation.

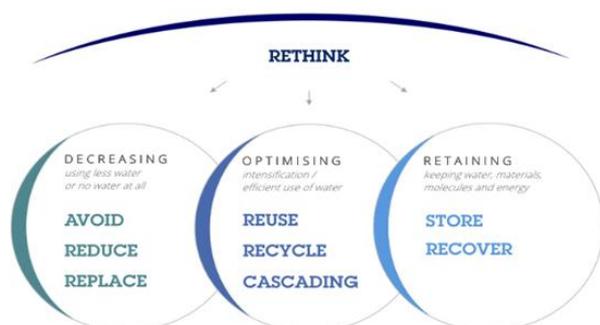


Figure 7 – The strategies of the circular economy of water [22]

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There are a few reported experimental works on the circular economy of surface water where natural coagulants are used. Authors [20] produced LENFLOC™ via continuous grafting of 2-methacryloyloxyethyl trimethyl ammonium chloride with 75 wt.% on h<sub>2</sub>o (DMC) onto lentil waste extract. They used the product to remove turbidity from agricultural wastewater, with circularity of water as one of the study's objectives. The results showed that the turbidity removal efficiency was approximately 99%. In addition, natural coagulation with LENFLOC generated a lesser volume of compact fluid than that generated with lentil waste extract as a coagulant. The LENFLOC-generated sludge was observed to have the potential for direct reuse, which supports water circularity.

## CONCLUSIONS

The review findings still affirm that using natural coagulants in surface water is promising, with many pieces of work, both review and experimental, found within the short time range. However, more experimental work is needed in the circular economy of water to achieve practical maximum water utilization, waste reduction, and water resource preservation.

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