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Enhancing the Efficiency of Banana Peel Bio-Coagulant in Turbid and River Water Treatment Applications

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Abstract: The aim of the present work is to investigate the potential use of banana peel waste as a natural coagulant and to enhance its coagulation performance using a green modification approach for the removal of synthetic water turbidity and river water treatment. Here, the regular banana peel powder had an average particle size and diameter of 978 ± 37 nm and 602 ± 13 nm, respectively, while the modified powder possessed 571 ± 41 nm and 360 ± 19 nm particle size and diameter, respectively. The coagulation performance was investigated at different pH levels, doses, sedimentation times, and NaCl quantities. The optimum dose was found to be 0.4 g/L for modified banana peel with turbidity removal of up to 90%. NaCl slightly enhanced the coagulation performance at low quantities of less than 0.4 g/L, but the activity was reduced at higher concentrations even in the modified powder. Banana peel powder had a weaker turbidity reduction of 76 and 84% for non-modified and modified powders in river water, respectively, in addition to significant reduction in water color, total dissolved and suspended solids, and chemical and biochemical oxygen demand. SEM and FT-IR characterization were performed to investigate and confirm the coagulation mechanism. Such a green modification of banana peel powder can be an alternative with significantly potential as a low cost and easily available bio-coagulant, which can certainly contribute to the waste reduction.

Keywords: banana peel powder; modification; coagulant; turbidity; water treatment; enhancement

Citation: Azamzam, A.A.; Rafatullah, M.; Yahya, E.B.; Ahmad, M.I.; Lalung, J.; Alam, M.; Siddiqui, M.R. Enhancing the Efficiency of Banana Peel Bio-Coagulant in Turbid and River Water Treatment Applications. *Water* **2022**, *14*, 2473. https://doi.org/10.3390/w14162473

Academic Editor: Tushar Kanti Sen

Received: 28 June 2022
Accepted: 8 August 2022
Published: 11 August 2022

1. Introduction

The consumption and usability of water worldwide have significantly increased in the past few years due to the surge in population [1,2]. Water bodies contain huge amounts of microscopic particles and dissolved impurities, making them unfavorable for human use, especially in tropical countries [3]. These impurities include organic and inorganic compounds, in addition to minerals, which significantly change the physico-chemical and biological characteristics of water [4,5]. Thus, surface water must undergo treatment and purification, which vary depending on the nature and characteristics of the water to be treated, and finally meet the standard limits for human use [6,7]. Coagulation is one of the water treatment approaches that depends on using plant or non-plant-based coagulants, which are substances used to remove water impurities such as color and turbidity from raw water, by forming large agglomerates that will eventually settle at the bottom of the container and can be removed [8].

Many chemical (non-plant)-based coagulants have been used in water treatment applications, such as iron and aluminium salts, in addition to some polymeric polysaccharides [9]. Aluminium-based salts (such as aluminum sulfate and chloride) and ferric-based salts (such as ferrous sulphate and ferric chloride) are the most widely used metal saltwater treatment coagulants [10]. Ferric chloride and aluminium sulphate are the most widely used metal-based coagulants that are characterized by their excellent performance in wastewater treatment; however, their use has the limitation of reducing the water pH to become close to acidic. In addition, they have been reported to cause some health issues to humans after the consumption of water, such as presenile dementia and Alzheimer's disease [11]. Another limitation of using metal salts as coagulant agents is the resulting large volume of sludge and the relative high coagulant cost [12]. Thus, plant-based coagulants are the suitable and safer alternatives for these chemicals.

Various plant-based coagulants have been used for water treatment applications, including *Moringa oleifera* [13], *Cicer arietinum* [14], and *Dolichos lablab* [15]. These materials have been found to contain several effective proteins that are responsible for coagulation processes, in which they chemically destabilize water suspended matters, making them come together to form bigger agglomerates known as flocs [16]. Coagulants from natural sources are often seen to be safe for human health [12]. Some natural coagulants have been studied and are known to have the following advantages: the sludge produced is usually biodegradable, virtually toxin-free, relatively cheap to obtain, and locally available [17]. A significant number of synthetic materials have been used in water treatment applications, such as cationic polymers [18], titania nanoparticle [19], and manganese ferrite nanoparticles [20], but these materials are potentially toxic and non-ecofriendly. However, some natural coagulants are valuable, expensive, and not highly available, which limit their usage. Ribeiro et al. [21] evaluated the efficiency of *Moringa oleifera* seeds as a natural coagulant and reported a high removal performance of turbidity and apparent color from wastewater. Kristianto et al. [22] investigated the potential of papaya seeds for the same purpose and reported a direct relationship between the coagulant dose and removal performance. Plant seeds may not be available in high quantities and they could be utilized for other purposes. In this study, we chose another form of plant waste consisting of banana peel waste as a natural coagulant.

The banana tree has been reported to produce from 3 to 20 fruits in a cluster only once a lifetime, and after the fruit has been consumed, different parts of the banana tree are not utilized, such as banana peels and stems, which are thus considered as waste [23]. This waste has a high quantity of many useful organic compounds, including cellulose, lignin, pectin substances, pigments, and chlorophyll, etc., in addition to low molecular weight organic compounds [24]. Worldwide, following the consumption of bananas, million tons of peels are mostly discarded and are rarely utilized. In Malaysia, banana is ranked as the second most widely cultivated fruit, and it can be utilised either ripe or unripe. The ripe banana is used for preparing fried banana and unripe banana is used for making chips [25]. Chip and juice factories consume huge amounts of banana and generate tons of banana peel waste every year. Banana peels, which account for approximately 40% of the total weight of fresh bananas, are normally dumped in landfills and result in environmental problems. Recent investigations have shown that the composition of banana peels mainly consists of several biopolymers, including pectin, cellulose, lignin, and hemicellulose, in addition to other chemical substances that contain a large amount of hydroxyl and carboxyl functional groups [26]. These active functional groups in banana peels are able to combine with contaminants via complexing, chelating, coordinating, hydrogen bonding, and/or other effects [27]. Thus, banana peel has gradually become a research hotspot as a highly available natural coagulant in water treatment applications. Several attempts have been made to enhance the coagulation performance of banana peels by either mixing them with other coagulants or conducting chemical modifications to the peels. Fu et al. [28] used chemical modification to produce oxidized banana peel in order to enhance the coagulation activity. Chemical modification may lead to chemical leaching in treated water and cause further issues. In this study, we used a facile and affordable preparation approach to enhance the coagulation performance of banana peel as a natural coagulant. This approach consists of multiple microwave radiation treatments followed by multiple grinding to reduce the particle size and modify the surfaces of the particles. The novelty of this research is to prove our hypothesis that the coagulation efficiency of the natural coagulant can be further enhanced without the need for any chemical reactions. Modified and non-modified banana peels were evaluated at different doses, different pH values, different sedimentation times, and different NaCl quantities. The coagulation mechanism of banana peel powder was also investigated by comparing the effect of the particle size and the solution of banana peels in a turbid water treatment.

2. Material and Methods

2.1. Materials

Matured and dry banana fruit (*Musa cavendish*) were obtained from a local market and were classified by a botanist to ensure the species. Kaolin clay was purchased from Kaolin Malaysia Sdn Bhd, Malaysia, while NaCl was obtained from Merck, Darmstadt, Germany.

2.2. Preparation and Modification of Banana Peel Powder

The banana fruits were peeled, carefully washed, cut into small pieces, and then air dried (At room temperature) for several days. After full drying, the peels were ground into a fine powder using a mortar and pestle to obtain the regular banana peel powder. Modified banana peel powder was prepared using a green approach, consisting of microwave treatment (Panasonic microwave oven-NN-CT254B, New Delhi, India). The powder was first prepared following the same mentioned steps in addition to multiple microwave treatments at a power of 800 W for 0.5 min, and then cooling and grinding after each treatment to reduce the particle size and modify the surface morphology of the particles.

2.3. Preparation of Banana Peel Solution

Ten grams of each banana peel powder were measured and added separately to one liter of distilled water to form the banana peel powder suspension. The suspension was stirred for 1 h with a magnetic stirrer to ensure all of the protein and active compounds were fully dissolved, and it was then left to settle for 30 min. The filtrate was finally collected and concentrations of 1 to 10 wt.% were prepared.

2.4. Characterization of Nano-Banana Peel Powder

The morphological characteristics of the modified and non-modified banana peel powder were examined using a Field Emission Scanning Electron Microscope (FE-SEM) model Leo Supra, 50 VP (Carl Zeiss, SMT, Frankfurt, Germany). The particle size distribution was investigated using a laser diffraction analyzer (Nano-ZS90, Malvern, UK). A 1 nm to 100 µm size range was used for a suspension of 0.01% consistency of each powder, which was dispersed for 15 min with ultrasound at 100% power. The surface functional groups of the banana peel powder were investigated using FT-IR spectroscopy (Thermo Scientific model Nicolet I S10 spectrometer, Thermo Fisher Scientific, Waltham, MA, USA).

2.5. Preparation and Standardization of Turbid Water

To ensure a constant turbidity value for all of the experiments, synthetic turbid water was prepared and used for all of the coagulation experiments. First, 10 g of kaolin clay particles was added to 1 L of deionized water to obtain the stock solution [29]. The turbidity was then standardized at 110 NTU by diluting the stock solution using deionized water. River water was obtained from Penang River on 22 January, and the sampling process was done following the process described in [30] and samples were directly sent to the laboratory for characterization.

2.6. Coagulation Experiment

The coagulation experiment was done using the jar test experiment. Water samples were added to 500 mL jars and the coagulants were added to the jars. Different types, doses, pH, and NaCl concentrations were used, and the time and stirring speed were fixed at 200 rpm for 2 min followed by 10 min of slow mixing at 20 rpm and then 30 min of settling [4]. A constant volume of 50 mL of each concentration of prepared banana peel solution was used. Each experiment was repeated three times and the average value was taken.

2.7. Characterization of River Water

Water temperature was measured using a regular digital thermometer in the field during sample collection, and it was held for 1 min in each water sample. The water color was observed with naked eye using different colored backgrounds. The pH was measured using automatic waterproof meters from Wagtech International Ltd. (Nairobi, Kenya), and the total dissolved and suspended solid was measured with a waterproof TDScan Low from Eutech Instruments (St. Louis, MO, USA), as described in [31]. The chemical oxygen demand (COD) and biochemical oxygen demand (BOD) were measured using a DR2800 spectrophotometer and dissolved oxygen meter, following the methodology described by Shan et al. [32].

3. Results

3.1. Characterization of Nano-Banana Peel Powder

Figure 1 presents the FE-SEM images of the modified and non-modified banana peel powder. The surfaces of the non-modified powder seemed smoother and had no signs of any fractions (Figure 1a). On the other hand, the modified powder seemed more homogeneous with rough and sticky surfaces. Multiple microwave treatments of the banana peel powder produced mild heating, which induced fractions in the particles, as highlighted with the arrows in Figure 1b, which also reduced the size of the particles. Eng and Loo reported that the microwave-assisted extraction of the banana peel bio-flocculant was found to be better than conventional heating extraction [33].

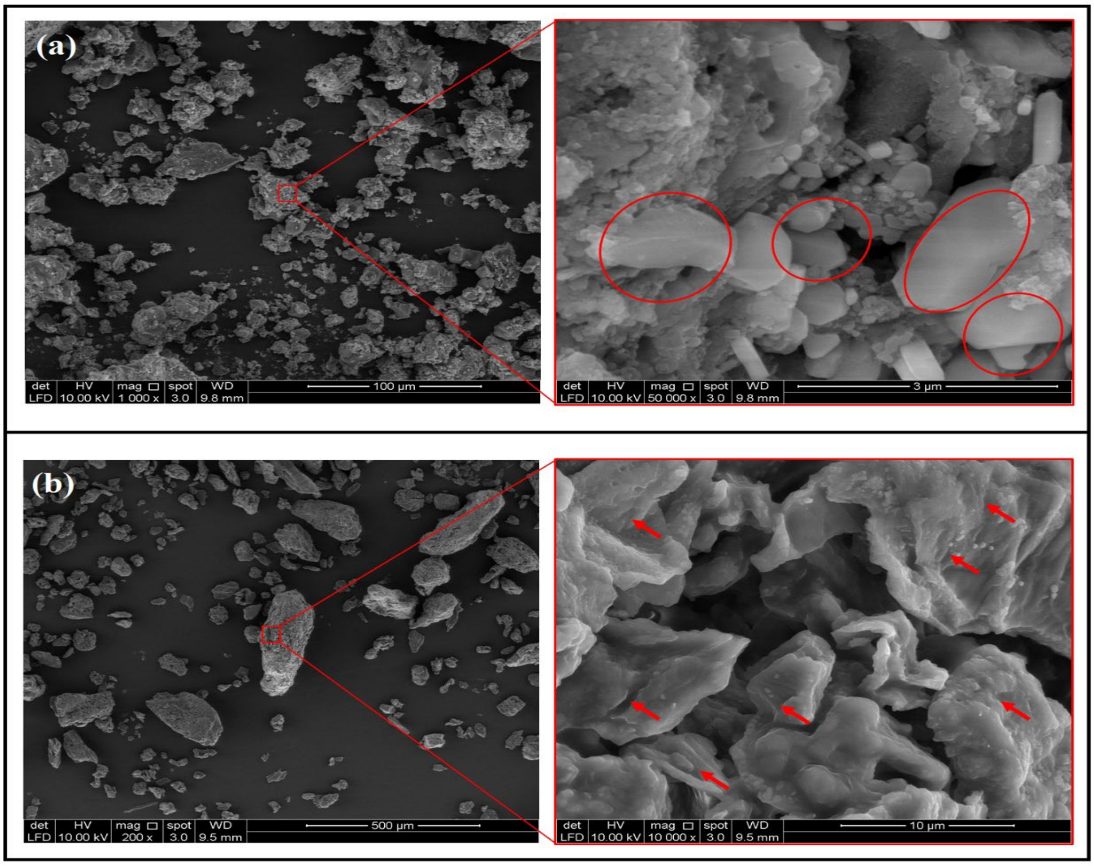

Figure 1. Morphological analysis of modified and non-modified banana peel powder; (**a**) non-modified powder exhibiting smoother surfaces and (**b**) modified powder exhibiting sticky surfaces, with clear fractions as the arrows indicate.

The regular banana peel powder had an average particle size of 978 ± 37 nm and average diameter of 602 ± 13 nm, as presented in Figure 2a, compared with modified banana peel powder, which showed an average particle size of only 360 nm and average diameter of 543 nm (Figure 2b). Microwave treatment did not significantly affect the particles diameters, and a huge reduction in particle size could be confirmed compared with the diameter. Many functional groups can be seen in the FITR spectra (Figure 2c), with a broad peak at 3421.57 cm^{-1} attributed to the hydroxyl groups. The sharp peak at 2923.06 cm^{-1} was due to CH stretching vibrations, including CH, CH_2, and CH_3 groups [34]. Another two interesting peaks, 1637.65 cm^{-1} and 1054.40 cm^{-1} are characteristics of C=O in aromatics rings and C-O stretching [35]. However, the FT-IR spectra did not show any significant difference between modified and non-modified banana peel function groups, and the particle size analysis and surface morphology confirmed the effect of treatment.

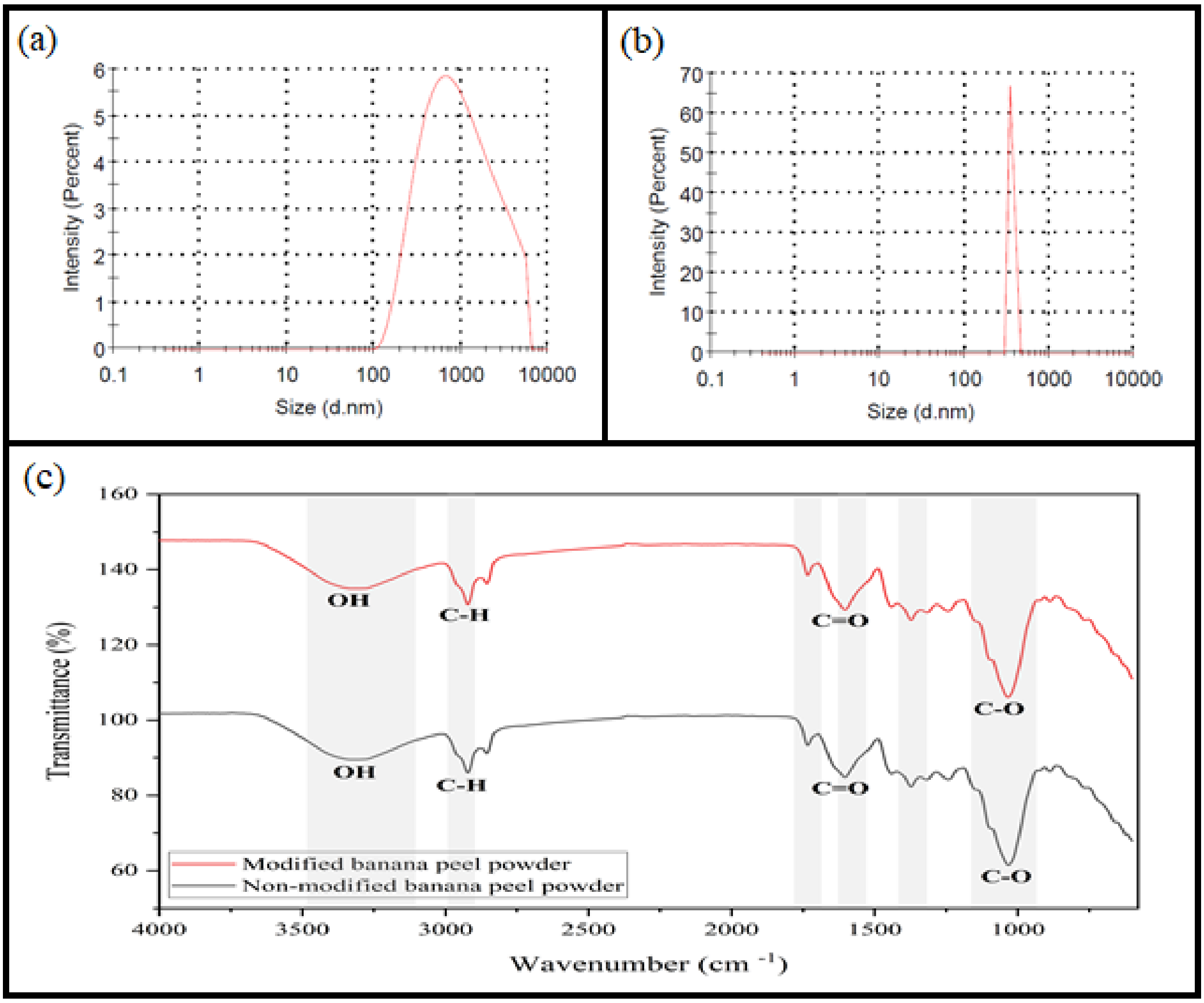

Figure 2. Particle size analysis and FT-IR of modified and non-modified banana peel powder; (**a**,**b**) average particle size of non-modified and modified banana peel powder, respectively, and (**c**) FT-IR spectra.

3.2. Coagulation Experiment

3.2.1. Effect of Dose on the Coagulation Performance

Figure 3 presents the effect of changing the dose of both the modified and non-modified banana peel powder on the coagulation performance. It can be observed that the effect steadily increased with increasing the dose concentration in a similar manner in both materials. The highest removal dose differed between the modified banana peel powder

(0.4 g/L) and non-modified powder (0.6 g/L). Higher doses led to a reduced removal efficiency, which could be attributed to the slight dissolving of polysaccharides and other materials in the banana peel powder, which led to a slight decrease in the removal activity. Our results were better than those obtained by Parvatham et al. [27], who used a lower turbidity of only 44 NTU and reported that the optimum dose of banana peel was 5 g/L. Banana peels contain several bio-flocculants [36], and the smaller size and sticky edges of the modified powder helped in releasing such materials, placing them in contact with turbid water. Thus, a smaller dose (0.4 g/L) in modified powder was enough to achieve w removal of 90% for the overall water turbidity.

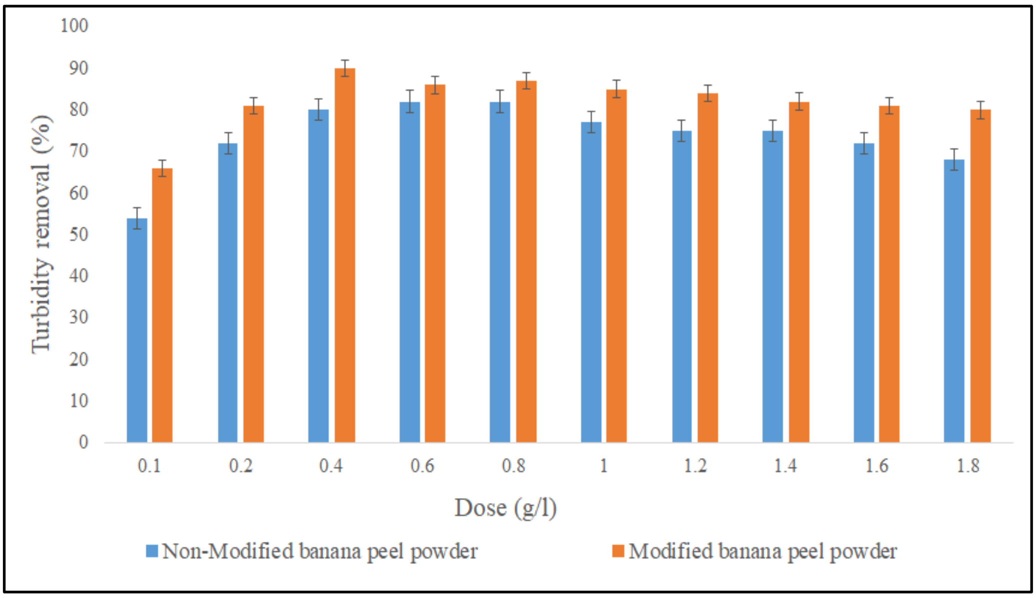

Figure 3. Coagulation activity of the modified and non-modified banana peel powder at different doses.

3.2.2. Effect of pH on the Coagulation Performance

A better coagulation performance was found in neutral conditions with a pH value of 6 to 8. Figure 4 presents the coagulation performance of banana peel powders in which can be clearly seen that it affected both of them in a similar manner, despite the superior activity of modified banana peel powder. Using the optimum dose of modified and non-modified banana peel powder, the turbidity removal was reduced when the pH become acidic, at (pH = 2) 57 and 55 % for the modified and non-modified banana peel powder, respectively. However, at an alkaline pH (pH = 11), the turbidity removal was reduced by 78 and 62% for modified and non-modified banana peel powder, respectively. A previous study a showed similar finding, that banana peel had the best turbidity removal in natural and slightly alkaline pH (pH 8.0) [37]. At natural and slight alkaline pH, the coagulant cationic charged banana peel particles were equal to the clay particles (anionic suspension), and thus destabilized them all through the coagulation mechanism. In a previous study by Chong and Kiew, the authors achieved turbidity removal in alkaline (93.4%) and acidic (81.4%) conditions, and reported a significant decrease in the coagulation performance when the pH of the solution was increased (from 4–8), while this increased drastically beyond pH 8 [38]. This can be explained by the complex structure of the banana peel material, which may contain amphoteric ions. As reported in a previous study, the removal mechanism of banana peel involves both coagulants and flocculants, which mean the action of more than one mechanism at the same time [39].

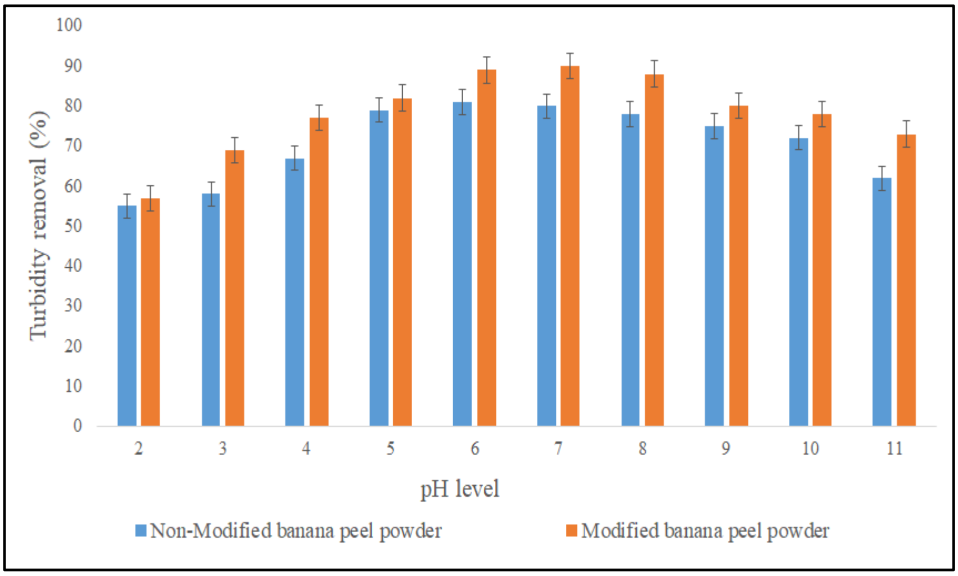

Figure 4. Coagulation activity of modified and non-modified banana peel powder at different pH levels.

3.2.3. Effect of Sedimentation Time on the Coagulation Performance

In this study, sedimentation time seemed to not have a significant effect on the coagulation performance. Similar results were reported after 30 min of sedimentation in both samples, as can be seen from Figure 5. The powder requires some time to sedimentate, only the huge flocs were directly sedimented after 10 min, in which the turbidity removal was 76 and 64% for modified and non-modified banana peel powder, respectively. Similar results were obtained by Mahmudabadi et al. [40], who reported that the removal efficiency of the coagulant remained constant after a sedimentation time of 100 min. In our study, only 30 min was needed to sedimentate all the flocs and to achieve the optimum turbidity removal. Another study used the aqueous extract of *Moringa oleifera* and showed results of turbidity removal with sedimentation time similar to ours [41]. However, although there were significant differences in the particle sizes in our study, modified particles were able to form large flocs and sedimentate in a similar time as the larger non-modified banana peel powder.

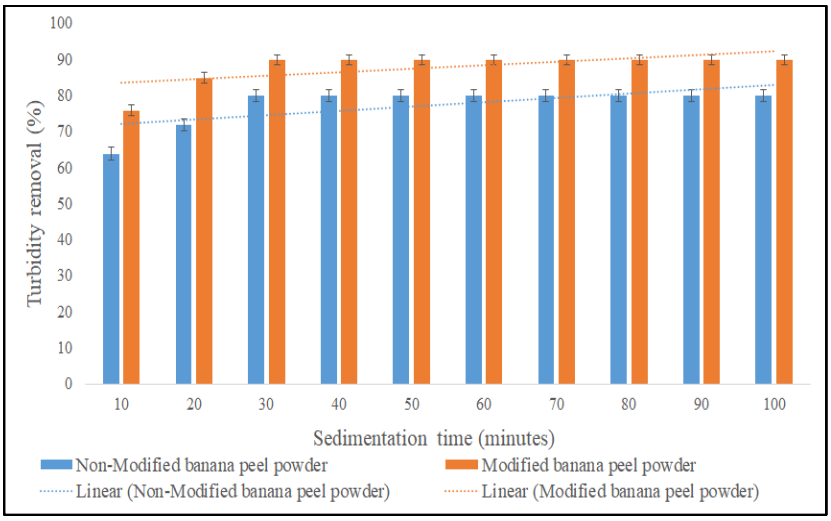

Figure 5. Coagulation activity of modified and non-modified banana peel powder at different sedimentation times.

3.2.4. Effect of NaCl Quantity on the Coagulation Performance

The effect of different quantities of NaCl on the coagulation performance of modified and non-modified banana peel powders is presented in Figure 6. It can be seen that NaCl in small amounts of less than 0.4 g/dm^3 showed enhancement in the coagulation performance by 2% (from 90% to 92%). A larger quantity induced a dramatic drop in the activity. NaCl was used to increase the solubility of banana peel proteins by the salting-in effect, which enhanced the breaking of protein associations, leading to increased protein solubility [42]. NaCl worked in a similar manner for both the modified and non-modified banana peel powders, which could be due to the ion exchange that occurred between the clays and Na^+ ions, and the coagulation efficiency of banana peel did not depend on the protein contents. This exchange led to increasing the negativity of the surface charge in the clay and enhancing the coagulation performance, while a larger amount of NaCl caused alterations in the coagulant charges, leading to limiting its coagulation performance. A previous study done by Eskibalci and co-workers reported the same results, where large quantities of NaCl increased the turbidity values and reduced the coagulation activity [43]. Although NaCl is not harmful to humans and the environment, adding it to drinking water could raise another issue of changing the water taste and it thus become unacceptable for drinking.

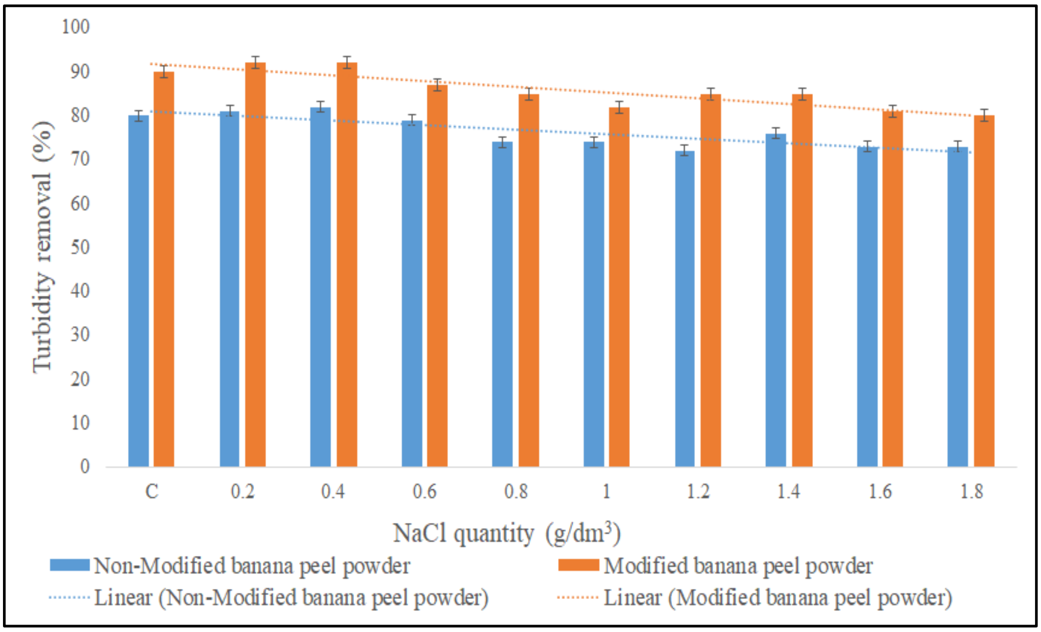

Figure 6. Coagulation activity of modified and non-modified banana peel powder at different NaCl quantities.

3.2.5. Effect of Powder Solution on the Coagulation Performance

The solution of banana peels had a weaker coagulation effect compared with the powder (Figure 7). The modified banana peel solution generally had a stronger effect than the non-modified banana peel solution, and the coagulation effect of both solutions steadily increased with the increase in their concentration. At the lowest concentration of 1 wt.%, the turbidity removal was almost similar for modified and non-modified banana peel solutions at 35 and 33%, respectively. However, at the maximum tested concentration (10 wt.%), the turbidity removal increased to 81 and 72%, respectively. Microwave treatment helped with the extraction of active compounds from banana peel [44], which explained the enhanced effect of the modified banana peel solution, although at the same concentration. The SEM figures show the fractions in the particle surfaces that allowed the particles to be fully hydrated, allowing the active compounds to be released from them. Pathak et al. [45] reported that the surface of their banana peel became rough and porous after microwave treatment, which confirmed the efficiency when releasing the active compounds. Similarly, Vu et al. [46] found that microwave treatment assisted the extraction of phenolic compounds from banana peels by inducing porous and surface fraction. Although the optimum solution in banana peel was found to be the strongest, it still considered weaker than the powder. Mokhtar et al. [36] used NaOH to enhance the extraction of active compounds from banana peels and reported that only 0.1 g/L was enough to achieve 88% turbidity removal. Our findings could have been less than that, but using NaOH will end up with the addition of another drawback, as further processes will be required to remove it from the water.

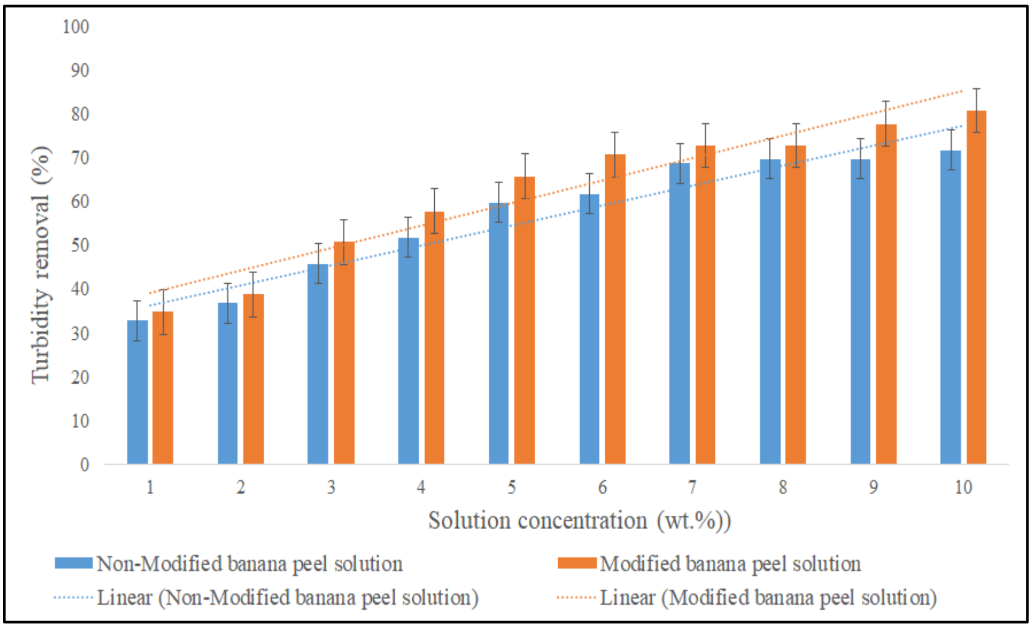

Figure 7. Coagulation activity of different concentrations of modified and non-modified banana peel solutions.

3.3. Effect of Modified Banana Peel Powder on River Water Treatment

Modified and non-modified banana peel powders were applied for actual river water at the optimized conditions to investigate their effect in other water treatment parameters. Table 1 presents the physico-chemical parameters of the river water before and after the treatment. It can be observed that the reduction in river water turbidity was less than that in the synthetic turbid water, which was 76 and 84% for non-modified and modified banana peel powder, respectively. However, this could be due to the initial turbidity level (36%) and/or turbidity of river water, which could be due other chemical or microorganisms in which banana peels have limited coagulation action in [28]. Recently, Yimer, and Dame reported that coliform bacteria can highly affect the initial river and surface water turbidity, which were significantly increased when increasing the dose of the natural coagulant up to certain dosage stage [47]. Banana peel biomasses contain various chemical groups such as carboxylic acid, phosphate, and hydroxyl groups, which also act as active centers for the adsorption of water color, TDS, TSS, and COD [48]. Microwave treatment of banana peels increases their adsorption capacity, which explains the enhanced removal of river water pollutants after modified banana peel treatment. Modified banana peel powder significantly increased the adsorption capacity of river water pollutants, which may be accredited to the superior ion exchange capacity and favorable microprecipitation on the surfaces due to the presence of a high porosity in the modified particles compared with the non-modified ones, as reported by Li [49].

Table 1. Effect of modified and non-modified banana peel powder in river water treatment.

Parameter	Before Treatment	After Treatment	
	Result (Mean ± SD)	Non-Modified Banana Peel Powder	Modified Banana Peel Powder
Temperature (°C)	29	29	29
Turbidity (NTU)	36.1 ± 3.4	8.5 ± 1.2 (76%)	5.76 ± 1.7 (84%)
pH	6.78 ± 0.1	6.92 ± 0.4	6.98 ± 0.6
Color	Faint brown	Colorless	Colorless
Total dissolved solid (mg/L)	43.6 ± 5.1	8.3 ± 1.1	5.7 ± 3.3
Total suspended solid (mg/L)	35.2 ± 1.3	11.8 ± 2.5	9.3 ± 1.4
Chemical oxygen demand (mg/L)	87.2 ± 4.2	61.8 ± 3.9	60.1 ± 2.8
Biochemical oxygen demand (mg/L)	31.7 ± 2.3	26.2 ± 1.8	24.4 ± 1.1

4. Discussion

Several studies used microwave and ultrasonic treatment during the coagulation process, without examining the effect of these treatments on the particles themselves [50]. The significant reduction in particles size could be due to the fragility of the fibers after multiple microwave treatments. Despite the mild heating in each treatment, microwaves are able to induce surface fractions on smooth surfaces, leading to their breaking and detachment, which explains the insignificant reduction in particle diameters [44]. Eng et al. [33] extracted bio-flocculants from banana peels and used them in pure form, and reported an optimum turbidity removal performance of only 45.16%. However, the results of this study were significantly higher than that. Based on our finding, it can be seen that modified banana peel powder had the best action compared with the non-modified one and their solutions. Exposing the powder to microwave radiation produces more fractions in the powder's particles, which enhances their adsorption and captures the turbidity, leading to a better performance. The scanning electron micrograph showed the existence of pores favorable for the sorption mechanism, which explains the reduction in river water pollutants, besides turbidity reduction. The modified banana peel powder exhibited a coagulation and sorption mechanism of action; the enhanced removal of river pollutants confirms the sorption action of the powder. Our findings confirm the results of several studies on the sorption mechanism of banana peel powder [49,51,52]. Charge neutralization and bridge formation are the two main known coagulation and flocculation mechanisms for most natural plant coagulants [53]. At a constant condition, the coagulation performance of the three materials of banana peels can be compared, as presented in Table 1. The filtrate of banana peels was considered to be one, as there were no significant different between the modified and non-modified filtrate at small concentrations, which presented only 38% removal capacity compared with the modified powder, which was 92% at the same conditions. Although the dose of banana peel was relatively higher than that of the literature, most previous literature used filtrate rather than raw powder, which increased the costs and processing time. Table 2 presents a comparison of our findings with other natural coagulants in different conditions. As shown in the table, different natural coagulants experimented under different conditions, and the turbidity removal among them ranged between 54 to 96% for apricot seed extract and moringa seed powder, respectively [54,55]. Our modified banana peel powder recorded a 92% reduction under natural conditions, which is comparative with other coagulants, considering it as a waste.

Table 2. Comparison of the coagulation performance of the modified banana peel powder with previous literature.

Bio-Coagulant	Optimal Experimental Conditions			Turbidity Removal (%)	Reference
	Dose (g/L)	pH	Type of Waste Water		
Banana peel extract	0.1	1	Synthetic domestic wastewater	88	[36]
Moringa seed powder	0.15	6–8	Paper mill effluent	96	[55]
White popinac	0.05	7	Synthetic turbid river water	76	[56]
Iraqi date seed extract	0.06	7	Synthetic turbid water	90	[57]
Apricot seed extract	0.03	7	Raw surface water	54	[54]
Jackfruit peel extract	0.1	2	Sewage synthetic wastewater	70	[58]
Banana peel powder	0.4	7	Kaolin synthetic wastewater	59	[59]
Non-modified banana peel powder	0.6	6–8	Kaolin synthetic wastewater	81	This study
Modified banana peel powder	0.4	6–8	Kaolin synthetic wastewater	92	This study

Figure 8 presents an illustration of the coagulation mechanisms for the three tested samples, namely non-modified banana peel powder, modified banana peel powder, and their solutions (filtrate). The primary purpose of using a coagulant, besides removing very fine particles from suspensions, is that this process results also in less turbidity of the water, i.e., clearer water. With the coagulants' positive charge, the negatively charged particles in the water are neutralized. Banana peel possesses positively charged proteins and polysaccharides that interact with opposite (negatively charged) suspended solids, leading to their neutralization and precipitation. Forming bridges between the particles enhances the removal efficiency, which could occur in modified banana peel as a result of modification. Although regular banana peel particles also possess positive charges, the larger size of the particles restricts the bridging performance of the particles. Vilardi et al. [60] reported that banana peel possessed a good adsorption capacity for heavy metals, which is a different mechanism of banana peels in water treatment. The smaller size of the modified powder helped to reduce the repulsive forces between the clay particles, resulting in a higher formation of microflocs and thus a better coagulation performance. Rapid mixing is normally used to enhance the formation of microflocs and to induce the collision between the coagulant particle and suspended solids [61]. However, as our study used constant mixing for the two powders, modified banana peel powder formed more micrflocs in a faster manner compared with the unmodified one, and this formation of bridge linkages then promoted the binding effect (due to the surface roughness) among them. This process results in the formation of much larger flocs, consisting of small banana peels and suspended solids in the subsequent flocculation process. In the case of using non-modified banana peel powder, the large particles may sediment without forming large flocs, thus producing a lower coagulation performance.

The raw water was faint brown in color, due to the high turbidity, and total dissolved and suspended solids. After the treatment with both powders, it can be observed that modified powder had better action in reducing all of the parameters. Although the chemical oxygen demand of raw water was 87.2 $\pm$ 4.2 mg/L, a small reduction occurred even in the case of modified powder, which reduced to 60.1 $\pm$ 2.8 mg/L. River water collected several types of chemical compounds and minerals, and the action of the banana peel was limited to the formation of flocs and/or formation of bridge linkages [61]. Not all the chemicals can be coagulated around the particles, and thus limited action was reported for COD. This hypothesis can be confirmed with the results of the biochemical oxygen demand, which reflected the action of microorganisms. It slightly reduced from 31.7 $\pm$ 2.3 mg/L to 26.2 $\pm$ 1.8 and 24.4 $\pm$ 1.1 mg/L for non-modified and modified banana peel powders, respectively. Similar findings were reported for BOD, and the authors reported a slight decrease and reported that the increase in BOD was due to the natural coagulant itself, especially at high dosage [62]. Based on the results obtained from the present study, modified banana peel powder has great potential in water treatment applications, and it could be also used in the adsorption of dyes and other pollutants [60,63].

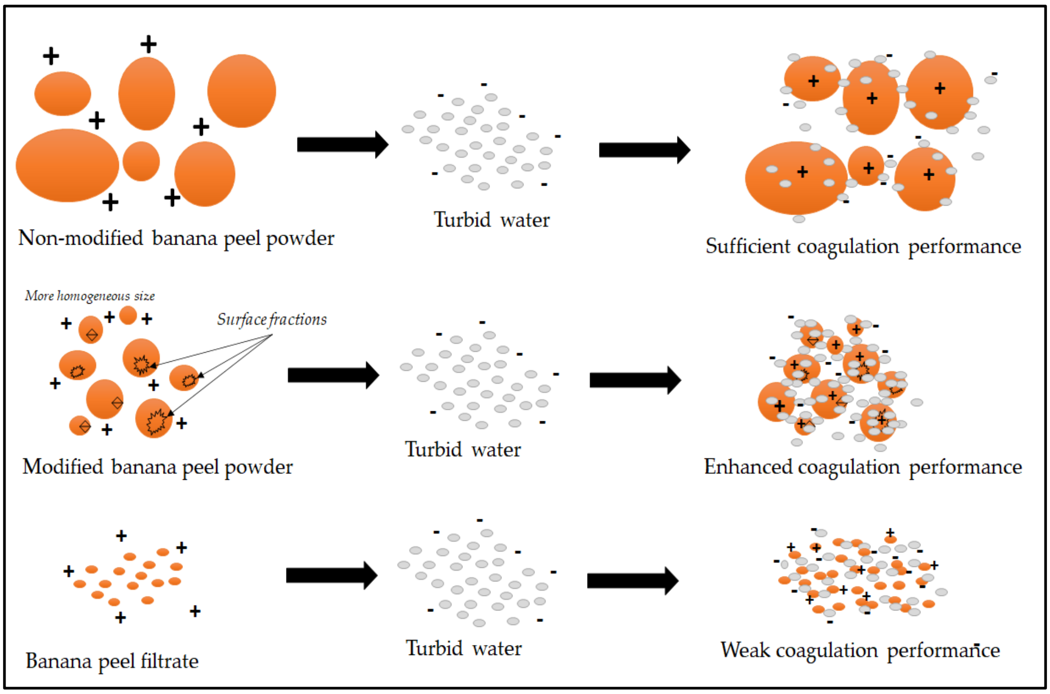

Figure 8. Schematic illustration of the coagulation performance of modified and non-modified banana peel powder, and banana peel filtrate.

5. Conclusions

The utilization of plant wastes has always been a golden goal for many scientists to ensure the sustainable utilization of natural material and minimize the use of chemical or synthetic substances. This study confirmed the ability to use green enhancement of banana peel waste in water treatment applications. Based on all the findings that have been gathered, it can be concluded that banana peels after microwave modification presented a high coagulation performance compared with non-modified powder. The filtrate of banana peel showed a weaker effect at the same dose, and increased with increasing the dose. Microwave treatment of banana peel powder induces fractions in the particles, leading to rough and porous surfaces that significantly enhanced the coagulation performance. The mild heating of treatment also assesses the grinding process, resulting in a smaller particle size, which also enhanced the coagulation performance. The significant reduction in river water turbidity, color, total dissolved and suspended solids, and chemical and biochemical oxygen demand demonstrated the potential of modified banana peel powder as an alternative solution to synthetic, chemical, or even expensive natural coagulants, in addition to added value to the utilization of banana peel wastes available.

Author Contributions: Conceptualization, A.A.A., E.B.Y. and M.R.; writing—original draft preparation, A.A.A. and E.B.Y.; writing—review and editing, M.I.A., J.L., M.A., M.R.S. and M.R.; supervision, M.I.A., J.L. and M.R.; funding acquisition, M.R. and M.R.S. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful to the Researchers Supporting Project Number (RSP-2021/326), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support this study are available in the article.

Acknowledgments: The authors are grateful to the Researchers Supporting Project Number (RSP-2021/326), King Saud University, Riyadh, Saudi Arabia.

Conflicts of Interest: The authors declare no conflict of interest.

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