Efficiency of Dextran as a Bioflocculant in the Treatment of Industrial Wastewater

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Manuscript received March 28, 2025; revised May 28, 2025; accepted August 7, 2025; published Mach 18, 2026

***Abstract*—Wastewater treatment using biopolymers produced by bacteria is an emerging approach that seeks to offer sustainable and efficient solutions for wastewater management. For this reason, the present work evaluated the efficiency of dextran as a in the treatment of industrial wastewater. A molecularly identified strain whose 100% identity corresponded to the species *Leuconostoc pseudomesenteroides* was used for this purpose. The flocculant activity of dextran was evaluated using doses of 20 and 40 ppm, while a concentration of 5 ppm was used for aluminum sulfate. Subsequently, the contents were transferred to 250 mL cylindrical test tubes and left to stand for 96 h. To analyze the effectiveness of these treatments in water purification, parameters such as turbidity, dissolved oxygen, and total solids were assesse in the treated samples and compared to an untreated control. While aluminum sulfate was found to be more effective in reducing turbidity and total solids, dextran demonstrated promising results, particularly at higher concentrations, where an enhancement in dissolved oxygen efficiency was observed. Additionally, dextran, at a concentration of 40 ppm, was identified as the most effective treatment in reducing fecal coliforms. In summary, dextran is presented as a promising option for wastewater treatment, highlighting its efficacy and environmental benefits.**

***Keywords*—bioflocculant, *Leucnostoc pseudomesenteroides*, dextran, industrial wastewater, coliforms**

I. Introduction

According to existing literature, a considerable proportion of wastewater in developing countries is discharged into untreated water bodies, posing a substantial threat to the environment [1, 2]. Untreated effluent discharges from various industries are frequently characterized by high levels of toxicity due to the presence of hazardous organic and inorganic contaminants, including phenolic compounds and colorants derived from various industrial activities. These effluents exhibit high concentrations of Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), in addition to considerable turbidity [3–5]. In this context, water contamination by microorganisms, particularly total coliforms, serves as a key indicator of microbiological contamination. Furthermore, the percentage of dissolved oxygen is a fundamental parameter for assessing water quality and its capacity to support aquatic life [6]. According to a United Nations report, approximately 80% of wastewater worldwide is untreated before being discharged into rivers or bodies of water, increasing pollution and seriously affecting aquatic ecosystems [7]. A similar situation is observed in Latin America. According to the World Bank, more than 70% of wastewater is discharged without adequate treatment, posing a threat to aquatic biodiversity and public health. This problem is particularly pronounced in regions with inadequate treatment infrastructure, where industrial activities contribute significantly to these discharges [8].

The 2023 Yearbook of Environmental Statistics by Peru's National Institute of Statistics and Census (INEI) reports that a considerable number of industries in Peru have fail to comply with established wastewater treatment standards. Between 2014 and 2019, it was observed that the volume of treated industrial wastewater was insufficient to cover the volume of wastewater generated, exacerbating the risk to water bodies. It is noteworthy that departments such as Amazonas and Huánuco showed a steady increase in wastewater generation, with Lima reaching a peak of more than 90 million cubic meters in 2020 [9].

Due to the aforementioned problems, it is crucial that wastewater receives adequate treatment before discharge in order to significantly reduce the level of contaminants present. In this regard, various technologies currently exist for the treatment of wastewater effluents, which are applied before discharge into water bodies. These treatments include conventional and advanced technologies [10, 11].

Most of these treatments incorporate coagulation and flocculation as essential processes to separate suspended particles from the water. This treatment stage requires various substances, such as aluminum, iron salts, and polymers [12, 13]. However, these compounds can cause adverse effects, such as excessive sludge generation and changes in water pH, leading to negative environmental consequences. They also pose a risk to human health, as they can accumulate in ecosystems and enter the food chain [14, 15].

Consequently, new alternatives have emerged for removing contaminants from treatment plant effluents, such as the application of bioflocculants. These compounds are derived from living organisms or their parts, including plants and marine fibers. They are completely organic and biodegradable, which positions them as an environmentally sustainable alternative, as they minimize pollution and reduce the health risks associated with chemical flocculants [16, 17]. It should be noted that research related to flocculants has gone through several stages before its large-scale implementation. In this regard, three main categories have been identified: chemical flocculants, grafted flocculants, and natural flocculants. The latter, known as bioflocculants, have comparable efficiency to chemical flocculants. Consequently, bioflocculants derived from various sources are considered a promising alternative for use in effluent treatment processes, potentially replacing the predominant chemical flocculants [18–20].

II. Literature Review

In this regard, it has been established that flocculation mechanisms are closely related to bioflocculants compounds, a subject that has been investigated by several authors. For instance, Tsilo *et al.* [21] studied the production of a bioflocculant from *Pichia kudriavzevii* for wastewater treatment. For the extraction of the bioflocculant, they used a mixture of butanol and chloroform. The identification of carbohydrates, proteins, and uronic acid was performed using phenol-sulfuric acid, Bradford, and carbazole assays.

The findings indicated that the removal efficiencies for Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Phosphorus (P) were 73%, 49%, and 47%, respectively. In addition, the characterization of the bioflocculant revealed the presence of carbohydrates (69%), proteins (11%), and uronic acid (16%). In addition, the bioflocculant exhibited a cluster-type structure and an elemental composition of C (16.92%), N (1.03%), O (43.76%), Na (0.18%), Mg (0.40%), Al (0.80%), P (14.44%), S (1.48%), Cl (0.31%), K (0.34%), and Ca (20.35%). Conversely, in the context of wastewater from coal mines, it exhibited removal efficiencies of 43% (COD), 64% (BOD), 73% (P), and 50% (N), thereby substantiating its viability as a wastewater treatment alternative.

In a similar study, Joshi *et al.* [22] investigated the removal of multiple pollutants from industrial wastewater using a bioflocculant produced by *Bacillus licheniformis*. The results indicated that turbidity was reduced by 69 to 87%, chemical oxygen demand by 50 to 80%, and oil by 87%. Furthermore, the bioflocculant was employed in the treatment of wastewater from pesticide, petroleum, and pharmaceutical processing, resulting in a reduction of suspended solids by 61.9–80%, turbidity by 54–94%, and total dissolved solids, oil, and fat, respectively. It was demonstrated that the sludge sedimentation process was much faster than with other flocculants, thus representing an economical and environmentally friendly alternative, since this bioflocculant is composed of 92% polysaccharides and 7% proteins, which makes it biodegradable.

The objective of this study was to assess the efficacy of a dextran-based bioflocculant in the treatment of industrial wastewater. It is imperative to continue research endeavors aimed at the sustainable and environmentally friendly recovery of this resource.

III. Materials and Methods

A. Collection of an Industrial Wastewater Effluent Sample

A sample of industrial wastewater was collected from a water channel in the district of Buenos Aires, Trujillo. The UTM coordinate (17 L 0712895, 9100614) of the location where 5 L of wastewater was collected for the experimental tests was identified and recorded with GARMIN ETREX 30X GPS equipment. The water sample was collected in a first-use plastic bottle and immediately transferred to the laboratories of the Institute and Research Centers of the Cesar Vallejo University-Trujillo Campus, where the experimental tests were carried out.

B. Obtaining the Bioflocculant from Leuconostoc Pseudomesenteroides

The L. pseudomesenteroides strain was provided by the laboratory of the Institute and Research Center of the Cesar Vallejo University (Trujillo, Peru). This strain was identified molecularly using sequencing of a polymerase chain reaction (PCR) product specific for the bacterium-specific 16S ribosomal gene region [23]. The BLAST program was subsequently employed to analyze the sequenced regions, yielding a 100% identity percentage corresponding to the species *L. pseudomesenteroides* (see Table 1 for details).

Table 1. Molecular identification of a bacteria isolated from cane juice

Identified species	pb	BLAST	
		Identity (%)	Accession number
Leuconostoc pseudomesenteroides	1470	100%	LC306846.1

The strain was reactivated to obtain the biopolymer dextran, used as a bioflocculant. A culture suspension was transferred to an Erlenmeyer flask containing 200 mL of sterile trypsin-soy broth. The flask was then incubated at 30 °C with magnetic stirring at 60 rpm for 48 h. Subsequently, 0.1 mL of the culture was inoculated onto glucose agar plates, which were incubated at 30 °C for 24–48 h. Gram staining was performed to verify culture purity.

C. Obtaining the L. Pseudomesenteroides Bioflocculant

To prepare the inoculum, Mayeux broth (900 mL) with sucrose (100 g/L) and 100 mL (10% v/v) of a bacterial inoculum (1.6×10^8 CFU) were used. This mixture was transferred to a 500 mL bioreactor, which was hermetically sealed to initiate the fermentation process. The fermentation process was carried out under the following conditions: pH 7.0 ± 0.2, temperature 30 °C, aeration rate of 0.5 volumes of air per volume of medium per minute, and stirring at 200 rpm. The process lasted 76 h with sterile aeration.

Dextran extraction was performed according to the method described by Pinchi, as detailed in [24]. The biopolymer was analyzed using a Nicolet iS50 Fourier Transform Infrared (FTIR) spectrophotometer (Thermo Scientific, USA). The objective of this analysis was to identify representative functional groups present in the extracted material and approximate the chemical composition of the polymer.

D. Tests on the Application of Bioflocculant in Wastewater

A volume of 300 milliliters of sample was meticulously measured and transferred into 500-milliliter capacity beakers. Subsequently, a portion of the samples were processed using a bioflocculant solution with concentrations of 20 and 40 parts per million (ppm), while the remainder were treated with a conventional flocculant, aluminum sulfate, at a concentration of 5 ppm. This latter treatment was utilized as a reference, serving as a basis for comparison. The mixtures were stirred at room temperature, with an initial agitation of 400 rpm for 5 min, which was subsequently reduced to 50 rpm for 30 min. Once the mixing process was completed, the contents of each beaker were transferred to cylindrical test tubes of 250 mL capacity, where they were left to stand for a period of up to 96 h. Turbidity measurements were performed with a LTLUTRON turbidity meter, model T2016; total coliform count was carried out using the membrane filtration technique; and dissolved oxygen was measured with Maca Hanna multiparameter equipment, model HI 98194. These measurements were taken at 18 and 96 h after treatment, in order to evaluate the efficiency of the treatment applied. Additionally, during the experiment, a sample was processed under the same conditions, but without adding any flocculant (sample WHITE), and each test was performed in triplicate.

IV. Result and Discussion

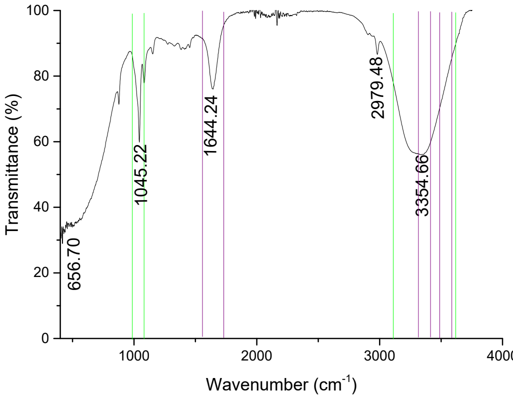

Fig. 1. Spectrum of dextran obtained from L. *pseudomesenteroides* using FT-IR.

Fig. 1 shows that the infrared spectrum (FTIR) of dextran derived from *L. pseudomesenteroides* reveals the presence of absorption peaks at distinct wavenumbers. These peaks offer significant insights into the functional groups present in the dextran.

A peak at 3384.66 cm^{-1} corresponding to the O-H (alcohol) vibration is identified, indicating the presence of organic substances, as corroborated by the width of the peak [25, 26]. Furthermore, the spectrum displays a peak at 1644.24 cm^{-1}, which is characteristic of the C=O vibration in the amide I (carbonyl) band [26], thereby supporting its assignment to a primary amide, as these two peaks are complementary [27].

A further peak is observed at 2979.48 cm^{-1}, which is associated with the alkane (C-H) vibration, as indicated by the existing literature [25, 28]. Finally, a peak was observed 1045.22 cm^{-1}, which could be linked to the C-O bond [29, 30]. The appearance of the peaks 3384.66 cm^{-1}, 2979.48 cm^{-1} and 1045.22 cm^{-1} can be highlighted, which correspond to specific functional groups and vibrational modes found in the structure of polymeric materials [31, 32].

Fig. 2 shows that the initial turbidity levels ranged from 106.33 to 120.00 NTU (nephelometric units). However, following the implementation of three distinct treatments in conjunction with a blank control, a notable reduction in turbidity values was observed. Specifically, treatment with aluminum sulfate resulted in a reduction of turbidity to 22.31 NTU, while dextran administered at a concentration of 40 milligrams per liter (ppm) led to a decrease to 17.87 NTU, yielding comparable outcomes.

According to Sepideh *et al.*, biopolymers offer numerous attractive features such as biocompatibility, hydrophilicity, and functionalization, which position them as ideal candidates for improving the efficiency of water purification processes [33]. Furthermore, Gowthama *et al.* highlight that natural and microbial-based biopolymers emerge as a greener alternative due to their low antigenicity, non-toxicity, antioxidant activity, and excellent physicochemical characteristics such as thermostability, high water solubility, a wide range of molecular masses, and their biodegradability [34].

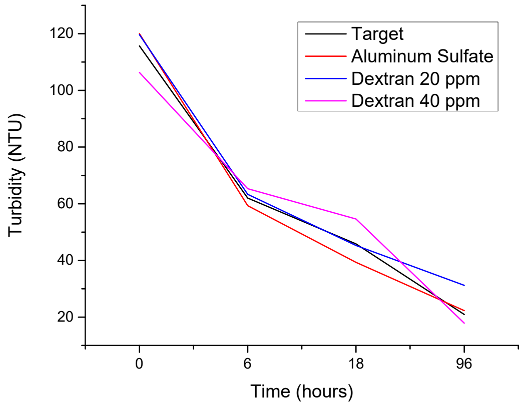

Fig. 2. Evaluation of turbidity over time using three treatments and a control.

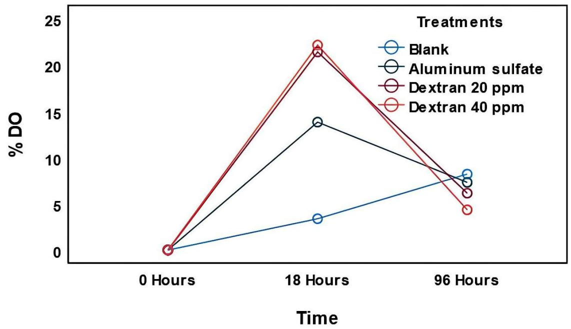

Fig. 3. Variation of % DO (Dissolved Oxygen) over time using three treatments and a control.

At the inception of the experiment, the percent dissolved oxygen (%DO) was nearly zero for all groups, due to the increase in organic matter.After 18 h, a considerable increase in %DO was observed for all groups. The group treated with aluminum sulfate exhibited an intermediate value for %DO. At 96 h, a decrease in %DO was recorded compared to 18 h. Conversely, the groups treated with dextran (20 and 40 ppm) exhibited higher %DO values, suggesting that oxygen demand increases with time as the decomposition of organic matter progresses. In contrast, the white group (untreated) demonstrated the lowest %DO value.

Fig. 3 shows that, an increase in dextran concentration from 20 to 40 ppm results in a modest enhancement in percent dissolved oxygen (%DO) efficiency. These findings are consistent with the observations reported by Ahmed *et al.*, who documented that biopolymer substantially reduce Biochemical Oxygen Demand (BOD) and Natural Organic Matter (NOM) by up to 90% in effluents [35].

It also represents the trend in biological oxygen demand (BOD) of the samples. This parameter indicates the amount of oxygen required for the oxidation of organic contaminants in aqueous media. In this regard, the results are analogous to a study by Ashok *et al.*, who utilized sustainable biopolymer-based self-cleaning membranes for wastewater treatment with an initial BOD demand of 200 mg·L^{-1} The study demonstrated chemical oxygen demand (COD) and BOD results of approximately 60 mg·L^{-1} and ~24 mg·L^{-1}, respectively, thereby substantiating the self-cleaning capability of biopolymer-based membranes and their efficacy in enhancing the flux rate for industrial wastewater purification [36].

In contrast, the aluminum sulfate treatment exhibited suboptimal outcomes, as evidenced by the lowest percentage of dissolved oxygen (%DO). These findings are consistent with the observations reported by Sun *et al.*, who noted that the average Chemical Oxygen Demand (COD) and Total Nitrogen (TN) removal efficiencies ranged from 70% to 93%, without the incorporation of additional chemicals [37].

However, the efficiency of aluminum sulfate is reduced due to its propensity to induce the formation of minute contaminants, which aggregate to form larger particles and precipitate at the bottom of the water tanks. Consequently, it is imperative to exercise restraint in the use of aluminum sulfate, as its excessive application can result in the wastage of reagents without conferring significant additional benefits. This stands in contrast to biological processes, which are characterized by their ecological sustainability and cost-effectiveness in the context of wastewater treatment [38].

Table 2. Evaluation results of the %DO Percentage in each experimental group tested during 0–96 h

Treatment	(%) DO averages at each time (hours)		
	0	18	96
Target	-	3.37	8.20
Aluminum sulfate	-	13.8	7.30
Dextran 20 ppm	-	21.36	6.13
Dextran 40 ppm	-	22.1	4.33
F-statistic (ANOVA)	-	311.81	42.50
P-value	-	<0.01	<0.01

As illustrated in Table 2, the findings of the analysis of variance that was conducted with two doses of dextran, aluminum sulfate, and a control group during a flocculation test revealed significant variations in the percentage of dissolved oxygen (p-value < 0.01) after 18 h. A similar trend was observed after 96 h, with highly significant differences in %DO being recorded between the groups (p-value < 0.01).

Fig. 4 shows that all groups tested had a similar initial Total Solids (TS) concentration of approximately 770 ppm. After 18 h, a decrease in TS concentration was observed in all groups, indicating that the treatments had an effect on solids removal. The group treated with aluminum sulfate exhibited the greatest reduction in TS, reaching values close to 730 ppm. On the other hand, the groups treated with dextran (20 and 40 ppm) also showed a reduction in TS concentration, although not as pronounced as in the case of aluminum sulfate. Likewise, at 96 h, a slight recovery of the TS concentration was observed in all groups compared to 18 h, but the values remained below the initial levels. The group treated with aluminum sulfate continued to show the lowest TS concentration, although with a slight increase compared to 18 h. Similarly, the dextran-treated groups showed intermediate TS levels, while the blank (untreated) group showed the highest TS concentration.

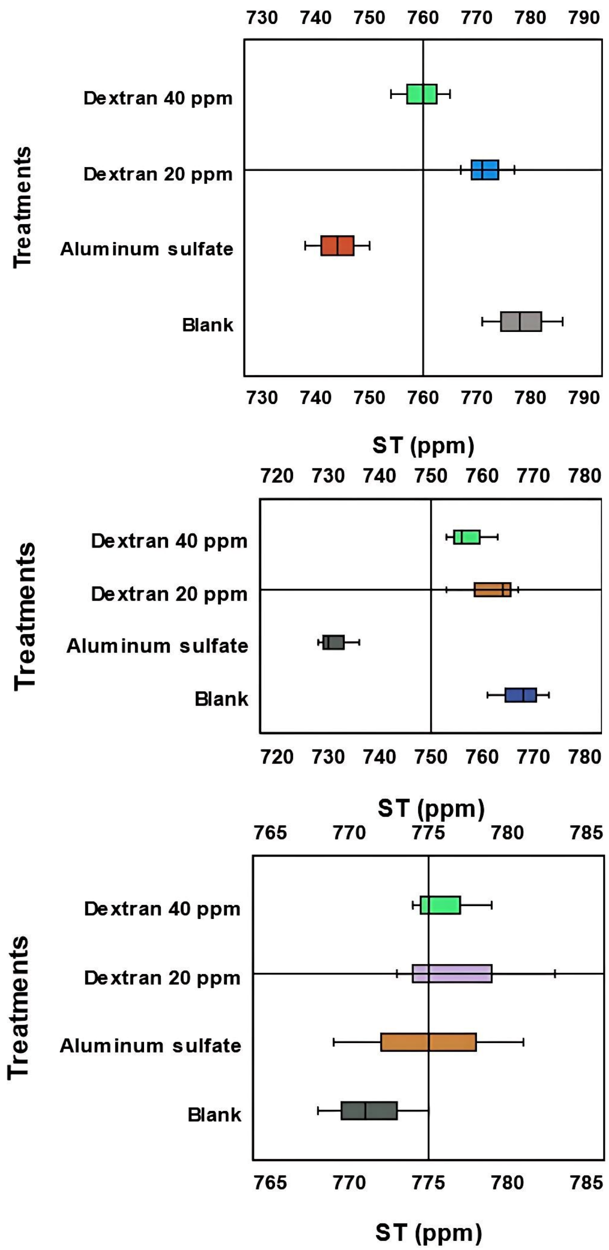

Fig. 4. Variation of Total Solids (TS) over time using three treatments and a control.

An increase in dextran concentration from 20 to 40 ppm resulted in a slight removal of Total Solids (TS) over time, a finding that aligns with those reported in a study by Ghorbani *et al*. In their study, Ghorbani et al. prepared membranes based on Polylactic Acid (PLA) physically mixed with biopolymers, a process that yielded membranes with desirable properties such as porosity and thermal stability. In addition, these membranes exhibited superior separation performance, with the capacity to remove up to 98.6% of Total Dissolved Solids (TDS) [39].

Furthermore, Cunha e*t al.* [40] have demonstrated that Extracellular Polymeric Substances (EPS) possess the capacity to generate electrostatic interactions and hydrogen bonds, thereby promoting the adhesion and cohesion of suspended solids. This renders them promising candidates for bioalternative solutions, in contrast to biofloculants salts and synthetic polymers employed in wastewater treatment, which have been observed to be hazardous and a source of environmental pollution.

The group treated with aluminum sulfate exhibited a greater reduction in Total Solids (TS). This phenomenon can be attributed to the destabilization of colloidal material caused by the addition of compounds such as aluminum salts to the effluent, resulting in the agglomeration of small particles into larger, settleable flocs. Aluminum is known to form strong complexes with polar molecules and oxygen-containing functional groups, including hydroxyl and carboxyl groups. These functional groups provide a local negative charge that reacts with the aluminum cation, leading to the neutralization of the charge and subsequent destabilization of the colloid. This process results in the precipitation of the aluminum cation and organic anions [41].

These results are in agreement with a study by Kang *et al.*, who used aluminum-based water treatment sludge as an effective coagulant to replace conventional chemical coagulant. This coagulation and flocculation mechanism was based on interactions for floc formation in wastewater from animal farms. The results were promising, as they observed that the efficiency of the treatments improved as the aluminum dose was increased. This allowed the removal of Total Suspended Solids (TSS) in a wastewater sample with 4480 mg/L TSS, achieving an efficiency of up to 89.3 %. However, the need for an environmental risk assessment before implementing this method in practice is emphasized [42].

Table 3. TS evaluation results in each experimental group tested during 0–96 h

Treatment	TS averages (ppm) at each time point (hours)		
	0	18	96
Target	771.33	767.33	778.33
Aluminum sulfate	775.00	731.33	744.00
Dextran 20 ppm	777.00	761.33	771.66
Dextran 40 ppm	776.00	757.33	759.66
F-statistic (ANOVA)	0.88	22.51	18.42
P-value	0.49	<0.01	<0.01

pH: 7.5, Sample, Industrial Waters

Table 3 presents the results of Total Solids (TS) concentration from baseline (0 h) to 96 h, highlighting that there are no significant differences in TS between groups (p-value = 0.49 > 0.05). Furthermore, at 18 h, the treatments employed present different means, with values of (p-value < 0.01), suggesting significant differences in mean ST concentration between groups. In this case, the treatment with aluminum sulfate shows the greatest reduction of ST (731.33 ppm). The dextran treatments also show a reduction in TS, although not as pronounced as that observed with aluminum sulfate.96 h later, significant differences in the mean TS between groups are also evident (p-value < 0.01). Aluminum sulfate continues to show a significant reduction in ST (744.00 ppm), although with a slight increase compared to 18 h, reflecting a treatment efficiency affected over time. On the other hand, dextran treatments show a reduction of ST compared to the blank group, but with a lower effectiveness than aluminum sulfate.

Table 4. Results of the evaluation of fecal coliforms (FC) in each experimental group at 96 h

Treatment	Fecal Coliform Averages	
	FC	Log
Target	2560000.00	6.4060
Aluminum sulfate	2261333.33	6.3533
Dextran 20 ppm	362666.66	5.5591
Dextran 40 ppm	104533.33	5.0180
Statistic F ANOVA	136.56	812.18
P-value	<0.01	<0.01

Table 4 shows the results of the comparison of three experimental groups and one blank group in Fecal Coliform (FC) count after 96 h, using a parametric ANOVA analysis. Significant differences in fecal coliform counts between treatment groups are observed (p-value < 0.01), both for the original CF count data and for the data transformed to Log CF. The blank (untreated) group has the highest number of fecal coliforms (2,560,000). The treatment with aluminum sulfate shows the lowest amount of fecal coliforms (2,261,333). On the other hand, the treatments with dextran show a much more notable reduction in the amount of fecal coliforms. The dextran dose at 20 ppm reduces the amount of CF to 362,666,67, while dextran at a dose of 40 ppm reduces the amount of Fecal Coliforms (FC) to 104,533.33, this treatment indicates the most effective way to decrease the amount of fecal coliforms in the water. This phenomenon can be explained by the fact that bioflocculants, being extracellular polysaccharides, proteins, or other biological polymers, adsorb on the surface of bacteria. This phenomenon is attributed to electrostatic interactions, hydrogen bonds, hydrophobic interactions, or ionic bonds [43].

Conversely, Huang *et al.* [44] synthesized a starch-based dual-function flocculant, Carboxymethyl Starch Grafted with Aminomethylated Polyacrylamide (CMS-g-APAM), by a simple and efficient procedure. This flocculant exhibited remarkable efficacy in turbidity removal and bacterial cell disintegration at specific pH conditions. The authors further suggested that the antibacterial activity of CMS-g-APAM was attributable to the interaction between the tertiary amino groups of the flocculant and the negatively charged bacterial surface, leading to the partial destruction of their cell walls. Future studies should directly confirm dextran-bacteria interactions by microscopy or zeta potential analysis.

Table 5. Efficiency of different bioflocculants reported in previous studies, compared to dextran.

Bioflocculant	Biological source	Flocculation efficiency (%)	Sample	Reference
Dextran	Bacterial polysaccharide	88.0	Waters of the Moche River	[45]
Aluminum Sulfate	Inorganic Chemical	92.0	Wastewater	[46]
B. licheniformis derivative	*Bacillus licheniformis*	87.2	Synthetic Wastewater	[22]
P. kudriavzevii derivado	*Pichia kudriavzevii*	80.01	kaolin particles	[21]

The data presented in comparative Table 5 indicate that dextran, a polysaccharide produced by bacteria, exhibits a remarkable flocculation efficiency of 88.0% under controlled conditions [45]. This yield is higher than that of bioflocculants obtained from Bacillus licheniformis (87.2%), and Pichia kudriavzevii (84.6%) [21, 22]. Although aluminum sulfate shows the highest efficiency at 92.0%, its inorganic chemical nature and potential environmental impact distinguish it from the biological alternatives analyzed [46]. The outstanding performance of dextran is especially relevant in the context of synthetic wastewater treatment with a neutral pH, indicating that it could be a viable option comparable to traditional chemical agents. This competitiveness, together with its biodegradable nature, supports its potential as an innovative bioflocculant.

V. Conclusion

Turbidity values were shown to decrease during treatment time with both aluminum sulfate and dextran, as well as in the blank group. Treatment with aluminum sulfate reduced turbidity up to 22.31 NTU, while dextran at 40 ppm achieved a decrease of 17.87 NTU, showing very similar results by sedimentation up to 96 h, at pH 7.5.

Furthermore, dextran treatment, at concentrations of 20 ppm and 40 ppm, exhibited an enhancement in dissolved oxygen levels in the treated water. This observation suggests a reduction in organic load, thereby indicating an improvement in water quality.

Additionally, a substantial decrease in total suspended solids was observed, which lends further support to the efficacy of dextran as a bioflocculant in facilitating particle agglomeration and sedimentation.

Furthermore, dextran, at a concentration of 40 ppm, was identified as the most effective treatment in reducing fecal coliform levels in water, suggesting that dextran may also contribute to the enhancement of water quality through microbiological processes.

The study highlights the potential of bioflocculants, such as dextran, as sustainable alternatives to conventional chemical coagulants in wastewater treatment, a matter of particular relevance in developing countries, where effective wastewater management represents a significant environmental challenge. The research suggests that the use of biopolymers can contribute to a more eco-friendly and effective water treatment technology, reducing the health risks associated with chemical flocculants.

However, a relevant limitation of the present study is that, although potential mechanisms such as electrostatic interactions and hydrogen bonds in the flocculant and antimicrobial action of dextran are mentioned, specific experimental analyses such as the measurement of zeta potential were not included to support these claims from a physicochemical perspective. Therefore, it is recommended that future work deepen the mechanistic characterization of the dextran-induced flocculation process. Despite its promising performance, dextran's scalability requires a cost-benefit analysis compared to established bioflocculants such as chitosan.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MDLCN conducted the research and wrote the article; WSE wrote the article; MGC conducted the research and wrote the article; LCCH developed the methodology; and KMV performed the statistical data analysis; all authors approved the final version.

Funding

The research was funded by Universidad Cesar Vallejo, with resolution code P-2023-99.

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