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Post-Treatment of Microbrewery Effluent Through Coagulation and Rapid Filtration

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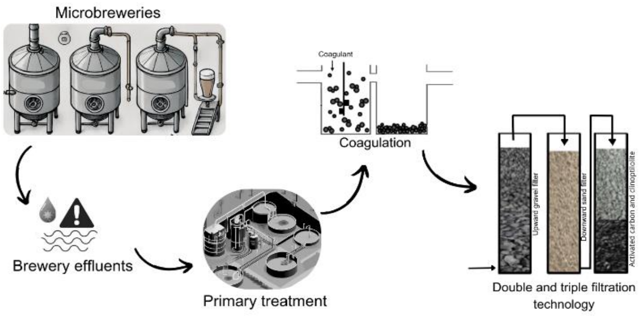
This study evaluated the efficiency of double and triple filtration technology associated with coagulation as a post-treatment of microbrewery effluent from an anaerobic decant-digester (ADD). The coagulants used were ferric chloride ($FeCl_3$), polyaluminum chloride (PAC), and a tannin-based natural coagulant (TAN). The filtration rate used was 120 m³/m²/day. The efficiency of the system was evaluated through physicochemical parameters. The post-treatment, which combined coagulation and triple filtration, achieved removals of 98% for apparent color, 64% for Chemical Oxygen Demand (COD), 59% for Biochemical Oxygen Demand (BOD), 100% for Phenols, 99% for Total Phosphorus (TP), 77% for Total Kjeldahl Nitrogen (TKN), 96% for Total Suspended Solids (TSS) and 99% for Turbidity, with results varying according to the coagulant used. Results indicated that PAC was the most efficient coagulant at lower concentrations, followed by TAN and $FeCl_3$. The post-treatment system proved to be highly effective in contaminant removal, offering a promising solution for the treatment of microbrewery effluents.

Graphical abstract



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1. Introduction

Breweries are one of the oldest and most widespread industrial branches in the world [1, 2]. In addition to large breweries, the craft brewery sector has been growing rapidly, characterized by small-scale production and the use of regional raw materials, promoting cultural and flavor diversity [3, 4]. However, many of these small breweries lack conventional wastewater treatment systems due to financial and space limitations [5]. As a result, large volumes of effluents are generated, containing high levels of organic and inorganic pollutants, reflected in high values of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), nitrogen, phosphorus, total suspended solids, turbidity, and pH variations. Without adequate treatment, these effluents compromise water quality and the health of aquatic biota, reinforcing the need for effective treatment methods [6-8].

Secondary and tertiary treatments are essential to improve

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the quality of the effluent after primary treatment, with aerobic and anaerobic processes standing out among secondary treatments [9]. Anaerobic decant-digesters are widely used in decentralized treatment systems, especially in rural areas and small industries, where they promote the reduction of solids and the stabilization of organic matter, improving the removal of COD and total suspended solids [10-12]. Although biological treatments are effective in reducing the pollutant load, additional post-treatment steps are required to ensure that the final effluent meets environmental standards [13, 14].

Coagulation is an efficient and economical technique for removing organic matter, solids, color, and turbidity, applied either before or after biological treatment [15, 16]. In coagulation, coagulants are added to destabilize colloidal particles, facilitating the formation of flocs that are subsequently removed by sedimentation or filtration [8, 17].

Coagulants such as ferric chloride ($FeCl_3$), polyaluminum chloride (PAC) and tannin (TAN) have been studied due to their efficiency in removing different parameters such as turbidity, color, TSS, BOD and COD, in addition to acting in a wide pH range [8, 15, 16]. $FeCl_3$ forms low-solubility ferric hydroxides with good sedimentation characteristics and shear strength [15, 17]. PAC, with a higher concentration of active product, generates rigid and heavy precipitates [18, 19]. TAN, due to its polymeric chains, forms larger, easily settled flocs, and produces reusable and environmentally friendly sludge [20-22].

These coagulants have shown significant results in brewery effluent treatment, with ferric chloride achieving approximately 80% removal of COD and turbidity [23]. PAC achieved up to 90.5% turbidity removal and 59.36% COD removal [8]. TAN coagulants have achieved removals of up to 99% of turbidity and apparent color [16].

The combination of coagulation with rapid filtration in the post-treatment of anaerobic effluents has proven to be highly effective, even allowing the production of noble reuse water. Double (DF) and triple filtration (TF) systems stand out in this context, removing organic compounds, metal and nitrogen ions, and making the effluents suitable for urban and industrial environmental reuse [17, 24-26]. DF (gravel and sand) can achieve up to 100% removal of total solids and 90% of turbidity [24], while DF with clinoptilolite (zeolite) has shown good results in removing COD, turbidity, BOD, nitrogen, and phosphorus [25]. The combination of DF and TF with activated carbon/clinoptilolite in the third filter resulted in water free of ammoniacal nitrogen and without toxicity to aquatic fauna [17, 26].

However, the literature on microbrewery wastewater treatment is scarce, and information on the use of double (DF) and triple filtration (TF) systems in this context is even more limited, particularly regarding their economic feasibility, and scalability for different brewery sizes.

This study evaluated a post-treatment system for microbrewery effluents using coagulation, DF, and TF after anaerobic treatment by decanter-digesters.

2. Material and Methods

2.1 Physicochemical Characterization of Microbrewery Effluents

The effluents from the microbrewery under study were collected from a unit that produces approximately 15,000 liters of beer per month, distributed among 16 different types. This production generates around 35,000 liters of monthly effluents. The initial treatment of the effluents occurs in an anaerobic pre-treatment system, consisting of eight decant-digesters, 6 of 1,000 liters and 2 of 2,000 liters, from where the samples were collected.

The physicochemical parameters analyzed in the characterization stage (collection in the decant-digester), coagulation stage, DF and TF of the effluents follow the methodologies present in the *Standard Methods for the Examination of Water and Wastewater* [27] and are presented in Table 1. The effluents were collected in bottles properly sanitized with 0.01% sodium hypochlorite, and placed in a refrigerated thermal box for transport, and stored at 4°C [8,13].

Table 1. Physicochemical parameters analyzed and the analysis methods used

Parameters	Method
Apparent Color (uH)	Spectrophotometric 2120 C**
True Color (uH)	Spectrophotometric 2120 C**
Biochemical Oxygen Demand - BOD (mg/L)	Oximeter 5210 B**
Chemical Oxygen Demand - COD (mg/L)	Spectrophotometric (Hach 6000®)*
Phenols (mg/L)	Spectrophotometric 5530 B, C**
Total Phosphorus -TP (mg/L)	Spectrophotometric (Hach 6000®)*
Total Nitrogen Kjeldahl - TNK (mg/L)	4500-N org B: Kjeldahl Method**
Ammoniacal nitrogen - N-NH_3 (mg/L)	Spectrophotometric 4500- NH3 F**
Nitrate - NO_3^- (mg/L)	Spectrophotometric (Hach 6000®)*
Nitrite - NO_2^- (mg/L)	Spectrophotometric (Hach 6000®)*
pH	Electrometric 4500H+ B*
Total Dissolved Solids -TDS (mg/L)	Filtration / Gravimetric 2540 C**
Total Suspended Solids -TSS (mg/L)	Filtration / Gravimetric 2540 D**
Total Solids -TS (mg/L)	Filtration / Gravimetric2540 B**
Turbidity (NTU)	Nephelometric 2130 B**

*Kit; **Standards Methods for the Examination of Water and Wastewater 23th

All analyses were performed in triplicate to ensure accuracy and repeatability of results. A Hach Ultra Violet Visible (UV/Vis) spectrophotometer, model DR 6000, was used for photometric analyses.

2.2 Jar Test Experiments

To evaluate the efficiency of the coagulant's $FeCl_3$, PAC, and TAN in the treatment of microbrewery effluents, preliminary jar test was conducted. These tests allowed for the determination of the optimal concentration range for the application of coagulants in the TF pilot unit.

In the bench tests, the investigated pH range varied from 4.5 to 8.0, with adjustments made using 1 M HCl or 4 M NaOH. The process followed the steps described by Silva et al. [17, 26]: rapid mixing at 300 s^{-1} for 15 seconds, followed by sedimentation at 5 cm/min. After sedimentation, the supernatant was collected for turbidity and residual apparent color analysis.

Based on the results obtained from the jar tests, the optimal coagulant concentrations for application in the pilot unit were determined: 130 mg/L for $FeCl_3$, 90 mg/L for PAC, and 95 mg/L for TAN. The treatment of the effluent from the settler-digester was conducted in the triple filtration unit, operating at a rate of 120 m³/m².d. The effluent pH was adjusted before filtration using NaOH.

2.3 Operation of the Rapid Filtration Pilot Unit

The DF and TF post-treatment system was studied with the assembly of three filters measuring 150 mm in diameter and 1800 mm in height, equipped with perforated bottom plates to ensure uniform distribution of the effluent (Fig. 1).

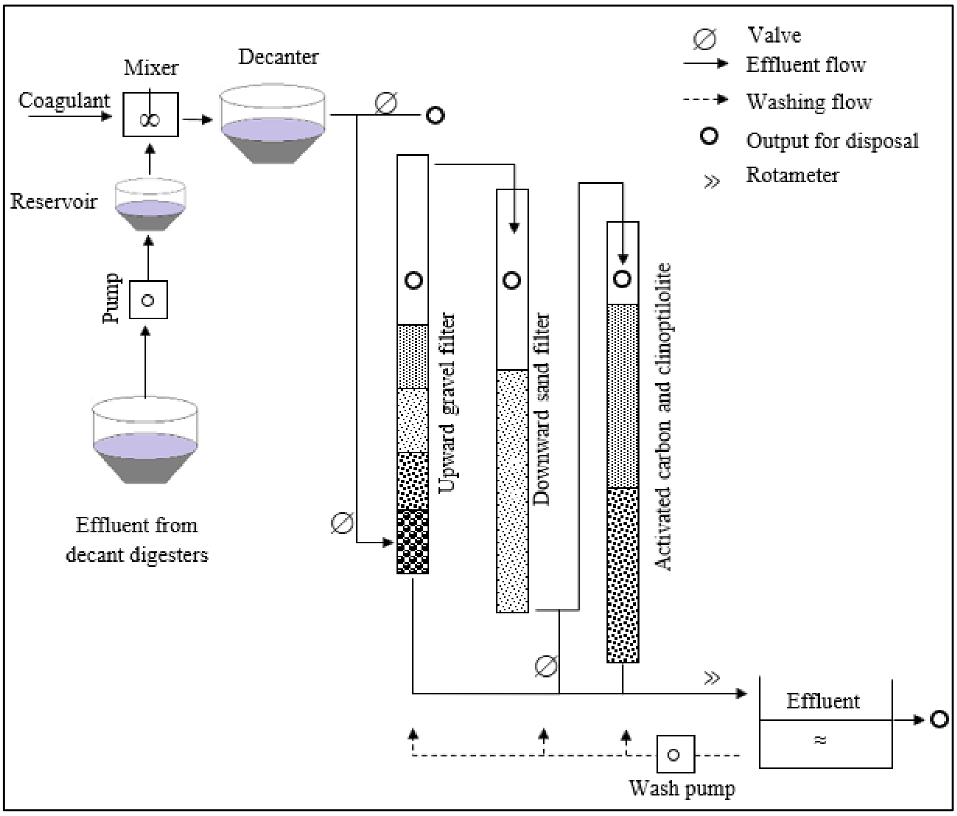

Fig. 1. Diagram of the pilot double and triple filtration system.

The first filter, called the Upward Gravel Filter (UGF), was composed of four 300 mm layers with particle sizes of 19.1 to 38.1 mm, 9.52 to 19.1 mm, 4.8 to 9.52 mm, and 2 to 4.8 mm. The second filter, the Downward Sand Filter (DSF), had particles with an effective diameter of 0.30 mm, a surface area of 0.348 m²/g and a pore volume of 0.00078 cm³/g, arranged in a 700 mm monolayer. The combination of the UGF and DSF filters comprised the DF system.

In the third filter, two layers of filter materials were used. An 800 mm layer of granular activated carbon, with a surface area of 21.3 m²/g and pore volume of 0.0601 cm³/g; and a 1000 mm layer of Clinoptilolite (Watercel ZS brand, supplied by Celta Brasil), with a surface area of 42.24 m²/g and pore volume of 0.0455 cm³/g, configuring the Activated Carbon and Clinoptilolite Filter (ACF). Together, the UGF, DSF e ACF filters formed the TF system.

Fig. 1 shows an illustration of the treatment system involving rapid filtration. The filtration rate in the DF and TF tests was set at 120 m³/m² day, following Silva et al. [17]. Samples were collected after the coagulation, DF and TF steps for 90 minutes. After 90 minutes of operation, there was no need for backwashing or regeneration of the materials in the third filter, allowing continuous evaluation of the system performance throughout the filtration time.

3. Results and Discussion

3.1 Jar Test Experiments

Fig. 2 shows the results of the Jar test, highlighting the pH variation of coagulants in brewery effluent and its effect on turbidity and color removal. It can be observed in Fig. 2A that the best turbidity removal was 95% for ferric chloride, 98% for PAC, and over 97% for TAN. It can be observed in Fig. 2B that the best color removal was 95.6% for ferric chloride, 97% for PAC, and 96% for TAN.

The efficiency of coagulants depends on pH, which influences the formation and stability of flocs. $FeCl_3$ is most effective at pH near neutrality, while below 5.8, its efficiency is reduced due to lower solubility and increased electrostatic repulsion. Above 8.0, the formation of complexes with OH^- compromises coagulation [28]

PAC performs better in slightly acidic to neutral pH, with maximum efficiency at 7.16 [29]. PAC is effective in alkaline waters, removing turbidity and organic compounds through sweep coagulation [30]. In brewery wastewater treatment, PAC achieves optimal performance at neutral pH (~7.0), where positively charged aluminum species maximize charge neutralization and floc formation, achieving up to 98% turbidity removal [31]. Below 5.5, insoluble species hinder coagulation, while above 8.0, anionic species reduce its effectiveness [31, 32].

Tannins also perform better at neutral pH, favoring the adsorption of colloidal particles and reducing turbidity and color [31, 33]. At acidic or alkaline pH, electrostatic repulsion impairs coagulation [31, 34].

Therefore, precise pH adjustment is essential to optimize the efficiency of these coagulants in wastewater treatment.

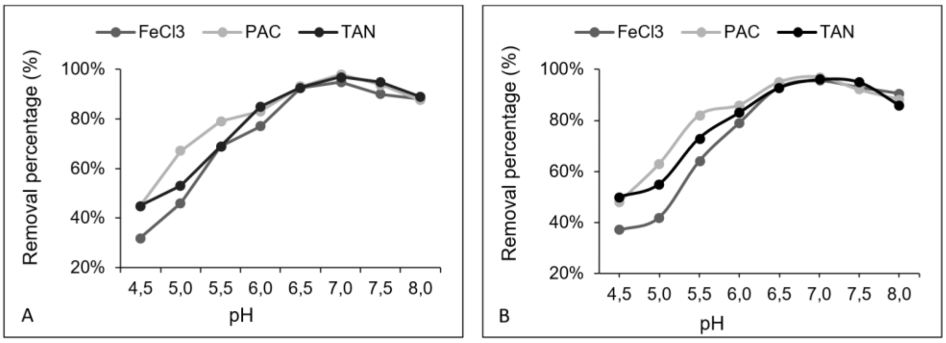

Fig. 2. Main results obtained in the Jar test, mixing gradient 300 s^{-1}; mixing time 15 s, $FeCl_3$ concentration at 130 mg/L, PAC at 90 mg/L, TAN at 95 mg/L and pH variation from 4.5 to 8.0 by: A - Turbidity; B - Apparent Color.

3.2 Evaluation of the Post-Treatment Efficiency of Anaerobic Decanter-Digester Effluent by Double and Triple Filtration Coagulation

The results of the values obtained for the coagulation and filtration study using $FeCl_3$, PAC and TAN, in concentrations of 130 mg/L, 90 mg/L and 95 mg/L, with a filtration rate of 120 m^3/m^2 and 90 min of filtration, are shown in Table 2. Next, the results related to the removal percentages of the main parameters studied were divided and discussions were held.

3.3 Removal of Color, Turbidity and Solids

Fig. 3 summarizes the performance of the three coagulants in terms of solids, color and turbidity removal in the coagulation steps, DF and TF, illustrating the removals for the concentrations of 130 mg/L to $FeCl_3$, 90 mg/L to PAC, and 95 mg/L to TAN.

Coagulation played a crucial role in the sedimentation of suspended particles, reducing the solids load for the subsequent stages. This process contributed to the higher efficiency of DF and TF in removing the remaining pollutants. The complete system, consisting of coagulation followed by DF and TF, showed high efficiency, with removals exceeding 90% for most parameters (Fig. 3). This combined configuration highlights the importance of TF as the final stage, which is essential for the retention of fine and colloidal particles that are not completely removed by coagulation or by DF.

It was observed that the order of performance of the coagulants was PAC > TAN > $FeCl_3$. PAC showed the best results, achieving the best removals at the lowest concentration. TAN, although used at a slightly higher concentration (only 5 mg/L above PAC), also obtained excellent results, especially in TF, where turbidity and apparent color removals were 99% and 98%, respectively. This reduction is attributed to the retention of colloidal particles and dissolved solids by the sand, activated carbon and clinoptilolite filters [17, 24].

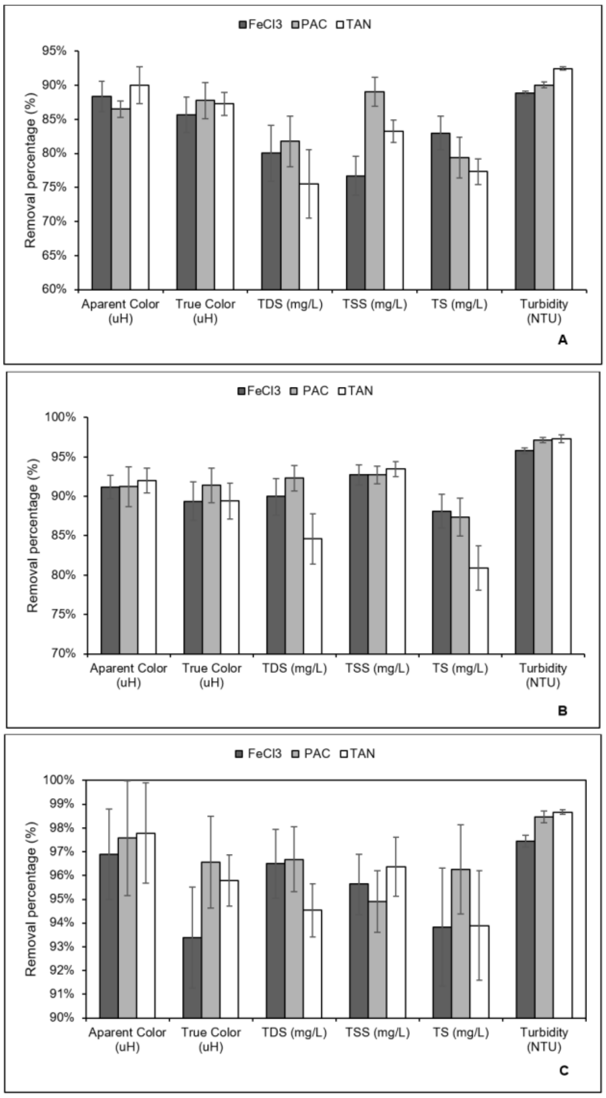

Fig. 3. Mean results obtained for brewery effluent treatment by: A - coagulation; B - DF; C - TF. $FeCl_3$ in 130 mg/L, PAC in 90 mg/L, and TAN in 95 mg/L; TDS: total dissolved solids; TSS: total suspended solids; ST: total solids. Filtration rate 120 m^3/m^2 d; pH ~ 7.0. (Mean (%) ± SD, n = 3).

Table 2. Physicochemical results obtained for the microbrewery effluent from decant-digester and post-treatment by coagulation, DF and TF

		FeCl3			PAC			TAN		
	ADD	COA	DF	TF	COA	DF	TF	COA	DF	TF
Apparent color (uH)	1864.5 ± 5.6	217.2 ± 2.2	164.8 ± 1.5	57.7 ± 1.9	251.1 ± 1.2	163.9 ± 2.6	45.2 ± 2.4	186.2 ± 2.7	149.0 ± 1.6	40.8 ± 2.1
True Color (uH)	398.3 ± 5.5	57.1 ± 2.6	42.0 ± 2.4	26.2 ± 2.1	49.3 ± 2.7	34.4 ± 2.2	14 ± 1.9	51.1 ± 1.7	42.3 ± 2.2	17.4 ± 1.1
TDS (mg/L)	2052.3 ± 10.3	410.4 ± 4.1	205.8 ± 2.3	72.4 ± 1.4	374.0 ± 3.7	157.8 ± 1.6	68 ± 1.4	502.4 ± 5.0	315.7 ± 3.2	112.0 ± 1.1
TSS (mg/L)	275.3 ± 12.7	63.9 ± 2.9	20.3 ± 1.3	11.8 ± 1.3	30.3 ± 2.1	20.2 ± 1.1	14 ± 1.3	46.2 ± 1.6	18.2 ± 1.0	10.1 ± 1.3
ST (mg/L)	2785.0 ± 14.0	474.1 ± 2.5	332.3 ± 2.2	172.2 ± 2.5	574.1 ± 3.0	352.1 ± 2.4	104 ± 1.9	632.0 ± 1.8	532.0 ± 2.8	170.3 ± 2.3
Turbidity (NTU)	128.5 ± 1.5	14.4 ± 0.4	5.4 ± 0.4	3.3 ± 0.2	12.8 ± 0.4	3.6 ± 0.3	1.98 ± 0.3	9.7 ± 0.2	3.4 ± 0.5	1.71 ± 0.1
BOD_5 (mg/L)	680.7 ± 23.5	548.8 ± 12.5	451.8 ± 14.1	343.4 ± 8.3	554.8 ± 14.2	434.2 ± 11.1	300.6 ± 12.5	507.7 ± 12.7	486.8 ± 10.1	276.6 ± 11.7
COD (mg/L)	1268.5 ± 28.5	957.0 ± 13.6	879.9 ± 12.3	496.0 ± 9.6	988.9 ± 12.4	936.5 ± 12.8	487.7 ± 11.0	889.5 ± 10.6	878.7 ± 14.7	455.2 ± 11.5
Phenols (mg/L)	12.9 ± 2.7	6.70 ± 0.6	2.9 ± 0.6	ND	6.2 ± 1.1	3.4 ± 0.3	ND	6.3 ± 0.6	3.0 ± 0.1	ND
PT (mg/L)	10.8 ± 2.5	4.4 ± 4.3	3.3 ± 0.1	0.2 ± 0.0	4.4 ± 0.2	3.8 ± 0.0	0.2 ± 0.0	4.5 ± 0.1	4.3 ± 0.5	0.1 ±0.0
Nitrate (mg/L)	9.7 ± 1.2	6.6 ± 0.2	5.4 ± 0.1	4.1 ± 0.1	6.7 ± 0.1	5.0 ± 0.1	4.3 ± 0.1	6.0 ± 0.1	4.7 ± 0.1	3.7 ± 0.1
Nitrite (mg/L)	2.7 ± 1.3	0.5 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	0.5 ± 0.0	0.4 ± 0.0	0.2 ± 0.1	0.5 ± 0.0	0.4 ± 0.1	0.2 ± 0.0
$N\text{-}NH_3$ (mg/L)	21.9 ± 2.5	0.5 ±0.1	0.3 ± 0.1	0.2 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.2 ± 0.1	0.4 ± 0.0	0.3 ± 0.1	0.2 ± 0.0
TNK (mg/L)	61.8 ± 2.2	0.7 ± 0.7	0.6 ± 0.2	0.4 ± 0.1	0.7 ± 0.3	0.6 ± 0.1	0.4 ± 0.1	0.7 ± 0.2	0.6 ± 0.1	0.3 ± 0.1

Mean results obtained for brewery effluent treatment by: ND: not detected; ADD: Anaerobic Decanter-Digester; coagulation (COA); double filtration (DF); triple filtration (TF). Ferric Chloride ($FeCl_3$) 130 mg/L, Polyaluminum Chloride (PAC) 90 mg/L, and Tannin (TAN) 95 mg/L. $N\text{-}NH_3$: ammoniacal nitrogen; TNK: total Kjeldahl nitrogen; TP: total phosphorus; TDS: total dissolved solids; TSS: total suspended solids; TS: total solids; uH: Hazen Unit; NTU: Nephelometric Turbidity Unit. Filtration rate: 120 m^3/m^2 d; pH ~ 7.0. (Mean (%) ± SD, n = 3).

When comparing these results with the literature on brewery effluent treatment, it is observed that the obtained removal values were similar or even higher. Tonhato et al. [16], with initial concentrations of 2420 uH for color, 1400 mg/L for TSS and 256 NTU for turbidity, achieved 99.4% color removal, but only 40.8% for TSS, using a TAN coagulant concentration of 0.23 ml/L (~246 mg/L) and pH 4.9. Simate [15], using $FeCl_3$, obtained 82.3% turbidity removal (from 85 NTU to 15 NTU) with 50 mg/L of coagulant. Shabangu et al. [8], with PAC at 70 mg/L, removed 75% of the turbidity in effluents with an initial turbidity of 76.20 NTU. In the present study, the effluent had an initial turbidity of 128 NTU, and it was possible to remove 89% of the turbidity with 130 mg/L of $FeCl_3$, 90% with 90 mg/L of PAC, and 92% with TAN in the coagulation stage. Alayu et al. [35], reduced TSS by 47.8%, starting from 113.12 mg/L, using a two-stage horizontal flow wetland system. In another example, Okolo et al. [36], using *Detarium microcarpum* as a flocculant, removed 96% of TSS from an initial concentration of 728.3 mg/L. With the post-treatment system in this study, which combines coagulation, DF and TF, it was possible to remove more than 96% of TSS, varying according to the coagulant used, demonstrating the high efficacy of the process for this parameter.

In the present study, with variations in removals between the coagulants, it was possible to achieve reductions of 89% for TSS, 90% for color and 92% for turbidity in the coagulation stage. In the TF, the removals were even more significant, reaching 98% for apparent color, 99% for turbidity, and 96% for TSS. These results demonstrate the high efficiency of the proposed post-treatment, highlighting the potential of the system for applications in brewery effluents.

Thus, the coagulation system followed by rapid filtration proved to be highly efficient in removing turbidity, color and solids from brewery effluents, presenting itself as a competitive and promising alternative, with performance comparable to or better than that of systems described in the literature.

3.4 Removal of Biochemical Oxygen Demand, Chemical Oxygen Demand, Phenols and Total Phosphorus

Fig. 4 shows the results of removal of BOD, COD, Phenols and Total Phosphorus.

In the coagulation stage (Fig. 4A), BOD removal ranged from 18% to 25%. In DF, removals ranged from 28% to 36% (Fig. 4B), and in TF (Fig. 4C), removals reached between 50% and 59%. For BOD, it was observed that the coagulation treatment using tannins and the TF system provided a removal of 60%. For COD, removals in the coagulation and DF stages were less than 31%, with the best performance observed in TF, where COD was reduced from 1268.5 mg/L to 455.2 mg/L (64% removal).

TAN demonstrated the best performance in BOD and COD removal during coagulation. This result can be attributed to its polymeric structure rich in phenolic groups, which are highly effective at removing organic compounds such as those in BOD and COD. This mechanism explains the superior performance of the tannin coagulant, compared to PAC and $FeCl_3$ in reducing these parameters in this study [20, 22, 37].

Much of the BOD and COD removal was attributed to the triple filtration process with activated carbon and clinoptilolite, which, due to its high porosity and adsorption capacity, contributed significantly to the removal of organic compounds. Clinoptilolite, with its ion exchange capacity, also played an important role in removing these parameters [17, 25].

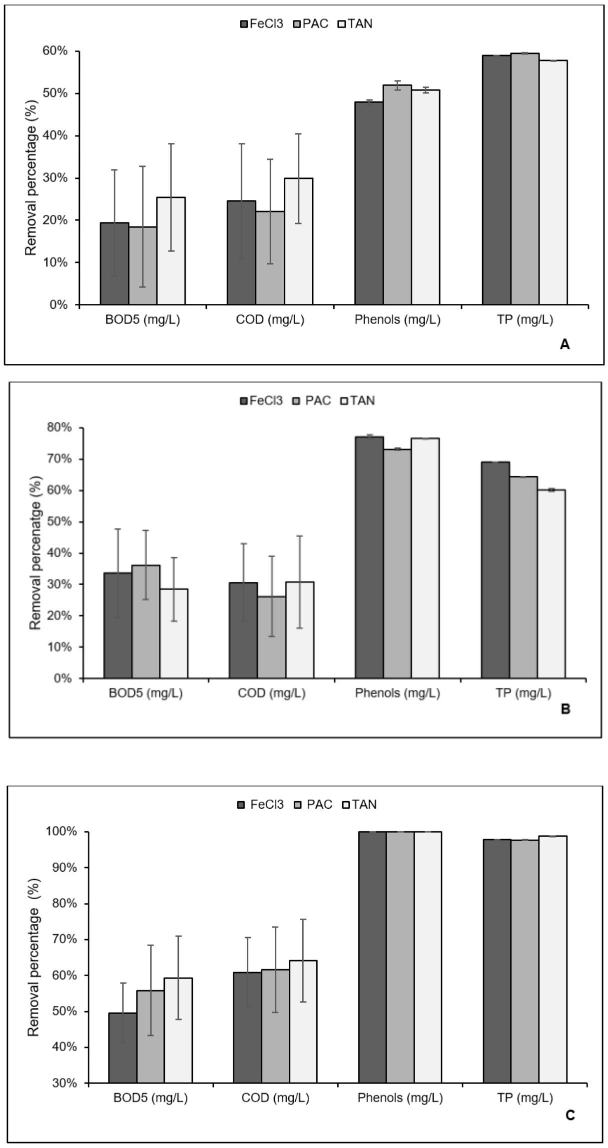

Fig. 4. Mean results obtained for brewery effluent treatment by: A - coagulation; B - DF; C - TF. $FeCl_3$ in 130 mg/L, PAC in 90 mg/L, and TAN in 95 mg/L. TP: Total Phosphorus. Filtration rate 120 m³/m² d; pH ~ 7.0. (Mean (%) ± SD, n = 3).

Comparing the results of this study with the literature on post-treatment of brewery effluents, the removals of BOD and COD are within or above the reported ranges. Innes et al. [13] recorded COD removals between 42.9% and 89.4%, while Tonhato et al. [16] reported 69.8% BOD removal. Shabangu et al. [8] observed removals of 59.36% for COD and 59.54% for BOD.

Studies combining coagulation with rapid filtration demonstrate efficiency in BOD and COD removal. Costa et al. [25], using filtration with gravel and clinoptilolite followed by ozonation, achieved removals of 84% to 95% for BOD and 66% to 81% for COD for sanitary effluents. Cavallini et al. [24] achieved COD removals between 65% and 69% and BOD removals between 55% and 79% with coagulation/oxidation and double filtration processes for sanitary effluents. Despite the significantly higher initial BOD and COD values in this study, the removals obtained ranged from 50% to 59% for BOD and from 61% to 64% for COD, demonstrating the effectiveness of the methods employed, even without the use of oxidizing agents.

The removal of total phenols varied according to the coagulant used in the coagulation (Fig. 4A), DF (Fig. 4B) and TF (Fig. 4C) stages, with ranges of 48% to 52%, 73% to 77% and 100%, respectively. Although there was no significant variation in the performance of the coagulants used, the stages showed different results, with TF achieving total phenol removal. This effectiveness is directly related to the absorbent materials used in the TF stage, such as activated carbon and clinoptilolite, which play a fundamental role in retaining phenols. Phenols can come from toxic compounds used during tank washing and their removal is extremely important to avoid toxicity to the environment [38].

This study demonstrated a progressive removal of TP, with efficiencies of 58% to 59% in coagulation (Fig. 4A), where the coagulants showed similar performance, 60% to 69% in DF (Fig. 4B), and 98% to 99% in TF (Fig. 4C), reaching a final value of 0.1 mg/L in the treated effluents. The results obtained with the applied post-treatment methods surpassed those achieved by previous methods for brewery effluent treatment, which ranged from 29.3% to 98.3%, depending on the treatment time and processes employed, such as ultrafiltration, reverse osmosis and adsorption with granular activated carbon [13]. Additionally, Tonhato et al. [16] reported 82.3% TP removal using vegetable tannin-based flocculant, and Swain et al. [2] obtained removals of 26% to 85% with electrocoagulation combined with chemical coagulation. The coagulation process in the initial post-treatment phase is essential for TP removal. With metal coagulants, the formation of metal hydrates facilitates phosphate incorporation into hydrated oxide structures, promoting the formation of mixed cationic and metallic phosphates [17, 24, 20]. The tannin-based coagulant stands out due to its chemical structure, which contains highly reactive phenolic and hydroxyl groups. These groups interact effectively with organic compounds and phosphate ions, facilitating the efficient removal of phosphorus [22, 37].

In the TF process, using clinoptilolite as a filter medium increased process efficiency. This occurs because it promotes ion exchange of the ammonium ion for Ca^{2+}, facilitating the precipitation of residual phosphate [17, 25, 26].

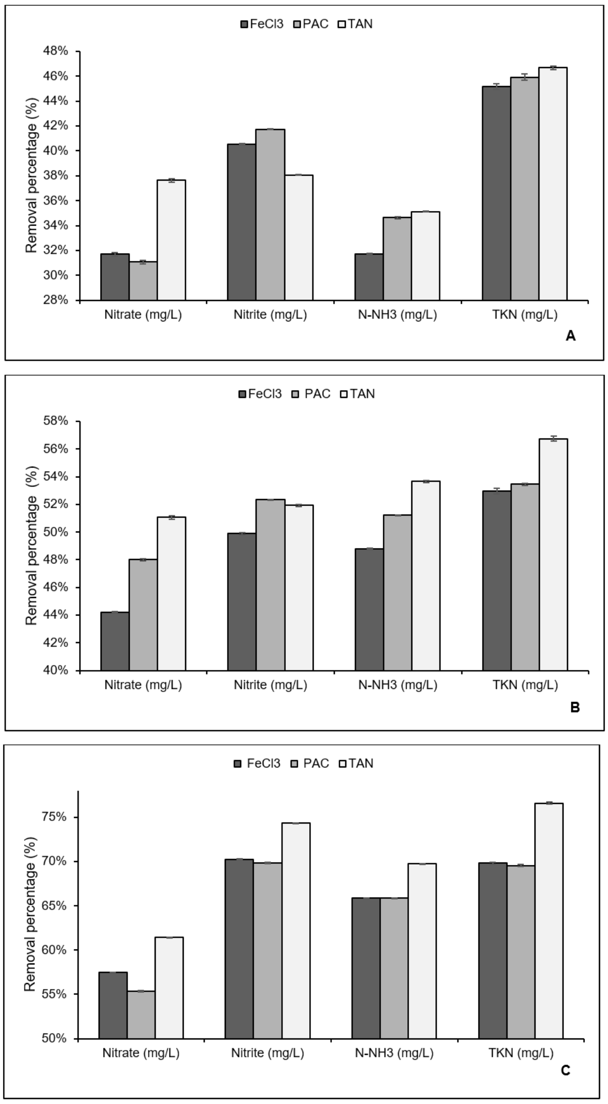

Fig. 5. Mean results obtained for brewery effluent treatment by: A - coagulation; B - DF; C - TF. $FeCl_3$ in 130 mg/L, PAC in 90 mg/L, and TAN in 95 mg/L. N-NH_3: ammoniacal nitrogen; TKN: total Kjeldahl nitrogen. Filtration rate 120 m³/m² d; pH ~ 7.0. (Mean (%) ± SD, n = 3).

3.5 Removal of Total Kjeldahl Nitrogen, Ammoniacal Nitrogen, Nitrite, and Nitrate

Fig. 5 shows the TKN, N-NH_3, nitrite, and nitrate concentrations of the analyzed effluent throughout the different post-treatment stages.

At the coagulation stage (Fig. 5A), the removal efficiencies of TKN, ammoniacal nitrogen, nitrate, and nitrite varied depending on the coagulant used, reaching 47%, 35%, 38%, and 42%, respectively. Coagulation, an essential step in wastewater treatment, promotes particle aggregation and can influence the removal of nitrogenous compounds, although its efficiency depends on factors such as coagulant dosage, pH, and temperature [17, 25, 26,39].

At the DF stage (Fig. 5B), the removal of these compounds increased to 57% (TKN), 54% (ammoniacal nitrogen), 51% (nitrate), and 52% (nitrite), highlighting the greater efficiency of filtration in nitrogen removal. The retention of coagulated particles and the adsorption of nitrogenous compounds by the filter media were key factors contributing to this improvement [17, 25, 26].

The TF stage (Fig. 5C) exhibited higher removal rates, reaching 77% (TKN), 70% (ammoniacal nitrogen), 61% (nitrate), and 74% (nitrite). The use of advanced filter media, such as activated carbon and membranes, contributed to this efficiency. Notably, clinoptilolite demonstrated removal rates of 93.8% for TKN and 99.5% for ammoniacal nitrogen in the post-treatment of anaerobic reactors [17, 26]. Additionally, its application offers advantages such as low cost and agricultural reuse of nitrogen [40].

Ultrafiltration systems can achieve TKN removal rates ranging from 68.2% to 80.3%, but they involve high operational costs [13]. In contrast, the combined coagulation-filtration approach represents a more cost-effective and efficient alternative for treating microbrewery effluents, ensuring environmental compliance and reducing the toxicity of ammoniacal nitrogen to aquatic fauna [17, 26].

The coagulation-filtration system (DF and TF) presents an efficient and economical alternative for removing nitrogenous compounds from microbrewery effluents, standing out for its high efficiency in ammoniacal nitrogen removal. The results indicate that filtration-based technologies can optimize wastewater treatment, making it more accessible and applicable to various industrial sectors.

4. Conclusions

This study demonstrated that the combination of coagulation and triple filtration is a highly effective approach for the post-treatment of microbrewery effluents, achieving significant pollutant removals of up to 98% for apparent color, 99% for turbidity, 96% for total TSS, 77% for TKN, and 64% for COD. Triple filtration played a crucial role in the final retention of particles and organic compounds, maximizing the quality of the treated effluent.

Among the coagulants tested, PAC achieved the best results at lower dosages, followed by the TAN, which stands out as an environmentally friendly alternative. $FeCl_3$, although effective, exhibited lower performance compared to the other coagulants.

The high efficiency of the proposed system reinforces its potential for practical application, ensuring compliance with environmental standards and enabling the reuse of treated water. Furthermore, this study paves the way for future research focused on optimizing operational parameters and assessing the economic feasibility of large-scale implementation.

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Author Contributions

Amanda Vedam Pupin: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Writing-original draft, Writing-review and editing. Cleber Pinto da Silva: Conceptualization, Methodology, Investigation, Resources, Formal analysis, Writing-original draft, Writing-review and editing. Sandro Xavier de Campos: Supervision, funding acquisition and review.

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