

Article

Sequential Treatment of Domestic Wastewater in Rural Zones Applying Aloe Vera Extract as Coagulant (Preliminar), *E. crassipes* in a Horizontal Biofilter (Secondary), and Activated Carbon from Soursop Seeds (Tertiary)

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Abstract

The absence of domestic wastewater (DWW) treatment in impoverished rural communities of the global south remains a pressing challenge for both public health and environmental sustainability. This study presents a simplified and decentralized treatment chain at laboratory-scale designed under the principles of nature-based solutions (NBS) and the circular economy (CE), emphasizing the integration of the macrophyte *Eichhornia crassipes* (EC) and bioproducts derived from aloe vera waste (AVW) and soursop seed waste (SSW). The system comprises three sequential stages: (1) coagulation using AVW, which achieved up to 39.9% turbidity reduction; (2) a horizontal flow biofilter system (HFB) employing the aquatic macrophyte EC, which removed 97.9% of fecal coliforms, 82.4% of *Escherichia coli*, and 99.9% of heterotrophic bacteria; and (3) a tertiary treatment step employing adsorbent derived from SSW, which attained 99.7% methylene blue removal in preliminary tests and an average 97.5% turbidity reduction in DWW. The integrated configuration demonstrates a practical, effective, and replicable approach for decentralized domestic wastewater treatment, fostering local waste valorization, reducing reliance on commercial chemicals, and enhancing water quality in resource-limited rural areas, with potential for scaling to pilot applications in rural communities.

Keywords: domestic wastewater; *Eichhornia crassipes*; nature-based solutions; horizontal flow biofilter; circular economy; natural coagulant; natural adsorbent



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1. Introduction

Innovative, sustainable, and low-cost solutions for domestic wastewater (DWW) treatment in vulnerable communities remain a critical research focus, with significant

implications for public health and environmental sustainability [1]. In many regions, centralized wastewater treatment infrastructure is either unavailable or unaffordable, leading to the discharge of untreated or partially treated wastewater into natural water bodies [2–4]. This not only exacerbates water pollution but also increases the risk of waterborne diseases, particularly in communities that rely on contaminated water sources for cooking and irrigation [4,5]. In this sense, it is required to propose alternatives, such as the use of natural waste materials to implement a treatment chain for DWW treatment, and in response to this challenge, there is a growing need for sustainable options that minimize environmental impact and are adaptable to resource-constrained settings. [6,7] Nature-based solutions (NBS) and circular economy (CE) principles have emerged as promising frameworks for developing such systems, as they emphasize the use of natural processes and waste materials to create efficient, eco-friendly treatment solutions [8–10]. This research was carried out in the Cimitarra River Valley Peasant Reserve Zone (ZRC-VRC) in Colombia, which has a high level of biodiversity that can be applied to model NBS [11,12]; moreover, most of the waste is discarded and not used to produce materials of natural origin that are easily synthesized and environmentally sustainable, thus exploiting the model of CE [6,9].

This study explores a lab-scale integrated DWW treatment system comprising the following sequential phases: primary coagulation with aloe vera waste (AVW), secondary biofiltration with *Eichhornia crassipes* (EC) inside a horizontal flow biofilter (HFB), and tertiary adsorption using adsorbent synthesized from soursop seed waste (SSW). The treatment chain was designed, based on the qualitative characteristics of the water to be treated, to break down turbidity with a coagulation-flocculation, act on some microbiological parameters through a biological treatment, and finally refine the quality through an adsorption to return it to the environment. In the primary treatment, natural coagulants derived from plant-based materials offer a biodegradable, environmentally compatible, and effective alternative to chemical coagulants. Proteins and polysaccharides from organic material destabilize colloids and reduce turbidity and are suitable for decentralized water treatment systems [13–15]. The physicochemical process of coagulation-flocculation relies on chemical coagulants, which, despite their efficiency in removing impurities, may pose health risks. Some coagulants, such as aluminum and iron salts, have been linked to potential adverse effects, including neurological disorders and gastrointestinal issues, if residual concentrations remain high in treated water [16,17].

The secondary treatment phase employs EC, commonly known as water hyacinth, which is a floating macrophyte that has demonstrated high efficiency in the biofiltration of wastewater, effectively removing nutrients, organic matter, heavy metals, and pathogenic microorganisms [18–20]. Its rapid growth, adaptability to diverse environmental conditions, and high nutrient uptake capacity make it a suitable candidate for phytoremediation processes [21–23]. Moreover, EC is considered an invasive species [24], and its utilization in wastewater treatment not only mitigates environmental risks associated with its uncontrolled proliferation but also promotes circularity by valorizing this otherwise problematic biomass. EC systems, such as HFB, have consistently shown high removal efficiencies for microbial contaminants, including fecal coliforms and *Escherichia coli*, while contributing to overall water quality stabilization [25,26]. These characteristics highlight the potential of EC-based biofiltration systems as a sustainable, low-energy, and practical solution for decentralized wastewater treatment, particularly in rural and resource-limited settings where conventional treatment infrastructure is often lacking [27–29]. The tertiary treatment phase involves adsorption and uses SSW. Soursop seeds, comprising up to 30% of the fruit, are otherwise discarded, but can be transformed into low-cost, porous adsorbents capable of removing dyes, heavy metals, and other pollutants [30–34]. Activation involves chemical

treatment, carbonization, cooling, and neutralization, yielding a safe material suitable for pollutant adsorption [35–38].

By leveraging waste materials and natural processes, the proposed system seeks to provide an appropriate technological alternative for domestic wastewater (DWW) treatment in underserved communities, particularly in rural and resource-limited areas. This approach addresses key challenges such as turbidity reduction, pathogen removal, and organic pollutant adsorption, while advancing the application of nature-based solutions (NBS) and circular economy (CE) principles [8].

The novelty and objective of this research lie in the design and evaluation, at laboratory scale, of an integrated treatment chain that combines natural coagulation with aloe vera waste (AVW), biofiltration with *Eichhornia crassipes* (EC), and adsorption with soursop seed waste (SSW)-derived activated carbon. While each process has been studied individually, their combined application within a coherent system remains largely unexplored. This study therefore aims to assess the efficiency, operational feasibility, and potential scalability of the integrated system, providing preliminary evidence that AVW, horizontal flow biofilters, and SSW adsorbent can be effectively combined into a replicable and context-appropriate technology for decentralized wastewater management in vulnerable communities.

2. Materials and Methods

Three phases of treatment were conducted in parallel. In the first phase, through an experimental design, the dose and efficiency of the use of the AVW in the clarification process were determined, and the results were compared with aluminum sulphate. The second phase provided for the study of the HFB with EC as a secondary treatment. Finally, in the third phase the production of adsorbents from SSW was studied to determine the best behavior as a tertiary treatment.

This study focused exclusively on the aqueous phase of domestic wastewater (DWW), without addressing sludge or solid fractions, in order to evaluate water-quality parameters directly associated with the liquid effluent. The treatment train was investigated in three phases: (i) primary treatment using aloe vera waste (AVW) as a natural coagulant, compared with aluminum sulfate; (ii) secondary biofiltration with *Eichhornia crassipes* (EC) in a horizontal flow biofilter (HFB); and (iii) tertiary adsorption with soursop seed waste (SSW). As shown in Figure 1, this configuration is framed within a conventional domestic wastewater treatment scheme, while focusing only on the liquid line. Sediments and sludge are anticipated to undergo anaerobic processing, which lies outside the scope of this research.

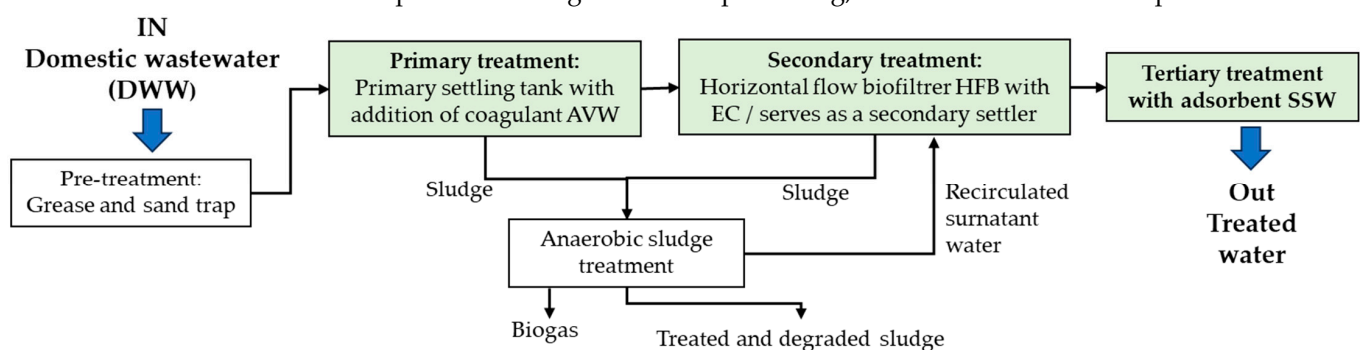


Figure 1. Schematic representation of a conventional domestic wastewater treatment scheme highlighting the proposed treatment train for the aqueous phase. The green boxes indicate the specific units developed in this study: AVW coagulation, HBF biofiltration, and SSW adsorption.

2.1. Characteristics of Domestic Wastewater (DWW) and Materials Used

To qualitatively characterize the DWW, a sample of 520 L of DWW was collected from the toilet, shower, and kitchen of a six-person peasant family from a rural community in the ZRC-VRC. It was stored and then transported to the Unipaz campus for experimentation. Table 1 shows the DWW analysis of the concentration of chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), and phosphorus and the values of pH, turbidity, and some microbiological parameters. Testing was carried out in the laboratory of environmental studies of the University of Antioquia (Medellin, Colombia); turbidity and pH analyses were carried out with instruments from the environmental engineering laboratory of Unipaz. Wastewater samples were collected using a grab sampling method in sterile polyethylene containers. Immediately after collection, samples were preserved at 4 °C and transported to the laboratory under refrigerated conditions within 24 h to prevent degradation. All analysis was carried out on the same batch of wastewater to ensure consistency and comparability of results across experiments.

Table 1. Qualitative characteristics of wastewater; the methods entered refer to *Standard Methods for the Examination of Water and Wastewater*, 23rd Edition. American Public Health Association [39].

Parameter	Value	Unit of Measurement	Standard Method (APHA) and Principle
COD	617	mg L ⁻¹	5220 C—Closed reflux, titrimetric (oxidation with dichromate, back titration, or colorimetric) [40]
BOD ₅	365	mg L ⁻¹	5210 B/C—5-day BOD test (incubation at 20 °C, dissolved oxygen depletion measurement) [41]
TP	1.27	mg L ⁻¹	4500-P (persulfate digestion, ascorbic acid method)—Colorimetric determination [42]
pH	6.5	-	4500-H ⁺ —Potentiometric with glass electrode [43]
Turbidity	325	Nephelometric Turbidity Unit (NTU)	2130 B—Nephelometric method [44]
Fecal coliform	3900	Most Probable Number (MPN) 100 mL ⁻¹	9222 D—Membrane filtration on m-FC agar at 44.5 °C (or 9221B/C multiple-tube) [45]
<i>Escherichia coli</i>	110	MPN 100 mL ⁻¹	9222 G—Membrane filtration with selective media/enzyme substrate test [46]
Heterotrophic bacteria	29 × 10 ⁴	Colony Forming Unit (CFU) 100 mL ⁻¹	9215 B/C—Heterotrophic plate count (pour/spread plate on plate count agar or Reasoner's 2A agar) [47]

2.2. Characteristics of Materials Used

Aloe vera is characterized by having a viscous substance inside, called mucilage. It is like a rubber that in water forms a viscous substance that is very easy to dissolve, and it is composed of polysaccharides that usually contain glucose and galactose. Thanks to the properties presented by the mucilage, it has been possible to determine the coagulating power of aloe vera to remove turbidity in the water treatment process [13,15]. Aloe vera residues were easily obtained in homes and farmers' markets in the area.

Eichhornia crassipes (EC) was chosen because it is very present in Colombian territory; it is a fast-growing aquatic plant that is considered invasive and can cause alterations in surface water bodies [24]. This condition provides an opportunity to identify new uses from a circularity perspective. It was collected in Lake San Lorenzo in the ZRC-VRC. Plants of the same size were used, with an average root height of 0.18 m and a leaf height and width of 0.15 × 0.17 m.

Soursop, a plant native to South America, is widely cultivated in the tropical regions of the world. The seeds, traditionally inedible, are a residue of high availability whose composition has been the subject of extensive research [35,36]. Soursop seeds were collected in marketplaces and natural juice outlets where only the pulp of the soursop is sold and used, and the seeds are left as waste.

2.3. Methodological Approach and Tests Carried Out

The research was developed on a laboratory scale and was divided into three phases with three different aims.

The first phase provided for the synthesis and experimentation with the coagulant from AVW. Once the natural coagulant was selected, we proceeded to the elaboration of the coagulant. For the development of this phase, the following activities were carried out: manufacture of the coagulant, jar tests, and comparison of the clarification with aluminum sulfate. To evaluate the optimum dosage of the natural coagulant, eight jar tests were carried out (Figure 2), all adding the coagulant in different dosages. For time and agitation speed, the NTC 3903 method was used [48], which establishes the procedure for the jar method in water coagulation-flocculation for time and agitation speed. Jar test experiments were conducted using six 250 mL beakers per test, with one replicate for each configuration. The first configuration (Test 1) employed a 1% aloe vera (AV) solution, while the second configuration (Test 2) used a 1% aluminum sulfate $\text{Al}_2(\text{SO}_4)_3$ solution. For each test, the coagulant dose was varied: 0–25 mg L^{-1} for the aloe vera solution and 0–50 mg L^{-1} for the aluminum sulfate solution. The average initial conditions for the aloe vera tests were a turbidity of 47.83 NTU and a pH of 6.91, while for the aluminum sulfate tests, the average initial turbidity was 44.5 NTU with a pH of 6.82. All experiments were carried out at the Environmental Engineering Laboratory of Unipaz University.

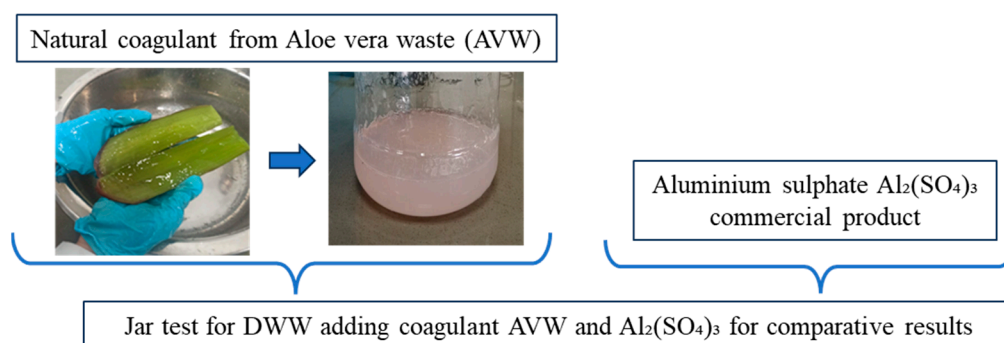


Figure 2. Characteristics of the systems used: Natural coagulant AVW.

The second phase focused on HFB; a continuous flow of DWW was fed through a container filled with EC, and the reduction of Fecal coliform, *Escherichia coli*, and Heterotrophic bacteria were monitored. For the design, a first-order removal kinetic model of the pollutant was utilized, along with a biological reactor exhibiting plug flow behavior. According to previous studies [49,50], and to establish a correlation with DWW, the calculation was made based on data on the bioaccumulation capacity of the EC. It was found that for a flow rate (Q) of 0.05 L s^{-1} , the required amount was 20 EC plants, ensuring that the entire surface of the tank was covered (plant density per unit area = $0.045 \text{ m}^2 \text{ EC m}^2 \text{ water surface}^{-1}$). The volume of HFB = 0.3 m^3 , the hydraulic retention time (HRT) = 1.7 h, and the hydraulic load rate (HLR) = $0.27 \text{ m}^3 \text{ d}^{-1} (\text{m}^2)^{-1}$. The HFB was constructed adapting a tank with the required sizing and geometry made of high-density polyethylene (HDPE). Inlet and outlet pipes (1.1 cm internal diameter) were made of polyvinyl chloride (PVC), Figure 3.

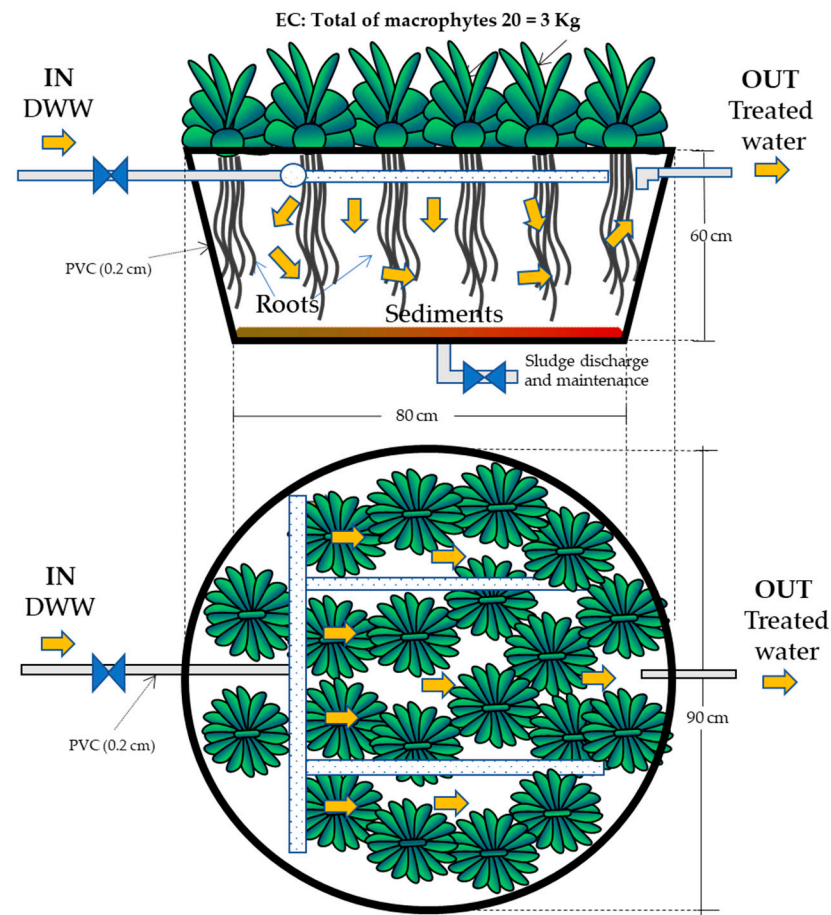


Figure 3. Characteristics of the horizontal flow biofilter (HFB).

The third phase concerned the preparation of the natural adsorbent SSW. Studies on the adsorptive potential of natural materials are numerous, given their significantly lower cost compared to commercially sourced granular activated carbon, where pH plays a key role in achieving higher adsorption rates at moderately alkaline values. Once the soursop seeds were collected, they underwent washing, drying, grinding, and sieving to obtain a uniform particle size. Figure 4 shows the SSW adsorbent at the end of the preparation process and the experimental setup and conceptual design described above. The adsorption capacity was evaluated through methylene blue removal tests, where residual dye concentrations were determined spectrophotometrically at the maximum absorption wavelength ($\lambda_{\max} = 664 \text{ nm}$) using a calibration curve. To allow comparison with other studies, the synthesized SSW was characterized by nitrogen adsorption–desorption isotherms. The material exhibited a Brunauer–Emmett–Teller (BET) surface area of $\sim 180 \text{ m}^2 \text{ g}^{-1}$, a total pore volume of $\sim 0.22 \text{ cm}^3 \text{ g}^{-1}$, and an average pore diameter of $\sim 5 \text{ nm}$, indicating a mixed micro–mesoporous structure [20]. Once characterized, two filtration systems were constructed manually using columns packed with adsorbent material—one filled with commercial granular activated carbon and the other with synthesized SSW—to directly compare their performance in DWW treatment [31]. To compare the SSW adsorbent with commercial activated carbon, two 18 L containers with taps (upstream reservoir) were used; rigid PVC piping was used to construct the column filled with adsorbent material. For monitoring operational parameters such as pH and turbidity, a pH meter and turbidimeter were used. The test lasted 12 h.

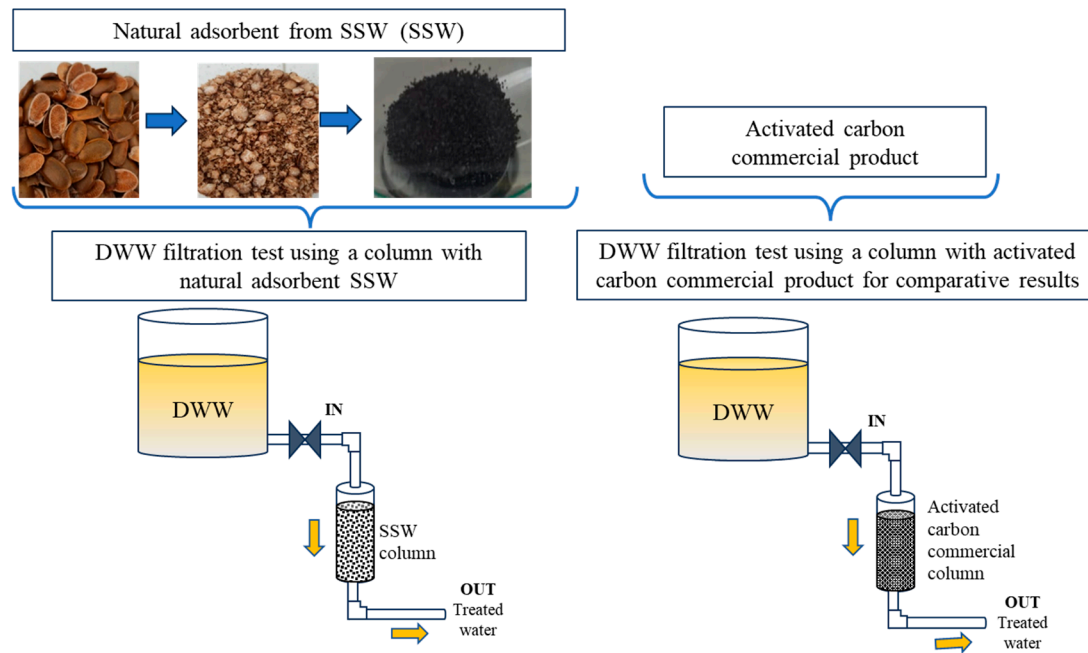


Figure 4. Characteristics of the systems used: Natural adsorbent SSW.

2.4. Experimental Design and Management Mode

This section focuses on the synthesis and evaluation of a natural adsorbent derived from soursoop seed waste (SSW). The raw material was first screened, then chemically activated by impregnation with phosphoric acid (H_3PO_4), and subsequently carbonized at $200\text{ }^\circ\text{C}$ for 1 h followed by $500\text{ }^\circ\text{C}$ for 1 h in a muffle furnace. After cooling in a desiccator, the activated material was neutralized with either a diluted alkaline solution or deionized water to stabilize its pH around neutral, ensuring its suitability for use [33,39–41]. This procedure is consistent with methods commonly applied for the valorization of agricultural residues into high-performance adsorbents [16,34,36]. Adsorption performance was evaluated in batch tests, where 200 mg of SSW was added to 50 mL of a 500 ppm methylene blue ($\text{C}_{16}\text{H}_{18}\text{ClN}_3\text{S}$) solution and stirred magnetically for 3 h. Samples were then allowed to settle for 24 h. The methylene blue index (MBI) and adsorption capacity (q_e) were calculated using the following standard equations [50,51]:

$$\text{MBI} = 100 (E V W^{-1}) \quad (1)$$

where:

- E [mg/mL]: concentration of methylene blue solution.
- V [mL]: volume of the methylene blue solution.
- W [mg]: weight of activated carbon.

$$q_e = 1000 [(C_0 - C_f) V] / (M V^{-1} V^{-1}) \quad (2)$$

where:

- C_0 [mg/L]: initial concentration of methylene blue solution.
- C_f [mg/L]: final concentration of methylene blue solution.
- V [L]: volume of the solution.
- $M V^{-1}$ [mg/L]: concentration of activated carbon.

For the second experimental part, aimed at comparing SSW with commercial activated carbon, the filter column was conceptualized using the empty bed contact time (EBCT), calculated as the adsorbent volume divided by the treated flow rate. This provides a

theoretical framework for potential future column studies. Theoretical empty bed contact time (EBCT) was calculated in the following equations:

$$\text{EBCT} = V_F Q^{-1} \quad (3)$$

$$V_F = M_F d^{-1} \quad (4)$$

where: V_F : filter media volume; Q : flow rate of DWW; M_F : weight of filter medium; and d : adsorbent density. Given similar inlet flow rates between the two systems, an almost equal EBCT contact time, and a comparable volume, parameters were determined, and these can be seen in Table 2.

Table 2. Operating parameters of column tests.

Operating Parameters	SSW Adsorbent	Activated Carbon Commercial
Dose filter material [g]	50	50
Ps [$\text{g}\cdot\text{L}^{-1}$]	470	625
W [L] = Dose/Ps	0.106	0.08
Q [mL min^{-1}]	10	10
EBCT [min]	10.64	8.68

It should be noted that surface area, micropore fraction, total pore volume, and column adsorption experiments were not performed due to laboratory and budget constraints. The methodology was intentionally limited to batch adsorption as a preliminary evaluation of SSW performance. The calibration curve for methylene blue used for concentration measurement is included in Appendix B.

In this preliminary phase, only microbiological and turbidity parameters were evaluated because they are widely recognized as key indicators of domestic wastewater quality in rural contexts, providing an initial assessment of treatment efficiency. Previous studies have demonstrated that these parameters are suitable for evaluating the performance of low-cost or natural treatment systems for domestic wastewater. They have reported significant reductions in *E. coli*, fecal coliforms, and turbidity in domestic wastewater treated with natural adsorbent [51,52]. Additionally, due to budget limitations and the exploratory nature of this stage, more detailed analyses were deferred to a subsequent pilot-scale phase to validate the model under broader operational conditions.

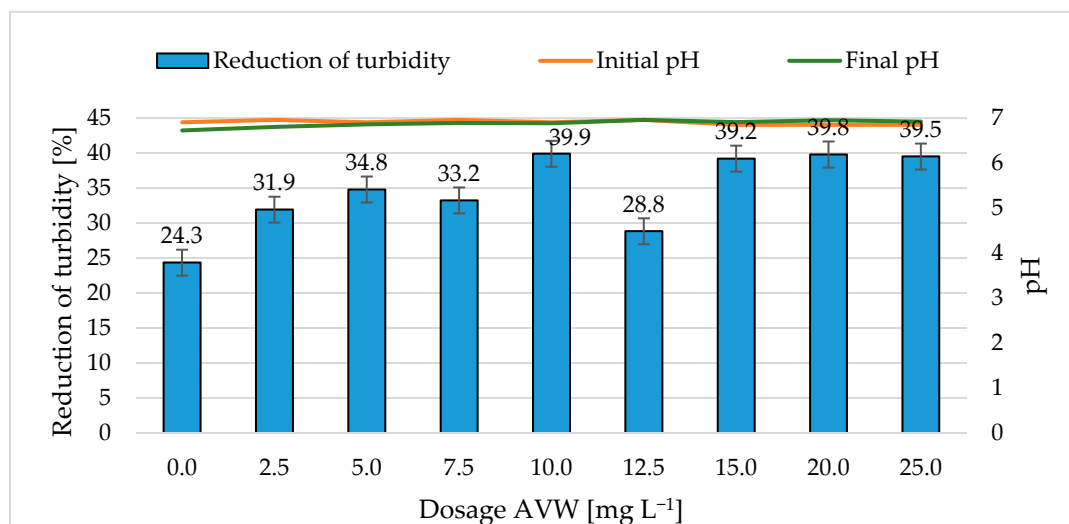
3. Results and Discussion

3.1. Primary Treatment—Evaluation of AVW: Optimum Dosage and Comparison with Aluminum Sulfate

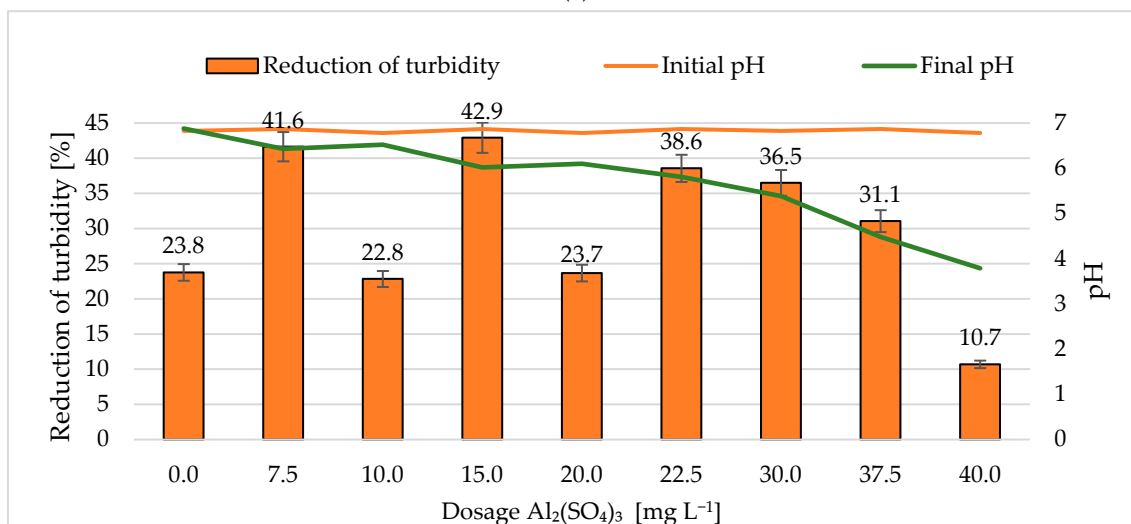
The Figure 5a,b shows the dosage used, the initial turbidity value, and the pH at the beginning of test. The table with the results of the specific jar tests according to the dose and the initial and final values of turbidity and pH can be seen in Appendix C.

The results show that aloe vera waste (AVW) achieved turbidity reductions of up to 39.9%, a performance comparable to aluminum sulfate under similar conditions [13,19]. A key difference, however, lies in the impact on water chemistry; while aluminum sulfate progressively acidified the treated water as the dosage increased, AVW maintained a nearly neutral pH [53]. This finding is particularly relevant for decentralized water treatment, where maintaining water quality without chemical alterations facilitates subsequent treatment steps such as biofiltration [15]. The coagulation capacity of AVW can be attributed to mucilaginous polysaccharides, which destabilize colloids and promote particle aggregation [13]. The efficiencies observed in this study (24–39%) are consistent with those reported in the literature for aloe vera-based coagulants, although removal rates

vary depending on the extraction method and dosage optimization [54]. Compared to aluminum sulfate, which achieved similar removal rates in the range of 24–43% but caused a significant drop in pH, AVW represents a more sustainable option with fewer secondary effects [14,18]. In relative terms, the 39% reduction obtained with AVW is lower than that achieved by *Moringa oleifera*, whose efficiency ranges from 50% to 85% [19]. Nevertheless, the valorization of aloe residues offers a clear advantage in regions such as Colombia, where this biomass is abundant and often discarded by agrifood processes [13,15]. Thus, even if AVW requires further optimization or combination with complementary treatments, it already represents a practical and low-cost strategy aligned with circular economy and appropriate technology principles [53].



(a)



(b)

Figure 5. (a): Behavior of the addition of a natural coagulant based on aloe vera. The blue columns represent the variation in turbidity reduction with variation in concentration of AVW. The orange line represents the pH result at the start of the experiment and the green line at the end of the experiment. (b): Behavior of the addition of aluminum sulphate. The light-brown columns represent the variation in turbidity reduction with variation in concentration of Al₂(SO₄)₃. The orange line represents the pH result at the start of the experiment and the green line at the end of the experiment.

According to these studies [13–15], aloe contains more than 130 compounds, among them polysaccharides that contain different amounts of mannose, glucose, and galactose.

In addition, the authors point out that in recent years great interest has been generated by ace-mannan (β -(1-4)-acetylated O-mannan) for its active component, which is defined as a mucilaginous polysaccharide. This is considered an interesting compound with regard to water treatment due to its colloid destabilization mechanism.

The AVW achieved a 39.9% reduction in turbidity, indicating a significant improvement in water quality. This suggests that AVW provides not only an economical way to treat wastewater but also utilizes local, biodegradable resources. This result demonstrates the potential of aloe vera waste as a sustainable coagulant for primary wastewater treatment. Natural coagulants, such as those derived from plant-based materials, are increasingly recognized for their ability to reduce turbidity and suspended solids without the environmental drawbacks of chemical coagulants [14]. While the 39.9% reduction is promising, further optimization or combination with other treatments may be necessary to achieve higher efficiency, as observed in studies using *Moringa oleifera*. In future work, a broader comparison between AVW and other natural coagulants such as *Moringa oleifera* will be considered, as suggested by [54].

3.2. HFB with EC as an Effective Secondary Treatment

Regarding horizontal flow biofilter with floating macrophytes (*Eichhornia crassipes*), the percentage of pathogens removed in terms of microbiological parameters is shown in Table 3.

Table 3. Percentage of removal of microbiological parameters.

Parameter	Units	Minimum Limit of the Measure	Average Value Obtained IN	Average Value Obtained OUT (3 Samples)	% of Removal
Fecal Coliform	MNP/100 mL	1	3900	80	97.9
<i>Escherichia coli</i> (<i>E. coli</i>)			110	19.3	82.4
Heterotrophic bacteria	CFU/100 mL	1	29×10^4	200	99.9

The horizontal flow biofilter with *Eichhornia crassipes* (HFB-EC) exhibited strong performance in microbiological removal, reducing fecal coliforms by 97.9%, *Escherichia coli* by 82.4%, and heterotrophic bacteria by 99.9%. Such reductions are particularly relevant for decentralized wastewater treatment, where pathogen control directly translates into lower public health risks [50]. These values are consistent with previous studies reporting >90% bacterial removal efficiencies using aquatic macrophytes in constructed wetlands and biofilters [16]. The high removal rates can be attributed to synergistic mechanisms: (i) filtration and sedimentation of suspended solids on dense root mats; (ii) nutrient uptake by macrophytes, which limits bacterial proliferation; and (iii) biofilm-mediated biodegradation driven by native microbial consortia attached to plant roots [19]. Together, these processes create a multi-barrier effect that explains the near-complete elimination of the heterotrophic bacteria observed [19].

Overall, the HFB-EC represents a sustainable and low-maintenance secondary treatment stage. Beyond its high efficiency and minimal energy demand, it adds value to *E. crassipes*, a species often regarded as invasive, by transforming it into a functional component of decentralized water treatment [20]. Its integration with coagulation–flocculation pretreatment and adsorption processes provides a viable multi-stage treatment train for rural or resource-limited contexts [21]. Since the reduction of the organic load in wastewater has not been studied in terms of BOD and COD, a complementary future analysis is proposed to strengthen the overall performance evaluation of the system, most likely at a pilot treatment scale [26].

3.3. Validate the Synthesis Process of the Selected SSW Adsorbent and Operating Conditions for Use as Tertiary Treatment

The results obtained in the verification process by comparing the SSW adsorbent produced with a commercial activated carbon using parallel filter columns can be seen in Table 4.

Table 4. Results of filter column test—adsorption.

Parameter	Column with Commercial Active Carbon			Column with SSW Adsorbent		
	IN	OUT	% Removal	IN	OUT	% Removal
pH 6 h	7.2	6.9	-	6.8	6.3	-
Turbidity [NTU] 6 h	325	60.3	81.4	356	9.02	97.5
Turbidity [NTU] 12 h	325	107	67.1	356	6.3	98.2
Q _{out} end test [mL min ⁻¹]	7.716		-	6.211		-
EBCT start test [min]	10.6		-	8.7		-
EBCT end test [min]	13.8		-	12.6		-

The soursop seed adsorbent (SSW) demonstrated outstanding adsorption performance, achieving a 99.7% removal rate of methylene blue from a 500 ppm solution under batch conditions. Using 200 mg of adsorbent, the concentration decreased to 1.48 ppm after 24 h, corresponding to an adsorption capacity of 124.6 mg g⁻¹ and a methylene blue index (MBI) of 12.5%. These values are comparable to those reported for bio-based adsorbents derived from mango peel and bamboo and approach the performance of commercial activated carbons, which typically show capacities between 100–150 mg g⁻¹ for methylene blue [36]. The nearly complete dye removal indicates that the SSW-derived adsorbent has a highly mesoporous structure, consistent with the ability to retain molecules larger than 1.5 nm, such as methylene blue [32]. When tested in parallel with commercial activated carbon, SSW achieved superior turbidity removal (97.5% vs. 74%), further corroborating its applicability in real wastewater treatment [30]. These results highlight both the technical effectiveness and the economic advantage of SSW, as it is produced from an abundant agrifood residue [30].

While the present study was limited to batch adsorption tests, theoretical parameters for column operation, such as empty bed contact time (EBCT), were calculated to provide a reference for future pilot-scale studies [49]. This step is crucial to evaluate breakthrough curves and validate the long-term operational stability of the adsorbent [38]. Overall, the performance of SSW underscores its strong potential as a sustainable tertiary treatment material. By transforming a local agricultural residue into a high-value adsorbent, this approach not only addresses wastewater contamination but also promotes circular economy principles and resource recovery [31]. The 99.7% reduction in methylene blue concentration is comparable to the reduction ability of commercial activated carbons, demonstrating their suitability for tertiary treatment [38]. This step is crucial for treating water and ensuring its safety for reuse or discharge.

3.4. Analysis of Integration and Future Scenarios on a Pilot Scale

The integrated treatment system combining aloe vera waste (AVW) as a natural coagulant, a horizontal flow biofilter with *Eichhornia crassipes* (HFB), and soursop seed waste adsorbent (SSW) demonstrated complementary and robust performance across all stages and could offer an effective and sustainable solution for domestic wastewater treatment. This treatment chain not only utilizes local natural resources but also reduces the need for costly chemical inputs and significantly improves water quality. The integration of these components offers a sustainable and cost-effective solution for domestic wastewater treatment, particularly in resource-constrained settings. The use of waste materials (aloe vera,

soursoy seeds) and natural processes (biofiltration) highlight the potential for scalability and local adaptation.

Figure 6 illustrates a proposed low-cost and appropriate technology for domestic wastewater management in isolated, vulnerable, or unsewered communities, designed for a case study of 20 families or houses (approximately 400 L/h of DWW). The system begins with a gauze and oil trap ($V = 100$ L), followed by two tanks of 200 L each, which serve a dual function (i) as pumped recirculation agitation tanks and (ii) as settling tanks when recirculation is turned off. Each tank is equipped with a device for the controlled addition of the coagulant. After phase separation, treated water flows to the secondary treatment stage, a horizontal flow biofilter with EC. The biofilter is designed with a hydraulic loading rate of $0.08\text{--}0.12\text{ m}^3\text{ m}^{-2}\cdot\text{d}^{-1}$ [48], in line with typical values for horizontal subsurface flow wetlands, and a plant density of $4\text{--}6\text{ plants m}^{-2}$ to ensure efficient pollutant removal and oxygen transfer. Plug flow behavior is assumed and validated through a salt tracer test, confirming negligible short-circuiting and supporting the design approach. The calculated hydraulic retention time (HRT) is approximately 2.5 days, based on the design flow and effective porosity, with a total reactor volume of 24 m^3 , ensuring sufficient contact time for biodegradation and nutrient removal [25]. In parallel, sludge generated is directed to an anaerobic biodigester. Finally, the tertiary treatment consists of an adapted tank containing the SSW adsorbent, operating in up-flow mode to maximize contact efficiency, after which treated water is discharged into a receiving surface water body.

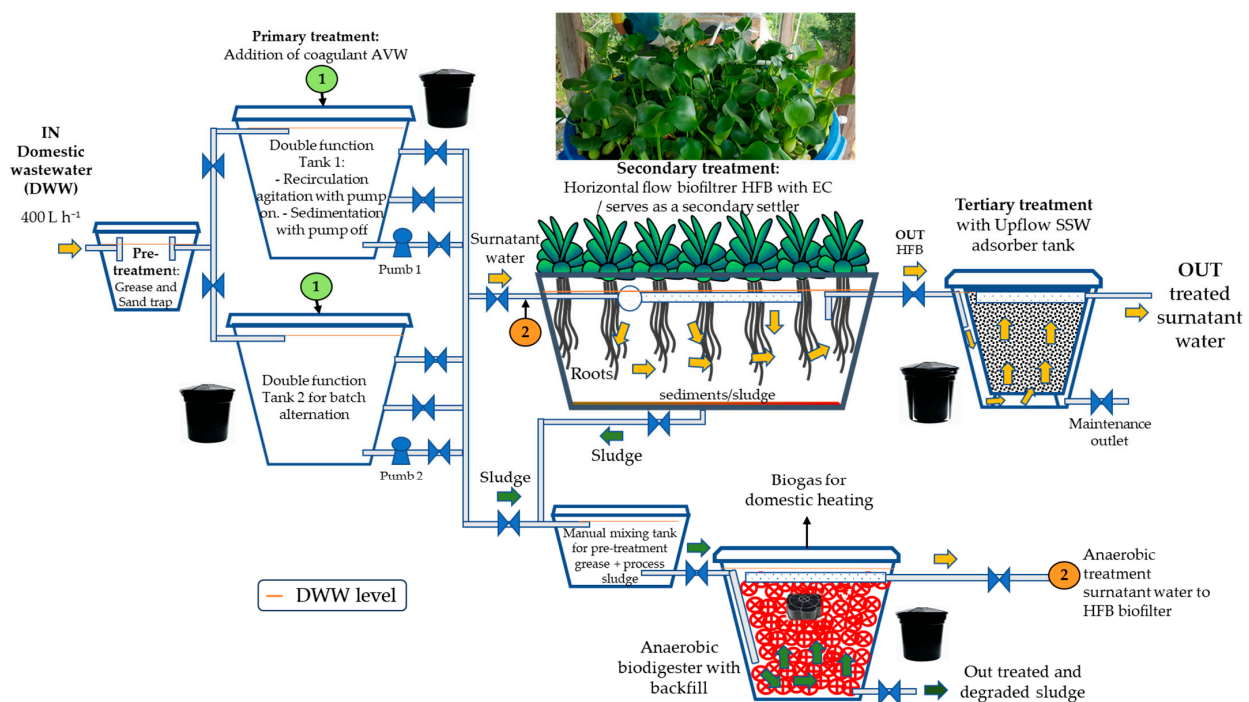


Figure 6. Configuration of the domestic wastewater treatment pilot plant to be installed in a rural community with a treatment capacity of 400 L h^{-1} .

Although the proposed integrated system is presented conceptually, some challenges in scaling up must be acknowledged. These include proper sludge management, which can affect digester performance, routine plant maintenance, and the influence of seasonal variations on biofilter efficiency and hydraulic loading. Operational costs also require careful assessment, particularly regarding the periodic replacement of the SSW adsorbent. Nevertheless, preliminary studies demonstrate the feasibility of anaerobic digesters for sludge stabilization and energy recovery in small-scale, decentralized systems [6–8], supporting their integration into community-based wastewater treatment solutions.

Scaling up to a pilot plant will enable long-term monitoring of operational stability, expansion of water quality parameters, and socio-economic assessments in collaboration with the community. Framed within the concept of appropriate technology, the system prioritizes sufficiency over perfection, resource circularity, and community adaptability, characteristics often overlooked in conventional wastewater engineering. The integration of natural coagulants, biofiltration, and waste-derived adsorbents highlights an innovative, resource-efficient path for decentralized wastewater management, with direct applicability to rural Colombia and other resource-constrained settings. The overall performance of the integrated treatment system across the three stages can be summarized as follows:

- Primary treatment—AVW coagulation: turbidity removal 42%; pH maintained near neutrality; sustainable, biodegradable coagulant.
- Secondary treatment—HFB with *Eichhornia crassipes*: fecal coliform reduction 97.9%, *E. coli* reduction 82.4%, heterotrophic bacteria reduction 99%; COD and BOD significantly decreased; mechanisms include filtration, sedimentation, biofilm activity, root oxygenation, and natural antimicrobial compounds.
- Tertiary treatment—SSW adsorbent: methylene blue removal 99.7%; turbidity reduction up to 98%; performance comparable or superior to commercial activated carbon; utilizes agricultural waste, aligning with circular economy principles.
- Technical and economic benefits: up to ~40% reduction in operational costs compared to chemical coagulants and commercial adsorbents; reduced environmental impact due to minimal chemical use and reuse of waste materials.

4. Conclusions

This study demonstrates the feasibility of a lab-scale domestic wastewater treatment system based on nature-based solutions and circular economic principles. Key findings include the following: the natural coagulant from aloe vera waste effectively reduced turbidity by 39.9%, offering a sustainable alternative to chemical coagulants.

The biofilter with *Eichhornia crassipes* achieved a Fecal coliform removal rate of 97.9%, *Escherichia coli* 82.4%, and Heterotrophic bacteria 99.9%. The color removal efficiency was 32%, highlighting its potential for pathogen reduction, but this requires further improvement.

The adsorbent from soursop seeds exhibited exceptional adsorption capacity, achieving a 99.7% reduction in methylene blue concentration, making it suitable for tertiary treatment and effective at high turbidity reduction in the treated wastewater, resulting in an average 97.5% reduction, exceeding the 74% removal rate obtained with commercial activated carbon at parity conditions.

The proposed system configuration provides a sustainable solution and eco-friendly alternative for wastewater treatment in underserved communities, addressing key challenges such as turbidity, pathogen removal, and organic pollutant adsorption.

While the results are promising, further research is needed to optimize the system's performance, particularly in terms of turbidity and color removal. Pilot-scale or field testing is also essential to validate the system's effectiveness under real-world conditions. By leveraging waste materials and natural processes, this study contributes to the growing body of knowledge on sustainable wastewater treatment solutions, offering a pathway for improving public health and environmental sustainability in the global south.

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Abbreviations

AVW	Natural coagulant from aloe vera waste
BOD	Biological oxygen demand
COD	Chemical oxygen demand
DWW	Domestic Wastewater
EC	<i>Eichhornia crassipes</i>
HFB	Lab-scale horizontal flow biofilter
NBS	Nature-based solutions
SSW	Natural adsorbent from soursop seed waste
ZRC-VRC	Cimitarra River Valley Peasant Reserve Zone

Appendix A



Figure A1. HFB system with macrophytes EC.



Figure A2. Filter columns with adsorbent SSW and commercial activated carbon.

Appendix B

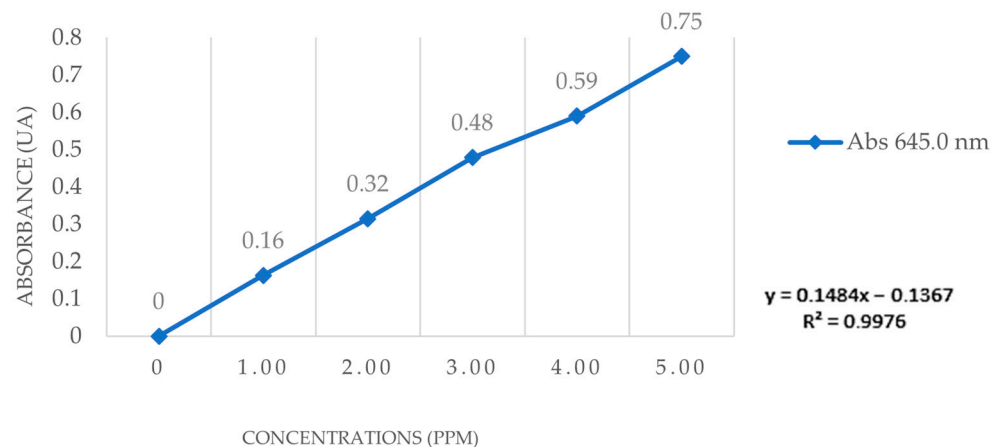


Figure A3. Methylene blue calibration curve.

Appendix C

Table A1. Results of the specific jar tests according to the dose and the initial and final values of turbidity and pH for aluminum sulphate and for natural absorbent AVW.

Test 1. Aloe Vera 1% solution						Test 2. Aloe Vera 1% solution					
Jar test	Dosage [mg L ⁻¹]	Initial Turbidity [NTU]	Final Turbidity [NTU]	Initial pH	Final pH	Jar test	Dosage [mg L ⁻¹]	Initial Turbidity [NTU]	Final Turbidity [NTU]	Initial pH	Final pH
1	-	47.84	36.19	6.91	6.73	1	-	47.84	36.19	6.91	6.73
2	5	49.43	28.78	6.85	6.86	2	2.5	46.24	31.48	6.96	6.80
3	10	49.43	28.66	6.85	6.84	3	5	46.24	33.61	6.96	6.86
4	15	49.43	30.05	6.85	6.91	4	7.5	46.24	30.87	6.96	6.89
5	20	49.43	29.76	6.85	6.95	5	10	46.24	28.84	6.96	6.93
6	25	49.43	29.90	6.85	6.92	6	12.5	46.24	32.91	6.96	6.96

Test 1. Aluminum Sulphate 1% solution						Test 2. Aluminum Sulphate 1% solution					
Jar test	Dosage [mg L ⁻¹]	Initial Turbidity [NTU]	Final Turbidity [NTU]	Initial pH	Final pH	Jar test	Dosage [mg L ⁻¹]	Initial Turbidity [NTU]	Final Turbidity [NTU]	Initial pH	Final pH
1	-	40.42	30.79	6.78	6.83	1	-	48.67	37.13	6.87	6.83
2	10	40.42	31.19	6.78	6.52	2	7.5	48.67	28.40	6.87	6.43
3	20	40.42	30.85	6.78	6.10	3	15	48.67	27.78	6.87	6.02
4	30	40.42	28.285	6.78	5.39	4	22.5	48.67	29.90	6.87	5.81
5	40	40.42	36.10	6.78	3.79	5	30	24.34	27.08	6.87	5.26
6	50	40.42	38.43	6.78	3.79	6	37.5	48.67	33.55	6.87	4.48

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