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Efficacy of Natural Coagulants in Treating Selected Industrial Wastewaters

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Abstract
Natural coagulants offer an eco-friendly and biodegradable alternative to conventional inorganic coagulants. However, in spite of their proved efficiencies in several investigations, the widespread adoption of innate natural coagulants for treating water and wastewater remains relatively less. This could be due to several factors such as regulatory barriers, limited research, lack of awareness and the need for further optimization of their performance. Industrial effluents contain a range of organic and inorganic substances, biological materials, and toxic compounds, which can pose risks to public health and the environment. Traditional inorganic coagulants have been effective in treating wastewater but can alter water characteristics and complicate sludge disposal. Natural coagulants are a potential solution due to their efficient coagulation properties, lack of adverse effects on water characteristics, eco-friendliness, and biodegradability. While natural coagulants have demonstrated efficacy in research, they have yet to gain widespread acceptance in the water industry, possibly due to various barriers. Five natural coagulants were screened and four were used for further studies. A conventional Jar test apparatus was used for performing coagulation experiments. Tested coagulants have reported removal of turbidity of 97% and 30-40% removal of total dissolved solids and color respectively. Removal of other chemical impurities along with the aforementioned was governed by pH. Higher pH of pharmaceutical wastewaters reduced the efficiency of the coagulants. Nevertheless, the lower coagulant doses proved to be quite effective. These findings suggest a sustainable approach for the pre-treatment or treatment of industrial wastewaters.

INTRODUCTION

Water is undeniably a cornerstone of human and natural ecosystems, with its significance deeply woven into the hydrological cycle. This essential resource shapes the development of both human societies and the intricate web of ecosystems that populate our planet (Theodoro et al., 2013). Recognizing the vital role that water plays, the imperative of responsible water management has gained increasing prominence in latest times. The global community has been cautioned by prominent organizations such as the World Health Organization and the United Nations about the escalating threats of scarcity of water and the uncontrolled release of contaminants into our water bodies. These concerns extend beyond mere environmental matters, as they have a profound impact on human lives (Das et al., 2022). Water scarcity and pollution stand as challenges intricately linked to the pursuit of the Millennium Development Goals. While the concepts of water availability and reuse are far from novel, the global concern surrounding water stress has persisted for years. As evidenced by the persistent worries of communities worldwide, this challenge remains a prominent obstacle that demands our attention (Konapala et al., 2020).

Inappropriate water usage due to factors like industrialization, urbanization, population growth, leads to various challenges related to its availability and quality. These factors contribute to the depletion and degradation of water reserves, which can have widespread consequences for societies and ecosystems. The scarcity of water affects entire aspects of a community, which include social and economic dimensions. Further, water scarcity also poses a threat to natural resource sustainability indicating that the mismanagement and overuse of water resources will eventually lead to severe societal and environmental consequences (Kingsely et al., 2017).

Contaminated water exerts negative effects on health, which is prevalent in developing countries, with inadequate access to safe water sources that leads to greater incidence of waterborne diseases. In this context the need of the hour is to address challenges of promoting sustainable practices in water management and ascertaining access to safe water sources. This requires a multi-faceted approach involving infrastructure development, policies, and awareness campaigns towards mitigating the negative impacts of water pollution and scarcity. The need for pure and safe water has compelled extended investigations into the methods for water treatment (Kumar et al., 2017). Poor water quality resulting in water borne diseases is a concern in many developing countries. On the other hand, the decontamination processes employed by advanced countries often involve the use of chemicals, which while being effective in removing contaminants, end up in the long-term health effects.

Surface water sources are characterized by varying turbidity which is at peak during rainy seasons. Most of these sources such as rivers and lakes, are commonly used for domestic water supply. Turbidity is attributed to the presence of sediments, suspended solids, and organic materials. Water with high turbidity causes aesthetic concerns which will also interfere with the treatment process and its effectiveness. Coagulation and flocculation are essential stages in treatment of water which aid in reducing turbidity and removing suspended particles. These processes entail addition of chemical coagulants to the water that will destabilize the suspended particles and aggregate them, which makes their removal easy. However, the important point to be noted is that the types of coagulants and the process of coagulation are to be tailor made based on the quality of the source water and the desired quality of the treated water.

More attention is being received by natural coagulants attributed to their eco-friendly nature and potentially safer option for water treatment over the concerns with chemical coagulants owing to their negative health effects such as water chemistry changes, like altered pH levels (Rajesh Banu et al., 2021). Moreover, reports on some chemical coagulants leading to health issues such as allergies, tumors and cancer are also documented. Hence. the pursuit for safer and more sustainable alternatives like natural coagulants is justified.

Plant based coagulants is perceived to be a better sustainable practice compared to the production and use of chemical coagulants. Additionally, the abundance of plant sources makes these alternatives readily available (Amir Hariz Amran, 2018). However, it's important to note that while natural coagulants offer promising benefits, the effectiveness of coagulants vary based on factors like source/type of water subjected to treatment and the type of coagulant used. Research and development in this context continue to be significant in order to fully understand the possible benefits and drawbacks of natural coagulants and towards optimizing their application for various water and wastewater treatments.

Peel from banana, a natural polyelectrolyte has been investigated for its ability to remove effectively various pollutants from water, including turbidity, sulfates, nitrates, and heavy metals like zinc, lead, chromium, copper and iron. The use of natural coagulants for water treatment is not only effective but also brings about several advantages, especially in rural areas. Natural coagulants being readily available in rural areas, making them economical solution for water treatment, particularly in resource-limited settings. Since, the rural communities are familiarized with use of certain plants for treatment of water owing to traditional knowledge, the process of adoption and implementation will be easier. Natural coagulants are biodegradable, and hence, do not contribute to the accumulation of non-treatable waste in the environment.

The process of coagulation using natural coagulants is comparatively simple, requiring least maintenance, which is specifically advantageous in areas with limited technical expertise or infrastructure. Nevertheless, there are also challenges associated with the large-scale use of natural coagulants. First, the extracting and processing cost of natural coagulants can be a limiting factor, which also varies depending on factors such as sourcing, processing, and transportation. Further, their performance can also vary depending on factors such as source of the coagulant, seasonal variations in its availability and processing methods. Hence, possibility of achieving consistent performance can be challenging. Research continues to address these challenges and find ways to optimize the use of natural coagulants in industrial settings. As technology advances and methodologies are refined, it's possible that natural coagulants could play a more significant role in large-scale wastewater treatment in the future (Choy et al., 2014; Yin, 2010).

A significant amount of waste, including lemon and banana peels, is discarded daily, leading to environmental concerns. However, these waste materials can be repurposed as natural coagulants due to their low cost, non-hazardous nature, and environmental friendliness. Research focusing on natural coagulants, particularly in combination with materials like banana peel and lemon peel, has demonstrated their potential for water treatment applications. These natural coagulants can serve as alternatives to harmful chemical coagulants like alum. The advantage of using these natural alternatives is that they can effectively aid in water clarification while also being safer for the environment and human health. Studies have identified optimal pH levels and coagulant dosages for these natural materials, ensuring their efficacy in the coagulation process. For example, research has shown that banana peel can act as a coagulant capable of absorbing substances like Biological Oxygen Demand (BOD), which is a crucial parameter in assessing water quality (Anyakora, 2022).

By utilizing waste materials as natural coagulants, researchers are contributing to sustainable environmental technology. These waste materials are renewable in nature, and their application can directly impact the enhancement of living conditions in underdeveloped communities. This approach aligns with the principles of circular economy and resource optimization, where waste is transformed into a valuable resource for a different purpose. Previous research has mostly concentrated on testing the efficiency of coagulants to treat surface water and a very few industrial wastewater. It is understood that coagulants are to be optimized or tested for their performance for individual industrial wastewaters as their efficiency varies or is governed by the initial quality of water to be treated. In these lines, the present study is an attempt to test the efficacy of natural coagulants for treating different wastewaters.

METHODOLOGY

The present study involves the investigation of various natural coagulants for water treatment efficiency. The study was conducted in three stages with the following objectives:

Stage 1: Initial Screening of Coagulants

Coagulant doses (1, 2, 3, and 4 mg/L) of different natural materials (Lemon peel, Banana peel, Groundnut shell, Onion Peel, and Papaya peel) were tested for their coagulation efficiency. The coagulants were selected based on their availability in the study region, apart from them being waste that can be reused sustainably.

Results from this stage guided the selection of coagulants for further experiments.

Stage 2: Efficiency Testing at Lower Doses

The selected coagulants were tested for their efficiency at lower doses (0.5, 1, 1.5, and 2.0 mg/L) based on promising results obtained from Stage 1.

Stage 3: Optimization and Industrial Effluent Testing

The third stage involved optimizing coagulant doses at even lower levels (0.05, 0.1, 0.15, and 0.2 mg/L). The optimized coagulants were then tested for treating industrial effluents from steel plant and pharmaceutical. The breakdown of the experimental process:

- ✓ **Procurement and Preparation of coagulants**

Analytical grade ferric chloride was acquired from Himedia chemicals. Natural coagulants (Lemon peel, Banana peel, Groundnut shell, Onion Peel, and Papaya peel) were collected locally or bought from the market. Ferric chloride was used directly, while the plant-based coagulants were oven dried, ground into powder, and stored for later use.

- ✓ **Jar test experiments**

The coagulation efficiency experiments were carried out using a conventional Jar test apparatus (Cintex Flocculator). Synthetic turbid water (1 liter) with known characteristics was prepared in 2-liter beakers using kaolin. Weights of powdered coagulants were measured and added to the beakers according to the desired concentrations. The solutions were agitated at 120 rpm for 2 minutes and then at 30 rpm for 30 minutes. The stirring speed was optimized previously and has been adopted for this study. After agitation, the solutions were allowed to settle under still conditions for 30 minutes.

- ➢ **Analytical methods**

The study followed protocols from the American Public Health Association (APHA) for the analytical methods used.

The research approach is thorough and methodical, covering initial screening, optimization, and testing on actual industrial effluents. This multi-stage formulation allows for comprehensive assessment of the coagulants' potential applications in water treatment, particularly in treating industrial wastewater. All the experiments were conducted in triplicates in order to ensure and minimize errors statistically.

RESULTS

Initial Screening:

The initial screening stage of the study aimed to evaluate the efficiency of different natural coagulants for water treatment. The results obtained from this stage are summarized in Figure 1, which reveal significant findings:

Turbidity Removal:

Among the tested natural coagulants, onion peel exhibited the highest turbidity removal at a concentration of 1 mg/L, achieving a remarkable 96% removal, suggesting its significant coagulation potential for reducing water turbidity.

Electrical Conductivity:

Most of the natural coagulants led to an increase in electrical conductivity after treatment. However, lemon peel was an exception, showing no increase. The changes in electrical conductivity can indicate alterations in the ionic composition of the treated water.

Total Dissolved Solids (TDS) removal:

Lemon peel demonstrated TDS removal of 17% at a concentration of 1 mg/L and 11% at 2 mg/L. This indicates that lemon peel may have the ability to partially reduce dissolved solids in water. On the other hand, the other coagulants seemed to contribute to an increase in TDS after treatment.

Colour Removal:

Onion peel emerged as the most effective coagulant for colour removal, with the highest removal observed at a dose of 1 mg/L. Additionally, all doses of onion peel showed better colour removal compared to other coagulants, while the remaining coagulants tended to add colour to the treated water.

Sludge Dewaterability:

The ability of coagulants to aid in sludge dewatering was assessed. Papaya seed achieved the highest sludge dewaterability at 28.97 mg/L, suggesting its potential in facilitating the removal of water from sludge. On the other hand, lemon peel at 1 mg/L showed the least sludge dewaterability at 6.30 mg/L. These findings provide valuable insights into the performance of various natural coagulants at different concentrations. Onion peel and papaya seed appear to be particularly promising coagulants based on their high turbidity removal and sludge dewaterability, respectively. Lemon peel's effects on TDS and sludge dewaterability are noteworthy, albeit in different ways. The overall results suggest that different coagulants have varying strengths and limitations in terms of water treatment effectiveness. Further optimization and testing on industrial effluents will likely help refine their practical applications.

Optimization of Coagulant dose

Figure – 2 illustrates the results for optimization of the coagulant dose, here the dose of the coagulants was decreased depending the requirement for treatment of the sample. For lemon peel the electrical conductivity showed nor increase nor decrease results whereas for remaining coagulants like banana peel, groundnut shell, onion peel increased concentration was noticed. Highest turbidity removal was observed for all the doses of onion peel with 98% followed by with groundnut shell, lemon peel and banana peel. Addition of total dissolved solids was noticed for all coagulants except for lemon peel, the highest removal rate was observed at 14% a lowest at 7% both by lemon peel coagulant. Highest colour removal was observed with 80% at 0.5mg/l dose of onion peel, remaining coagulants induced colour to the treated water.

Figure – 3 illustrates the optimization of the coagulants dose for the treatment of water samples with decreasing the doses. There was no increase nor decrease in the electrical conductivity of the lemon peel coagulant after treatment whereas remaining coagulants showed increase levels of conductivity in the treated water. Highest and lowest turbidity removal was observed with 97% and 85% at 0.15mg/l dose of onion peel and 0.05mg/l dose of groundnut shell. Not much of total dissolved solids removal was observed after the treatment, the variation noticed was of 1% and the least removal was observed with 0.43% at 0.05mg/l dose of groundnut shell and no change at 0.1mg/l dose of groundnut shell, remaining showed increasing levels after treatment. Highest colour removal of 91% at 0.2mg/l dose for onion peel and least was noted with 13.17% for 0.15mg/l dose of lemon peel.
Figure – 4 presents the efficacy of onion peel with reducing coagulant doses where its performance was stable even at reduced doses.

pH changes pre and post treatment and Sludge settleability and dewaterability produced from treatment of Steel Plant Wastewaters

Figure – 5 illustrate the pre and post changes of pH concentration and sludge settleability and dewaterability produced from treatment of Steel Plant Wastewaters. There were few doses where the pH level was decreased compared to the initial pH range and the best result was achieved with the chemical coagulant that was Alum. Sludge weight difference was observed to be highest in alum followed by onion peel, banana peel, lemon peel and groundnut shell.

Treatment of Steel Plant Wastewater using natural coagulants

Table 1 illustrates the treatment of steel plant wastewater using both natural and chemical coagulants where the electrical conductivity was seen with no change except for alum and onion peel. Highest turbidity removal was observed for alum with 98% followed by onion peel, groundnut shell, banana peel and lemon peel with least turbidity removal of 80% at 0.2mg/l dose. Highest removal of total dissolved solids was observed with banana peel at 94% for 0.15mg/l and least was noted with groundnut shell at 57% for 0.05mg/l dose, whereas alum at 0.15mg/l dose showed addition of total dissolved solids to the treated wastewater sample. Highest removal of colour was noted at 0.1mg/l with 94% for alum later followed by lemon peel at 0.05mg/l with 92% and the least was observed at groundnut shell with 1% at 0.05mg/l dose. Few coagulants induced colour to the treated water like banana peel and groundnut shell.
100% removal of total hardness was noted for both natural and chemical coagulants except for lemon peel. 100% removal of calcium hardness was observed for the coagulants. Highest chloride removal was observed at 11% for alum, and least was 6% for alum as well. Remaining coagulants showed either no change or increased concentration of chlorides in treated wastewater samples. Lemon peel at 0.1mg/l dose showed highest removal of iron from the wastewater sample after treatment with 97% and later followed by banana peel at 0.1mg/l dose with 83% removal, all the coagulants at 0.15mg/l dose showed an increase of iron to the treated wastewater sample (Figure – 6).

pH changes pre and post treatment and Sludge settleability and dewaterability produced from treatment of Pharmaceutical Wastewaters

Figure – 7 illustrates the pre and post pH changes after treatment and Sludge settleability and dewaterability produced from treatment of Pharmaceutical Wastewaters. Increase in pH concentration was observed compared to the initial values. Sludge difference was highest for onion peel followed by lemon peel, banana peel, groundnut shell and least with alum.

Treatment of Pharmaceutical Wastewater using natural coagulants

Table 2 illustrates the treatment of pharmaceutical wastewater treatment using natural coagulants where the highest electrical conductivity removal was observed with alum followed by lemon peel, banana peel, onion peel and groundnut shell. Turbidity removal of 97% was highest observed for alum, lemon peel and banana peel. 44% of total dissolved solids removal was noted for lemon peel at 0.05mg/l dose and least was observed at 3.55% removal for lemon peel at 0.20mg/l dose.

Increase of total hardness was observed after wastewater treatment for the except for few dose of alum, banana peel and onion shell which showed no change after treatment. Alum and lemon peel showed no change in removal of calcium hardness from treated wastewater sample whereas onion peel, groundnut shell and banana peel showed increase in concentration at few doses. Highest chloride removal was observed at 0.10mg/l dose for banana peel with 64% and least with 18% at 0.05mg/l dose for lemon peel. Colour removal was in the range of 27% - 36% whereas highest was observed for alum at 0.05mg/l dose and least for banana peel at 0.20mg/l dose with 22.39%.

Nitrates with highest removal was seen for alum at 0.10mg/l dose with 30% and least was observed for alum at 0.05mg/l dose with 0.86% removal. Few doses showed increased levels of nitrates after treatment for onion peel, groundnut shell, and banana peel. Highest phosphate removal was noted for banana peel with 40% at 0.20mg/l dose and least was observed for groundnut shell with 0.58% at 0.10mg/l dose. For sulphates the highest and least removal was observed for groundnut shell and alum at 0.20mg/l and 0.10mg/l dose with 37% and 3.56% followed by onion peel, lemon peel, whereas banana peel at 0.15mg/l dose showed increased range of sulphate in the treated wastewater sample (Figure – 8).

DISCUSSION

Initial Screening

The study presents that natural coagulants are considered a promising alternative to synthetic chemicals due to their safety for consumption and their ability to biodegrade in the environment. Moreover, utilizing plant waste for coagulation offers an economical option compared to using synthetic chemicals. Natural coagulants have also demonstrated effectiveness in water treatment applications (Nath, et al., 2020). The initial stage of the study involved screening five different natural coagulants: lemon peel, banana peel, groundnut shell, onion peel, and papaya seeds. The efficacy of these coagulants was evaluated based on parameters such as turbidity reduction, and reduction in electrical conductivity, colour, total dissolved solids (TDS) as well as sludge dewaterability. Onion peel reported greatest efficiency in removing turbidity (96%) and its sludge dewaterability was reported to be 23.79 mg/L. On the other hand, papaya seeds were modest to perform and hence were excluded from further studies as it induced electrical conductivity and TDS in the treated water. These results are basis for the subsequent sections of our study.

The results of screening experiments provided a clear understanding of influence of coagulant dose on removal of turbidity. The experiments indicated that turbidity removal was inversely proportional to the increased doses of coagulant. This trend is consistent with findings from previous studies (Mohd-Salleh et al. 2019). Maintaining the optimum coagulant dose is crucial to avoid both over-dosing and under-dosing, which can lead to reduced performance during the flocculation process (Ahmad et al., 2022). During initial screening, coagulant doses of 1, 2, 3, and 4 mg/L were tested, and it was observed that lower doses (1 and 2 mg/L) were more effective in turbidity removal. As a result of these findings, the decision was made to focus on lower coagulant concentrations for further studies.

Previous studies indicated that the efficiency of adsorption by coagulants is governed by various factors such as surface morphology, adsorbent surface area, polarity, functional groups attached to the surface, and distribution of pore size of the adsorbent. Turbidity removal in other studies has shown an increase with increasing coagulant dose, but this increase becomes less significant beyond a certain point. This observation aligns well with the results of your present study (Gaikwad and Munavalli, 2019).

Optimization of Coagulant Dose

This stage of the study delves into the importance of determining the optimum coagulant dosage for effective treatment while considering cost-effectiveness.

Importance of Optimum Dosage:

Optimal dosage determination is crucial to strike a balance between treatment performance and cost reduction. This consideration is supported by various studies (Rozainy et al., 2014; Hassan et al., 2009; Daud et al., 2015, 2018; Ahmad et al., 2022). The experiments were carried out using reduced coagulant doses of 0.5, 1.0, 1.5, and 2.0 mg/L. Similar trends to the initial screening were observed with coconut fibre coagulant, while other coagulants showed an increasing turbidity removal with increasing dose. Interestingly, the increase in total dissolved solids (TDS) and electrical conductivity in the treated water was reduced with the application of lower coagulant doses. All coagulants showed less color removal due to the lower doses applied.

Coagulant Dosing Conditions:

Generally, there are three dosing conditions in coagulation: low, optimum, and overdosing (Choy et al., 2015). The optimum condition is achieved when the right amount of coagulant is added, resulting in efficient removal. Overdosing can lead to similar or slightly lower removal rates, but it may result in higher sludge volume. Excessive coagulant presence can lead to re-charging and re-stabilization of colloid molecules, hindering floc growth and leading to porous and voluminous sludge. This phenomenon aligns with research that has explored the complexities of coagulant dosing and its impact on floc formation and sludge characteristics (Kristianto et al., 2019; Kristanda et al., 2021).

Impact of Turbidity on Coagulation:

The concentration of colloidal and suspended solids tends to be lower in water with low turbidity. An excessive dose of coagulant can lead to an increase in residual turbidity due to coagulant that remained un-combined. This is because of non-availability of sufficient particles to react with the coagulant protein. The optimal coagulant dose depends on the initial turbidity of the water being treated. For high turbidity water like kaoline-spiked water, the optimal dose was found to be in the range of 0.05 mg/L to 0.2 mg/L. This range achieved turbidity removal of up to 98%, as well as reducing other physico-chemical impurities. The coagulant dose required increases with increasing initial turbidity, particularly for water having high and medium turbidity. This is because greater charged sites are needed for adsorption and chemical bridging processes (Gaikwad and Munavalli, 2019).

pH and Coagulation:

The coagulation performance is influenced by the optimal relationship between coagulant dosage and the enhancing concentration of cations in the water. pH plays a critical role in the coagulation-flocculation process, as the coagulation reactions occur within specific pH ranges. For example, the optimum pH range for coagulation is around 6 to 7 when using alum and 5.5 to 6.5 when using ferric coagulants. In some cases, especially for high alkalinity water, adjusting the pH might be necessary to bring it within the optimal range for effective coagulation. Previous studies have indicated that the pH can affect the efficiency of natural coagulants. For example, banana pith was found to work best under acidic conditions (pH 4) for contaminants removal (Kakoi et al., 2016). Other studies have shown that the pH might not significantly change after using natural coagulants, such as neem leaf powder, banana stem juice, banana peel powder and papaya seed powder which maintained pH values between 7.1 and 8.0 (Maurya and Daverey, 2018). The pH range of 7–7.5 has been found to provide better turbidity removal when using watermelon seeds (Muhammad et al., 2015). Thus, pH of the coagulant is an important factor influencing better coagulation (Dollah et al., 2021).

pH plays a crucial role in turbidity removal during the coagulation process, although its impact is slightly less pronounced than that of coagulant dosage. The study observed the highest turbidity removal efficiencies at extreme pH values, such as close to 9.00 using onion peel and near 12.00 using banana peel. Justina et al. (2018) observed that tannin effectively removed turbidity from dairy effluent with an efficiency above ninety percent in the pH range of 5.00 to 10.00. Agarwal et al., (2003) noted variable behavior of natural polysaccharides based on changes in contact time and pH of the coagulant with the impurities in the medium. They also found that using okra as a flocculant for tannery wastewater achieved 98.26% and 93.08% removal of suspended solids at acidic pH i.e 4.00 and alkaline pH i.e. 9.20, respectively, after 1 hour of contact time. Utmost removal of suspended solids was 91.55%, at pH 7.00, which was noted after 3 hours of contact time, making neutral pH treatment less feasible due to the extended contact time required. Previous literature has reported that the activity of natural coagulants is owed to the protein long chains present in their molecules, that are responsible for aggregation of pollutants and floc formation (Bouchareb et al., 2021). Further the efficiency of these coagulants' changes with several factors such as raw water quality, coagulant type, dose etc but are more or less stable at a wide range of pH. On the other hand, metal-based coagulants release H^+ ions in water through hydrolysis which reduces the pH. Hence, chemical-based coagulants need adjustment of pH prior to coagulation, which increases costs of chemical reagents for water treatment (Benalia et al., 2021).

Treatment of Steel plant and Pharmaceutical Wastewaters

Numerous investigations have demonstrated the capability of natural coagulants for treating wastewater originating from various industries. Natural coagulants have presented potential in comparison to chemical coagulants in terms of treatment efficiency across different parameters of interest. Industries such as textiles (Dotto et al., 2019), dairy (Triques et al., 2020), tannery (Ahmed et al., 2020), and others have benefited from natural coagulation as a viable treatment option. pH 8 was found to be optimum for removal of chemical oxygen demand (86.1%), total suspended solids (99%), Ammonia (79%) and Nickel (100%) from steel industry wastewater using rose-hip powder as natural coagulant (Abujazar et al., 2022). Similarly, 99% removal of turbidity, 59.4% removal of chemical oxygen demand, 87.1% removal of ammonia and 80.3% of nickel were removed from iron and steel industry effluents with date stone powder as natural coagulant (Amr et al., 2023).

Oily steel works wastewater was treated by crude extract of *Moringa oleifera*, which is compared against alum. The results showed that *Moringa oleifera* was much effective in removing oil over alum and has also produced greater sludge volume (Lester-Card et al., 2023). Ahmad et al., 2025 used plant-based blended coagulants (neem, cassava and wild betel plant leaves) as coagulants for treating aquaculture wastewater. They obtained 85.17% removal of turbidity, 80.28% removal of total suspended solids and 59.42% removal of colour at a dose of 0.79mg/L and coagulant mass of 3.94mg. Diclofenac sodium containing pharmaceutical wastewater was treated with biochar prepared from chestnut shell. The study reported 92.5% removal of chemical oxygen demand, 84.545% removal of nitrate and 97.25% removal of phosphate from the wastewater (Bano et al., 2024). *Moringa oleifera* seeds were used to remove microorganisms and pharmaceutic residues from domestic wastewater. The results indicated reduction in the feacal coliforms (Sane et al., 2024).

Bioactive compounds from fruit peel waste:

Wastes of fruit peel contain bioactive compounds, which include phenolics (glycosides, flavanone hydroxycinnamic acids), ascorbic acid, citric acid, and carotenoids. These bioactive compounds play a role in influencing turbidity reduction and overall treatment efficiency. Past studies have highlighted the significance of these compounds in the coagulation process. Research by Asrafuzzaman et al., (2011) indicates that once turbidity reduction efficiency surpasses 70% using natural coagulants, acceptable limits set by the World Health Organization (WHO) can be achieved through filtration. Other studies have explored the use of specific fruit peel wastes for coagulation. For instance, Ismail et al., (2018) utilized dragon fruit peel waste and achieved an optimal dosage of coagulant with a turbidity removal efficiency of 67%. Mango peel waste (Duncan and key lime) have also shown potential for turbidity reduction, with reported removal rates of 74 and 66.4 percent respectively. Similar results have been acquired from experimenting with *Moringa oleifera*, where a turbidity removal at 50 NTU was reported to be 83.2% for low turbid water (Prodanović et al., 2025; Hartal et al., 2014). The environmental impact of agro-wastes is ever increasing and hence, there is a need for finding a sustainable solution for waste management as well as the possible potential of using such waste as value-added products like for example natural coagulants in water treatment.

Citrus peels generate a substantial amount of waste, which can be as much as forty four percent higher over juice production (Choy et al., 2014). To address this issue, citrus peel waste can be repurposed as secondary components containing antioxidants. This approach maximizes the utilization of the entire fruit and reduces waste. Some studies have explored the combination of chemical-based coagulants with natural-based coagulants. For instance, a combination of *Moringa oleifera* and alum has been used (Pise et al., 2015). This approach aims to reduce the reliance on chemical coagulants and leverage the potential of natural coagulants for turbidity removal in water treatment.

Fruit waste, which is readily available in households and restaurants, holds potential for water treatment. Utilizing fruit waste for coagulation can help in reducing waste volume, lowering production costs, and promoting environmental sustainability. Improper handling and disposal of fruit waste can have detrimental effects on the environment, leading to potential leaching into soil and water sources and contributing to pollution. In primary treatment, metallic coagulants are commonly used to aid in floc formation. However, this process often leads to the generation of greater volumes of sludge possessing characteristics that are not desirable. Using metallic coagulants can have environmental implications and contribute to waste management challenges.

Agro-industrial residues applications as coagulants aligns with the principles of bioeconomics and circular economy. The aim of such studies is to enhance coagulation process efficiency by reducing coagulant dosage and investigating reuse potential for waste products (like sludge) generated during the process. This approach contributes to a more sustainable treatment process by promoting the beneficial use of by-products and reducing the reliance on chemical coagulants. The production and application of naturally occurring coagulants fit well within the bioeconomic framework and contribute to a more environmentally friendly and sustainable effluent treatment process. The present study established the potential of fruit peel waste from citrus as a replacement for chemical-based coagulants in water treatment (Dollah et al., 2019). Similar findings were reported by other studies, such as Subashree et al. (2018) and Nair et al., (2019), which also indicated reductions in parameters like BOD and COD in wastewater (Muniz et al., 2020).

CONCLUSION

Natural and environment-friendly methods for treating industrial effluents are not only economical and sustainable but also address challenges in regions with limited technical expertise and access to chemical coagulants. These solutions are particularly important for developing and under-developed areas where conventional options may not be viable. Natural materials offer an environmentally-friendly approach to wastewater treatment, making them appealing for various applications. Natural coagulants can be further developed by addressing their limitations and considering them as aids or composite materials, combining the advantages of both natural and chemical coagulants. The growing interest in water and wastewater treatment industries, especially through coagulation-flocculation methods, indicates a promising future for natural coagulants. Preliminary studies have presented that agro-industrial wastes such as coconut shells, rice straws, peels of fruit and vegetables, among others, hold great promise as alternatives to conventional wastewater and water treatment methods. These agro-waste materials have unique chemical properties, peculiar structures, renewable nature, high selectivity and strong affinity properties.

This study outlines the multifaceted benefits of natural and environmentally-friendly solutions, considering their potential for various contexts and their role in shaping the future of wastewater treatment. It also emphasizes on the unique properties and characteristics of agro-industrial wastes highlights their viability as alternatives in water treatment processes. In summary, the use of waste materials as natural coagulants presents a practical and eco-friendly solution for water treatment. It not only addresses the issue of waste disposal but also offers a sustainable and affordable way to improve water quality and support communities, especially those with limited access to conventional treatment methods.

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Figure – 1: Initial Screening of Coagulant

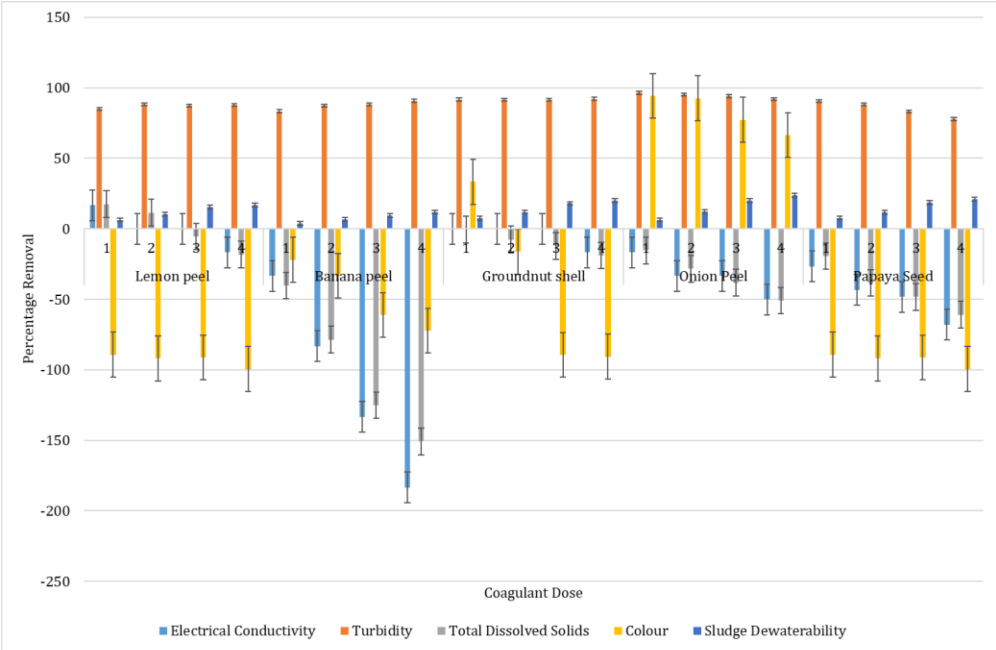

Figure – 2: Optimization of Coagulant dose

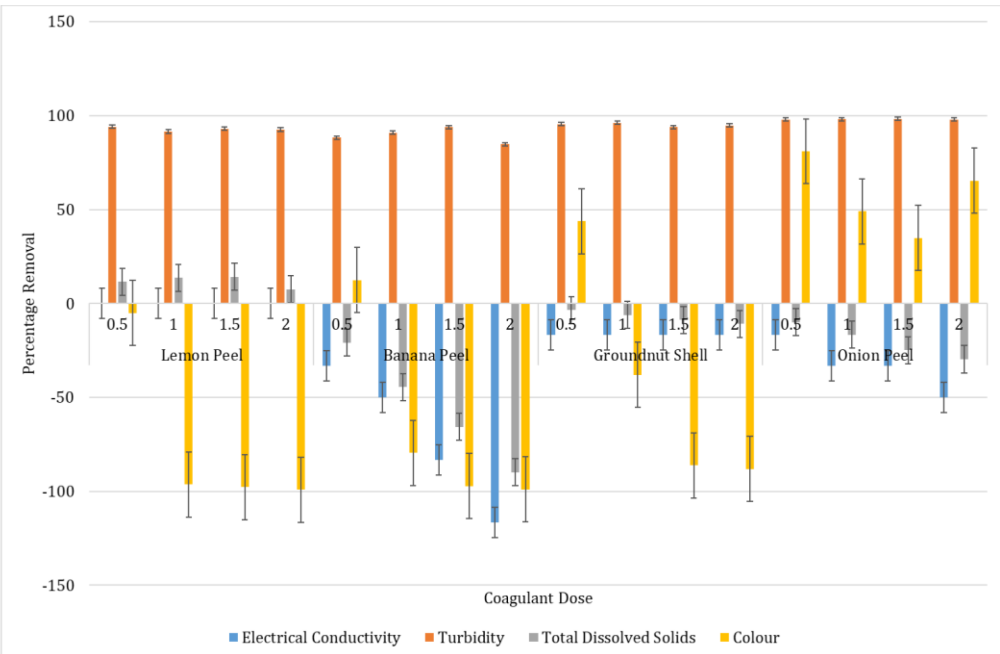

Figure – 3: Optimization of Coagulant dose

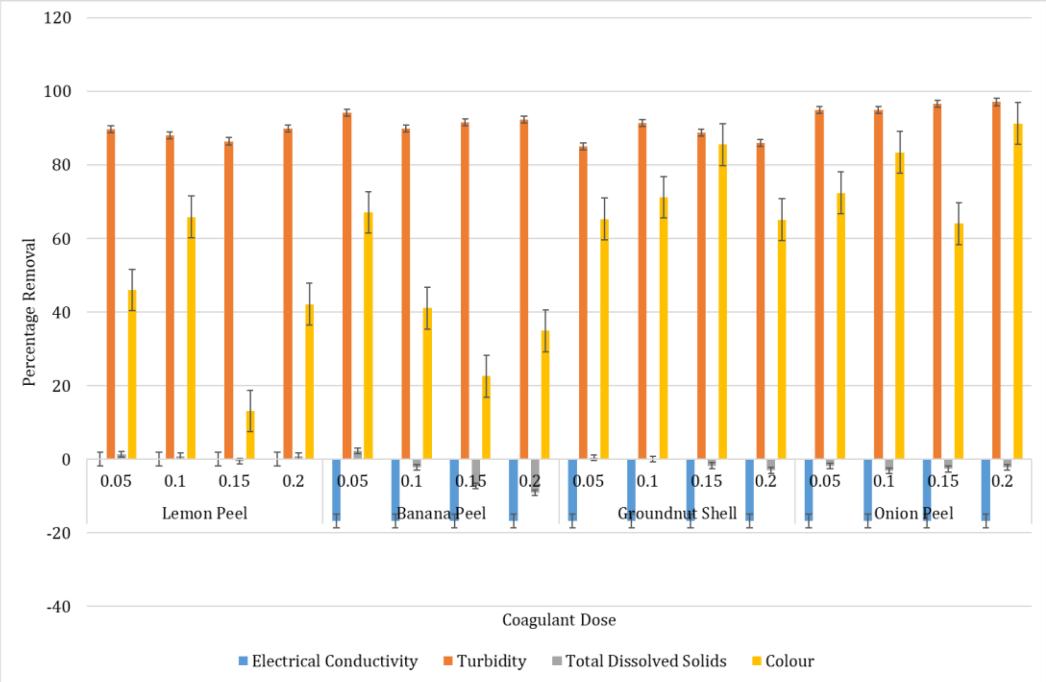

Figure – 4: Efficacy of Onion Peel with reducing Coagulant Dose

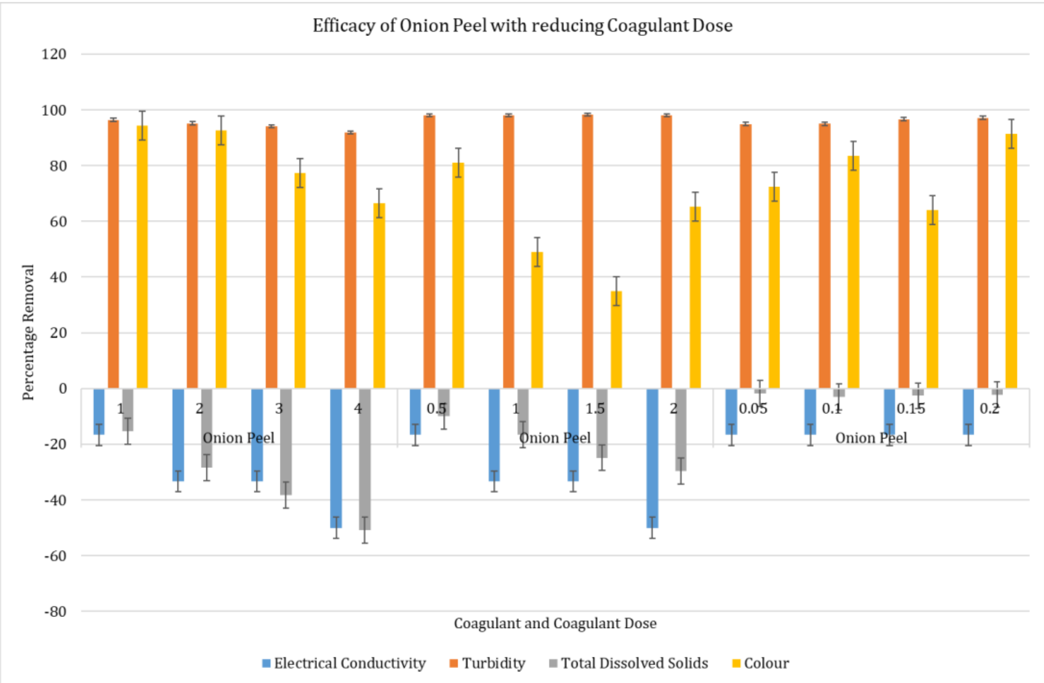

Figure – 5: Sludge settleability and dewaterability produced from treatment of Steel Plant Wastewaters

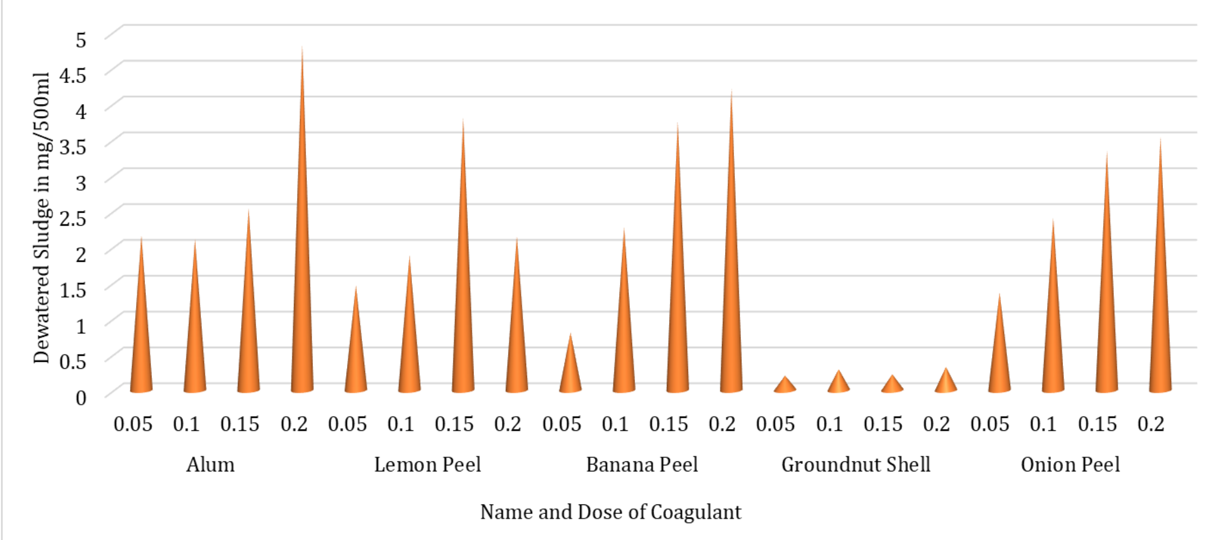

Figure – 6: Treatment of Steel Plant Wastewater using natural coagulants

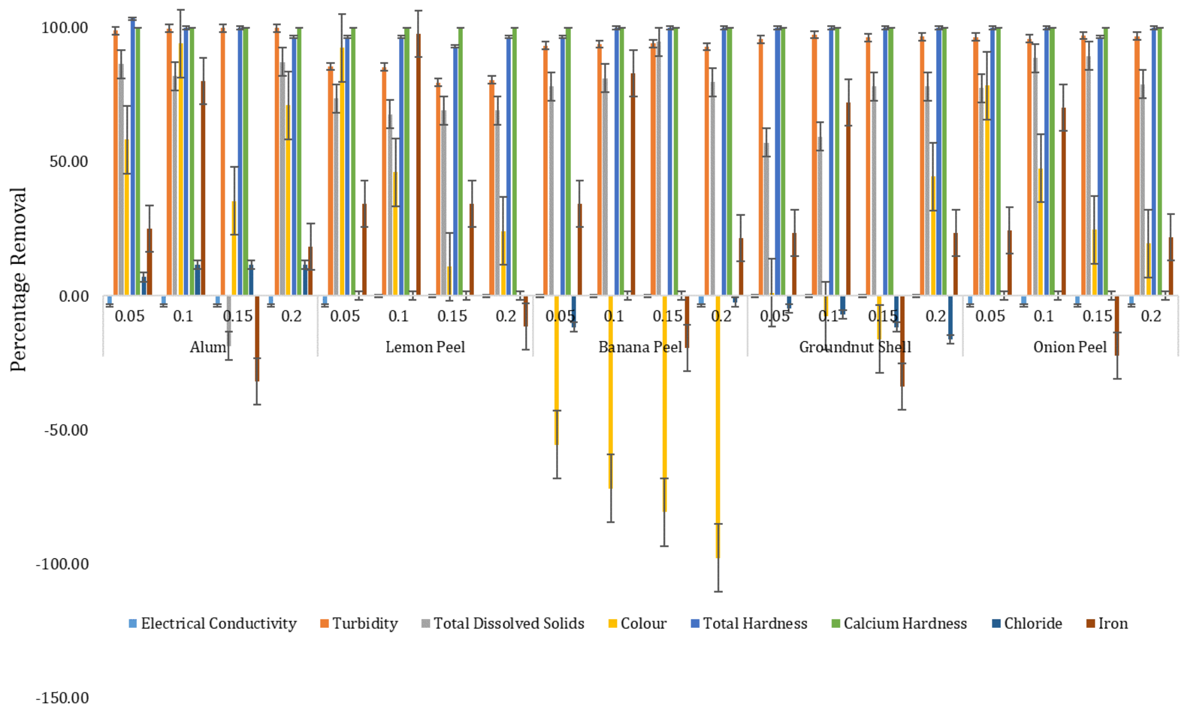

Figure – 7: Sludge settleability and dewaterability produced from treatment of Pharmaceutical Wastewaters

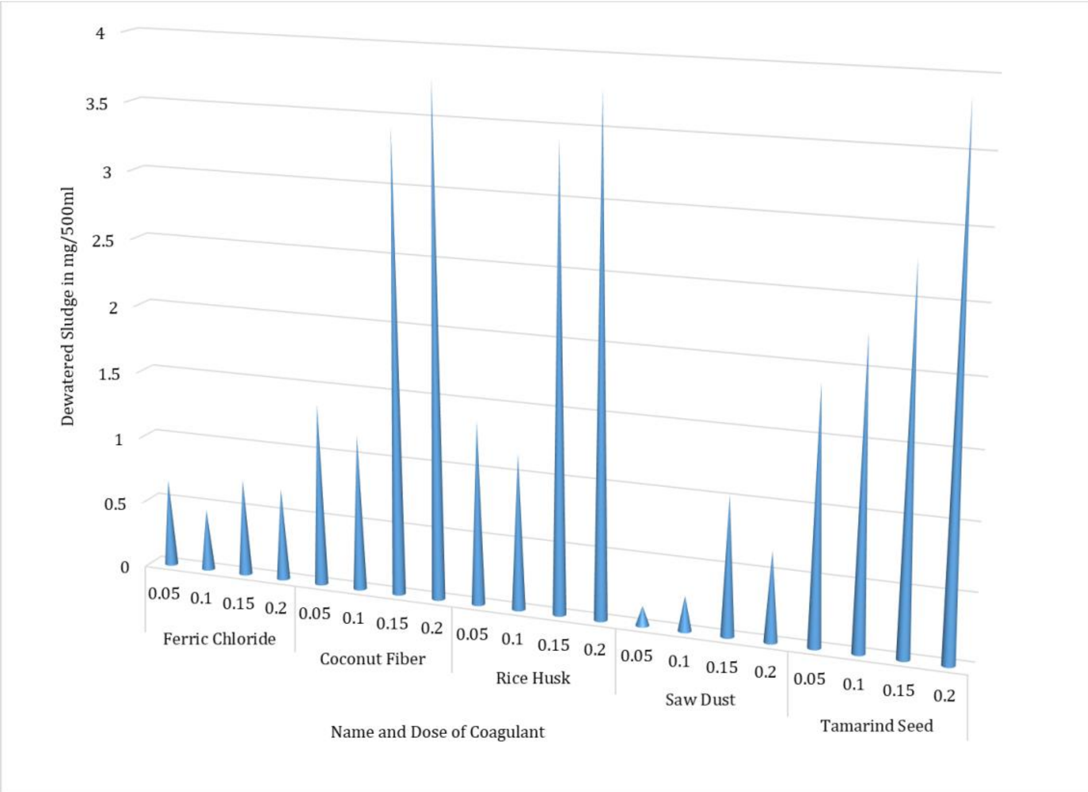

Figure – 8: Treatment of Pharmaceutical Wastewater using natural coagulants

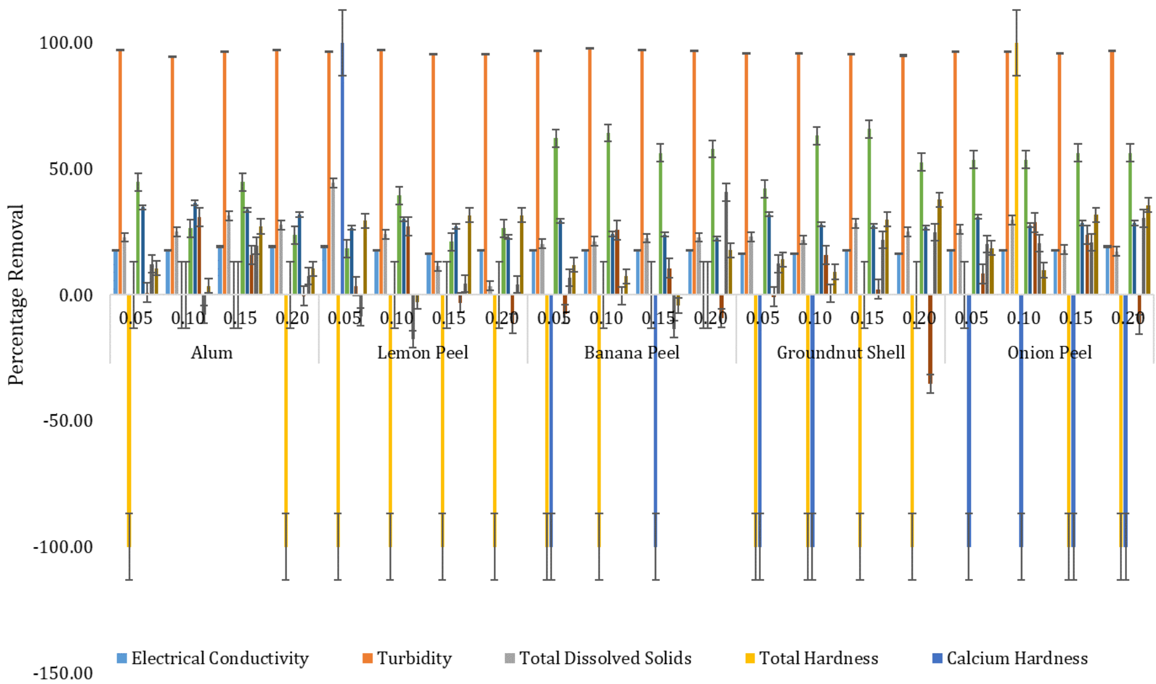

Table – 1: Treatment of Steel Plant Wastewater using natural coagulants

Name of the Coagulant	Coagulant Dose in mg/L	Electrical Conductivity	Turbidity	Total Dissolved Solids	Colour	Total Hardness	Calcium Hardness	Chloride	Iron
Alum	0.05	-3.57	98.91	86.47	58.29	103.45	100.00	6.98	25.06
	0.1	-3.57	99.78	81.95	94.11	100.00	100.00	11.63	80.00
	0.15	-3.57	99.89	-18.80	35.34	100.00	100.00	11.63	-32.05
	0.2	-3.57	99.89	87.22	71.15	96.55	100.00	11.63	18.31
Lemon Peel	0.05	-3.57	85.64	73.68	92.55	96.55	100.00	0.00	34.22
	0.1	0.00	85.42	67.67	46.15	96.55	100.00	0.00	97.83
	0.15	0.00	79.65	69.17	10.94	93.10	100.00	0.00	34.22
	0.2	0.00	80.63	69.17	24.16	96.55	100.00	0.00	-11.33
Banana Peel	0.05	0.00	93.36	78.20	-55.53	96.55	100.00	-11.63	34.22
	0.1	0.00	93.91	81.20	-71.88	100.00	100.00	0.00	83.13
	0.15	0.00	94.12	94.74	-80.67	100.00	100.00	0.00	-19.52
	0.2	-3.57	93.04	79.70	-97.79	100.00	100.00	-2.33	21.45
Groundnut Shell	0.05	0.00	95.76	57.14	1.08	100.00	100.00	-4.65	23.61
	0.1	0.00	97.50	59.40	-7.45	100.00	100.00	-6.98	72.05
	0.15	0.00	96.41	78.20	-16.23	100.00	100.00	-11.63	-33.73
	0.2	0.00	96.74	78.20	44.59	100.00	100.00	-16.28	23.61
Onion Peel	0.05	-3.57	96.63	77.44	78.49	100.00	100.00	0.00	24.58
	0.1	-3.57	95.97	88.72	47.60	100.00	100.00	0.00	70.12
	0.15	-3.57	97.17	89.47	24.64	96.55	100.00	0.00	-22.41
	0.2	-3.57	96.95	78.95	19.59	100.00	100.00	0.00	21.93

Table – 2: Treatment of Pharmaceutical Wastewater using natural coagulants

Name of the Coagulant	Coagulant Dose in mg/L	Electrical Conductivity	Turbidity	Total Dissolved Solids	Total Hardness	Calcium Hardness	Chloride	Colour	Nitrate	Phosphate	Sulphate
Alum	0.05	17.65	97.25	22.80	-100.00	0.00	44.74	34.78	0.86	12.28	10.52
	0.10	17.65	94.50	25.00	0.00	0.00	26.32	36.51	30.86	-7.77	3.56
	0.15	19.12	96.33	31.42	0.00	0.00	44.74	33.76	15.83	19.47	27.10
	0.20	19.12	97.25	27.70	-100.00	0.00	23.68	31.80	-0.48	7.38	10.29
Lemon Peel	0.05	19.12	96.33	44.43	-100.00	100.00	18.42	26.57	3.44	-8.74	29.34
	0.10	17.65	97.25	23.99	-100.00	0.00	39.47	29.99	27.11	-17.57	-2.80
	0.15	16.18	95.41	11.32	-100.00	0.00	21.05	27.13	-3.11	4.42	31.65
	0.20	17.65	95.41	3.55	-100.00	0.00	26.32	22.90	-11.33	4.03	31.65
Banana Peel	0.05	17.65	96.79	20.27	-100.00	-100.00	62.11	29.45	-7.57	6.75	11.87
	0.10	17.65	97.71	21.28	-100.00	0.00	64.21	24.15	25.71	-0.39	7.29
	0.15	17.65	97.25	22.47	0.00	-100.00	56.32	23.87	10.52	-13.64	-4.29
	0.20	17.65	96.79	22.80	0.00	0.00	57.89	22.39	-9.29	40.73	17.67
Groundnut Shell	0.05	16.18	95.87	22.97	-100.00	-100.00	42.11	31.94	-0.75	12.33	13.98
	0.10	16.18	95.87	21.79	-100.00	-100.00	63.16	27.94	15.78	0.58	9.13
	0.15	17.65	95.41	28.38	-100.00	0.00	65.79	27.45	2.15	21.75	29.94
	0.20	16.18	94.95	25.00	-100.00	0.00	52.63	26.70	-35.32	24.71	37.72
Onion Peel	0.05	17.65	96.33	26.01	0.00	-100.00	53.68	30.90	8.32	20.15	18.56
	0.10	17.65	96.33	29.73	100.00	-100.00	53.68	27.52	28.66	20.44	9.79
	0.15	17.65	95.87	17.91	-100.00	-100.00	56.32	28.47	23.78	20.78	31.68
	0.20	19.12	96.79	17.23	-100.00	-100.00	56.32	28.47	-11.76	30.34	35.58