Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

Type of the Paper (Original Research)

Optimization of Coagulation-Flocculation Mechanism to Reduce Chemical Oxygen Demand in Domestic Wastewater

Susan Montes-Bujaico[1], Oliver Taype-Landeo[2], Richerson Piscoche-Chinchay[2], Deyvid Cruz-Ventura[3], Wilson Montañez-Artica[2] and Lucia Pantoja-Tirado[2]

[1]Academic Department of Forestry and Environmental Engineering, University National Autonomous at Tayacaja Daniel Hernandez Morillo, Huancavelica, Peru

[2]Academic Department of Food Industry Engineering, University National Autonomous at Tayacaja Daniel Hernandez Morillo, Huancavelica, Peru

[3]Academic Department of General Studies, University National Autonomous at Tayacaja Daniel Hernandez Morillo, Huancavelica, Peru

†Corresponding author: Lucia Pantoja-Tirado; luciapantoja@unat.edu.pe

ORCID IDs of Authors

https://orcid.org/0009-0008-2981-0898

https://orcid.org/0000-0003-4197-1164

https://orcid.org/0000-0002-1893-2952

https://orcid.org/0009-0006-2057-1742

https://orcid.org/0000-0001-9157-6088

https://orcid.org/0009-0003-5681-4142

Key Words	Wastewater, Coagulation, Flocculation, PAC, Jar test
DOI	https://doi.org/10.46488/NEPT.2025.v24i04.D1817 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Montes-Bujaico, S., Taype-Landeo, O., Piscoche-Chinchay, R., Cruz-Ventura, D., Montañez-Artica, W. and Pantoja-Tirado, L., 2025. Optimization of coagulation-flocculation mechanism to reduce chemical oxygen demand in domestic wastewater . *Nature Environment and Pollution Technology*, 24(4), D1817. https://doi.org/10.46488/NEPT.2025.v24i04.D1817

ABSTRACT

The efficient treatment of Domestic Wastewater (DWW) through the coagulation and flocculation mechanism is essential to reduce the Chemical Oxygen Demand (COD), which not only contributes to the improvement of the environment, but also to the possible reuse in agricultural irrigation. The objective of this research was to optimize the coagulation and flocculation process to reduce the COD in the DWW of a tributary of the Mantaro River in the district of El Tambo-Huancayo. The developed methodology included the collection of DWW through representative sampling, the initial and final measurement of the COD and pH, the preparation of the coagulating agent and the adjustment of the intensity of agitation using the jar test equipment; using a 4×2 factorial design. Four PAC concentrations (40, 60, 80 and 100 ppm) and two agitation speeds (100 and 200 rpm) were tested using jar tests under controlled conditions. The results showed statistically significant differences between treatments ($p < 0.001$). The combination of 60 ppm PAC and 100 rpm achieved the highest efficiency, with a 69.33 % COD removal. At higher doses, a decrease in performance was observed, attributed to the phenomenon of overdosing. The coagulation process proved to be effective in decreasing COD in DWW, and optimization of treatment parameters can further improve its efficacy.

1. INTRODUCTION

Water is an essential and fundamental natural resource for all living beings and is necessary for various agricultural, industrial, domestic, and other activities. However, excessive consumption of water has led to a significant increase in the generation of DWW, which generates higher Chemical Oxygen Demand (COD) due to effluents from various sectors. These effluents compromise the quality of surface and groundwater, introducing contaminants that are harmful to the environment and human health.

Currently, the generation of DWWs is of great concern, due to its discharge into water bodies without any treatment, therefore, an adequate method is essential to guarantee its safety, cleanliness and suitability to be discharged again into water resources (Tauseef et al. 2023, Vishali et al. 2023, Narayanan et al. 2025), since they offer potential as a source of water, energy and in agriculture due to having nutrients and fertilizing elements such as nitrogen and phosphorus (Abdo 2023, Narayanan et al. 2025).

Untreated water represents a risk to public and environmental health, hence, efforts are being made to reduce environmental impact and improve quality of life (Tauseef et al. 2023, Worku et al. 2024).

DWW generally present high levels of ammonia, total phosphorus, COD, pharmaceutical residues and a substantial population of microorganisms (Chen et al. 2024). Due to their salt content, they are treated by a combined sedimented coagulant process (Li et al. 2024). DWW have a high content of organic compounds and nutrients, as well as some pollutants such as suspended solids and heavy metals, which can be recovered through physical and chemical treatments; the nutrient content benefits plant growth and production; however, in high concentration they generate eutrophication in surface waters such as rivers and lakes, altering the ecosystem and generating a negative impact on water quality (Buslima et al. 2024).

COD is an essential parameter to assess organic pollution in water bodies, removing and determining the amount of oxygen equivalents needed to oxidize the organic material present in wastewater and industrial waters

(Gilpavas et al. 2018, Medina-Valderrama et al. 2020, Worku et al. 2024). Increasing levels of COD indicate an organic concentration in domestic wastewater. This leads to a decrease in oxygen in the wastewater (Gilpavas et al. 2018, Worku et al. 2024).

High concentrations of COD in wastewater and industrial waters cause deoxygenation of waters in contact with some substance affecting the O2 requirement of aquatic organisms (Mayta and Mayta 2017, Gilpavas et al. 2018). COD measurement is very useful to estimate the oxygen requirements of industrial discharges, when the biochemical oxygen demand is not very effective due to the presence of toxic or other inhibitory substances (Mayta and Mayta 2017). Optimizing the coagulation mechanism can not only result in a decrease in COD, but can also contribute to the reduction of operating costs and improve the sustainability of wastewater treatment (Hidalgo et al. 2023).

The coagulation process has been established as an essential technique in wastewater treatment, which is realized by the addition of coagulants that facilitate the agglomeration of particles and organic matter, allowing their subsequent elimination (Zhang et al. 2023). However, efficiency of the coagulation process depends on factors such as coagulant choice, applied dose, pH and specific characteristics of the wastewater (Muniz et al. 2020). Recent research has shown that the optimization of these variables can lead to a significant reduction in COD, improving the operational efficiency of treatment plants (Wang et al. 2022).

Coagulation, flocculation and decantation are physical and chemical processes aimed at optimizing the removal of suspended solids and reducing COD in DWW effluents (Addich et al. 2024, Corpus et al. 2024). Efficiency of the coagulation/flocculation mechanism in jar tests depends on the type, dosage and nature of the coagulant, as well as mixing speed and water quality (pH, ionic strength and presence of contaminants) (Acarer 2023). The application of mixed coagulants is found to be effective in reducing COD (Getahun et al. 2024). Coagulation has been widely used in most processes due to its phase change, easy operation, low cost and high efficiency. Conventional coagulants include inorganic coagulants based on iron (Fe) and aluminum (Al) and prehydrolyzed inorganic coagulants such as polyferric sulfate and polyaluminum chloride (PAC) (Shi et al. 2023, Addich et al. 2024).

Currently, inorganic polymer compounds used as coagulants are of scientific interest because they contain various chemical groups such as iron, sulfate, aluminum and silicate, and are easily forming molecular structures with improved coagulation efficiency (Addich et al. 2024). In the combined flocculation-flotation process, the flocculated particles containing hydrophobic polycyclic aromatic hydrocarbons meet and adhere to the microbubbles and float to the surface, thus effectively reducing the COD content (Li et al. 2024).

PAC can be harmful to health, and it is recommended to reduce its concentration, which also reduces the turbidity of wastewater (Nti et al. 2021). The use of PAC as a coagulant agent in the treatment of wastewater with domestic effluents significantly optimizes the removal of suspended solids and microplastics (Kwon et al.

2022). The jar assay test and the preparation of the coagulant solution must be carried out in parallel to avoid alterations in the results (Meza-Leones et al. 2018).

The present study is focused on optimizing the coagulation-flocculation process in domestic wastewater, and identification the optimal conditions for reducing COD and contributing to more efficient management of water resources.

2. MATERIALS AND METHODS

This study was classified as propositional, aimed at developing solutions for optimizing the treatment of DWW and reducing COD, with a view to promoting the use of treated effluents.

Wastewater Collection

The DWW samples were collected from a collector that flows into the Mantaro River, located in the Pio Pata urban province, in the district of El Tambo, province of Huancayo. This wastewater comes from various domestic sources, including kitchens, sinks, showers and toilets.

Study Location

The sampling was carried out in the Pio Pata urban province, located at an altitude of 3225 meters above sea level, with geographic coordinates of longitude X = 8665910 and latitude Y = 0474853.

Sampling Process

Representative sampling was carried out according to the Surface Water Monitoring Protocols relevant to the region. A representative sampling was carried out in 16 samples every 5 minutes according to the Surface Water Monitoring Protocols pertinent to the region. 25 liters of DWW were collected in sterilized plastic containers, the samples were kept at room temperature for immediate transport to the laboratory. The samples were divided into 16 portions. pH and temperature (degree Celsius, °C) were measured in situ using a waterproof multiparameter meter (HANNA, HI 9829 model). COD was analyzed in the water analysis laboratory of the Faculty of Chemical Engineering of the National University of the Center of Peru, by the method of Meza-Leones et al. (2018).

Preparation of the Coagulant

For coagulant preparation, 1 g of PAC (Aln(OH)mCl(3n-m)) was weighed using a high-precision analytical balance (Armotec, VE-204 model). The coagulant was dissolved and diluted to a final volume of 100 mL with deionized water to obtain concentrations of 40, 60, 80 and 100 ppm, according to the protocol described by Meza-Leones et al. (2018). These concentrations between 40 and 100 ppm of coagulant were based on previous studies that worked similarly at 50 and 100 ppm in aluminum sulfate and natural coagulant such as Moringa oleifera, in the clarity of wastewater, surface, as for the removal of turbidity and organic matter; likewise the jar test showed that below 40 ppm there is no good coagulation, while above 100 there is a favorable improvement. For this reason, the range of 40 - 100 ppm is efficient, balanced and rational in the use of natural inputs as proposed by Liu et al. (2021) and Shan et al. (2017).

Wastewater Treatment

The DWWs were subjected to a coagulation process using the coagulant PAC (Aln(OH)mCl(3n-m)). A pilot test was carried out using a jar test, with four Lovibond brand glasses (ET-740 model).

Coagulation Process by Jar Test

A jar test equipment consisting of four 2 L vessels each was used, where random treatments were carried out following a factorial design. One liter of homogenized DWW sample was introduced into each vessel and the coagulant was supplied by syringes, according to predefined concentrations. The equipment was configured to carry out the coagulation and flocculation mechanisms, following the protocol adapted from (Perez et al. 2022).

Conditions of the Coagulation and Flocculation Process

The coagulation process was carried out for 5 minutes, with stirring intensities of 100 rpm and 200 rpm, according to the factorial design. Flocculation was carried out for 20 minutes, followed by a 30-minute sedimentation phase. Subsequently, 2 mL of sample from each treatment was transferred to vials for COD quantification. The samples were subjected to digestion in an ET reactor at 150 °C for a period of 2 hours, with capacity for 8 test tubes. After a 30-minute cooling period, the COD concentration was determined using a UV-Vis Spectrophotometer 1203.

Statistical Data Analysis

A 4 x 2 factorial arrangement experimental design was applied to evaluate the optimum for coagulant concentration and agitation intensity to achieve COD decrease. This statistical factorial design of 4X2 serves to compare 8 combinations, served to evaluate the concentrations of the coagulants in 4 levels such as: 60, 60, 80 and 100 ppm and 2 levels such as acid and neutral; being the only variables of study and of interest to maintain the operative viability in the study and to focus only on the most critical factors identified in the stage of previous diagnosis, by the interaction between both factors, making impossible a unifactorial as a design. Coagulation tests were performed using various concentrations of PAC (Aln(OH)mCl(3n-m)) and variations in agitation intensity in the jar test apparatus. The obtained samples were subjected to quantitative analysis to evaluate the COD concentrations before and after treatment. Subsequently, ANOVA was performed to test difference between the treatments (the difference was significant at $p < 0.05$) and then the Tukey Test was applied to solve, which was the best treatment. Normality tests (Shapiro-Wilk); homogeneity of variances (Levene) and the residuals plot were performed using Minitab 2019 statistical software, applied to the results obtained in the 4×2 factorial design.

3. RESULTS AND DISCUSSION

The DWWs were initially subjected to a coagulation process to determine the optimal treatment conditions. Chemical coagulation was carried out by means of a jar test using a pilot test design. The presented in Table 1 results indicate COD of 298.95 ppm and pH of 6.83. These values show high levels of COD, according to the Technical Standard of Environmental Quality of Law No. 28611 of Peru, as well as pH that is classified as slightly acidic, which is relevant for the analysis of the quality of treated water.

Table 1: Initial physicochemical characterization of ARD.

Initial sample	COD (ppm)	Temperature (°C)	pH
Mi (x)*	300.60	14.00	6.83
Mi (y)*	297.30	14.00	6.83

*Mi: Initial sample

(x) first measurement.

(y) repetition of the first measurement

Table 2: Conditions of treatments.

Sample	Concentration of the coagulation agent (ppm)	Intensity of agitation (rpm)	Treatment
M1	40.00	100.00	Tr1
M2	60.00	100.00	Tr3
M3	80.00	100.00	Tr5
M4	100.00	100.00	Tr7
M5	40.00	200.00	Tr2
M6	60.00	200.00	Tr4
M7	80.00	200.00	Tr6
M8	100.00	200.00	Tr8

Table 2 shows the parameters established for the eight treatments applied, considering coagulant concentration and agitation speed as independent variables. Each experimental configuration was identified by a specific code (Tr1 to Tr8), which made it possible to systematically organize and analyze the trials. This experimental approach allowed a comprehensive evaluation of the combined impact of both variables on the effectiveness of the coagulation-flocculation process in the treatment of domestic effluents.

Table 3: Treatments according to the 4x2 factorial arrangement.

SAMPLE	Coagulating agent concentration (ppm)	Stirring intensity (rpm)	COD (ppm)	pH
M1x	40.00	100.00	163.50	6.57
M1y	40.00	100.00	158.20	6.50
M2x	60.00	100.00	91.70	6.40
M2y	60.00	100.00	94.10	6.43
M3x	80.00	100.00	132.40	6.27
M3y	80.00	100.00	129.50	6.31
M4x	100.00	100.00	190.80	6,11
M4y	100.00	100.00	193.40	6.13
M5x	40.00	200.00	123.20	6.41
M5y	40.00	200.00	126.60	6.42
M6x	60.00	200.00	162.40	6.40
M6y	60.00	200.00	158.00	6.40
M7x	80.00	200.00	171.80	6.23
M7y	80.00	200.00	174.10	6.19
M8x	100.00	200.00	183.50	6,11
M8y	100.00	200.00	186.70	6.10

*M1: Sample 1; M2: Sample 2; …..M8: Sample 8
x , y: Treatments

Table 3 shows the data obtained after the application of a 4×2 factorial design, which included four coagulant concentration levels (40, 60, 80 and 100 ppm) and two agitation speeds (100 and 200 rpm). Each combination was replicated (x, y) to ensure statistical validity and reproducibility of the experimental results.

Although the treatment with 60 ppm PAC at 100 rpm presented the highest efficiency in COD separation, a reduction in performance was identified when the coagulant dose was increased to 100 ppm. This decrease is generated by a common phenomenon in coagulation-flocculation systems called overdosing. When an excessive amount of coagulant is added, suspended particles can experience a surface charge reversal, generating repulsion instead of attraction, which prevents the formation of stable flocs. According to Guo et al. (2015); in the treatment of wastewater with high colloidal content, a high dose of flocculants can cause the dissolution of already formed flocs, reducing their weight and sedimentation capacity.

According to Liu et al. (2023), in waters with potato starch, increasing coagulant above the optimum level resulted in a more dispersed colloidal structure, making clarification more difficult. These findings coincide with what was observed in this research, and show the importance of maintaining a balance between effective dosage and flocculant stability.

Table 4: Decrease in COD.

SAMPLE	Initial COD (ppm)	Post treatment COD (ppm)	Decrease in COD (ppm)	Decrease in COD (%)
M1x	298.95	163.50	135.45	45.31
M1y	298.95	158.20	140.75	47.08
M2x	298.95	91.70	207.25	69.33
M2y	298.95	94.10	204.85	68.52
M3x	298.95	132.40	166.55	55.71
M3y	298.95	129.50	169.45	56.68
M4x	298.95	190.80	108.15	36.18
M4y	298.95	193.40	105.55	35.31
M5x	298.95	123.20	175.75	58.79
M5y	298.95	126.60	172.35	57.65
M6x	298.95	162.40	136.55	45.68
M6y	298.95	158.00	140.95	47.15
M7x	298.95	171.80	127.15	42.53
M7y	298.95	174.10	124.85	41.76
M8x	298.95	183.50	115.45	38.62
M8y	298.95	186.70	112.25	37.55

The initial value 298.95 ppm corresponds to the average of three independent COD measurements, performed on the same composite wastewater sample. The low observed variability of ±1.3 ppm is due to the good homogeneity of the sample before the tests, which allowed obtaining consistent values in the initial measurements.

Table 4 presents the COD values before and after the treatment applied to the DRAs, indicating the absolute and percentage reductions achieved with each treatment. The most efficient result was the one corresponding to 60 ppm of poly aluminum chloride (PAC) with an agitation of 100 rpm (M2x), reaching an average decrease of 69.33 % in COD, which evidences a high efficiency of the process. This performance is attributed to the action of PAC at that concentration, which favors the formation of highly charged polynuclear hydrolyzed species, such as $[Al_{13}O_4(OH)_{224}(H_2O)_{12}]^{7+}$. These species possess a high positive charge that favors the neutralization of colloids present in water. As the zeta potential decreases, the attraction between particles intensifies, facilitating their agglomeration into dense and easily sedimentable flocs. This mechanism, described in recent studies (Wang et al. 2015; Youssef et al. 2023; Sun et al. 2024), supports the effectiveness observed in the treatment applied.

This balance between contaminant load and coagulant dosage avoids adverse effects. Insufficient doses may not completely neutralize the particles, while high concentrations (such as 80 or 100 ppm) may cause colloidal re-stabilization, generated by a positive overload. This excess of coagulant ions reverses the charge of the particles and hinders the formation of stable flocs, significantly reducing the effectiveness of the treatment. Such behavior has been documented in studies on chemical coagulation using metallic salts (Amiri et al. 2022; Singh et al. 2024; Xiao et al. 2024).

In coagulation, the initial rapid agitation seeks to maximize the contact between the coagulant and the suspended particles, facilitating the formation of floc nuclei. Then, slow agitation allows these to increase in size and density, favoring their sedimentation. This sequential process is key to improving organic matter removal. Recent studies indicate that both the intensity and duration of agitation influence the physical characteristics of the flocs. Rapid agitation promotes initial floc formation, but over-stirring can fragment the flocs and reduce their efficiency. In contrast, subsequent moderate agitation favors more uniform, porous and easily separable flocs. This dynamic has been extensively documented by Hudson (1965), Yu et al. (2022) and Jin et al. (2025).

Getahun et al. (2024) reported effectiveness of COD removal so high as 98.24% to 98.41%, wherein mixed coagulants presented better results than using a single type; pH value was 8.76, and coagulant dose was 0.750 g per one liter. For his part, Abdo (2023), reached COD levels of 169 molar at 68.4% and 40 molar at 84.9%. Medina-Valderrama et al. (2020) documented that, when using the Fenton process in the processing of wastewater from a slaughterhouse, a final COD of 934.14 mg O_2/L and a pH of 7.10 were obtained, evidencing a significant reduction in COD and, therefore, an improvement in water quality. To optimize the reduction of COD in domestic wastewater (DWW) by the coagulation mechanism, the jar test was used, a laboratory analytical method designed to evaluate the effectiveness of coagulating agents and the operating conditions of the coagulation and flocculation process. This approach mainly aims to identify the optimal conditions for wastewater treatment.

Meza-Leones et al. (2018) suggested careful verification of the preparation of the jar test in each repetition and the immediate preparation of the coagulant solution to avoid discrepancies in the results. Perez et al. (2022)

performed jar tests on secondary effluents generated in a wastewater treatment plant on two different dates. Dosages of $Al2(SO4)3$ from 40.00 to 220.00 mg/L and from 10.00 to 100.00 mg/L, as well as anionic polyelectrolyte from 0.4 to 1 mg/L. According to the manufacturer, these concentrations are crucial for the control and optimization of tertiary treatments in a wastewater treatment plant.

Coagulation and flocculation are commonly applied processes to remove suspended solids and reduce COD in domestic wastewater. Corpus et al. (2024) also highlight their effectiveness against emerging pollutants, underlining their versatility. However, the presence of complex organic compounds such as humic acids can hinder floc formation by blocking the active sites of the coagulant. This makes it necessary to adjust both the agitation intensity and the applied dosage according to the water composition. Research by Yu et al. (2022) and Liu and Yu (2022) agree that a combination of fast followed by slow agitation, proper dosing and precise pH control are key to achieving stable and effective flocs for contaminant removal.

The efficiency of the coagulation/flocculation mechanism in jar tests is determined by the type, dose and nature of the coagulant, as well as by the mixing speed and water characteristics (pH, ionic strength and presence of contaminants) (Acarer 2023).

Table 5: Results corresponding to % of COD in DWW treatments.

Repetitions	40 ppm		60 ppm		80 ppm		100 ppm	
	100 rpm	200 rpm	100 rpm	200 rpm	100 rpm	200 rpm	100 rpm	200 rpm
	Treatments							
	Tr1	Tr2	Tr3	Tr4	Tr5	Tr6	Tr7	Tr8
1	45.31	58.79	69.33	45.68	55.71	42.53	36.18	38.62
2	47.08	57.65	68.52	47.15	56.68	41.76	35.31	37.55
Average	46.20	58.22	68.93	46.42	56.20	42.15	35.75	38.09

Table 5 presents a summary of the analysis of the COD percentage based on the experimental design applied to the eight treatments, each replicated twice, resulting in a total of 16 trials. To assess the differences between treatments, a Completely Randomized Design (CRD) with a 4 x 2 factorial arrangement was used, as detailed in Table 5. The optimal concentration of the coagulant agent PAC ($Aln(OH)mCl(3n-m)$) was set at 60 ppm, and the optimum stirring intensity was 100.00 rpm, achieving a 68.92% reduction in COD. According to Meza-Leones et al. (2018), $Al2(SO4)3$ is another coagulant, which can decrease turbidity by up to 96%, while Moringa oleifera seed reduces turbidity by 64%. Note, Moringa oleifera, being a low-cost and low-toxicity natural coagulation agent, is presented as a partial alternative to $Al2(SO4)3$, without harmful effects on human health. In addition, the use of PAC as a coagulating agent in the treatment of domestic effluents significantly optimizes the removal of suspended solids and microplastics, according to Kwon et al. (2022). Table 6 shows the analysis of variance (ANOVA), where a p-value less than 0.05 indicates that the analyzed factor has a significant influence on the response variable of the study. On the contrary, a p-value greater than 0.05 suggests that the factor has no significant effect.

This behavior observed in the tests agrees with the principles of the DLVO (Derjaguin, Landau, Verwey and Overbeek) theory, which states that, as the repulsive forces between particles are reduced, Van der Waals attractive forces predominate, facilitating the formation of stable aggregates (Zhang et al. 2015; Galli et al. 2020).

Table 6: ANOVA for percentage reduction of DWW COD.

Source of variation	GL	SC Ajust.	MC Ajust.	F value	p-value
Concentration	3	1389.20	463.065	1386.80	0.000
Agitation intensity	1	184.73	184.732	553.24	0.000
Concentrations*Intensity	3	1096.54	365.512	1094.64	0.000
Error	16	5.34	0.334		
Total	23	2675.81			

S = 0.577849 R-squared = 99.80% R-sq.(adjusted) = 99.71%

It was observed that the p value = 0.0001 indicates that both, the coagulant agent dose and the agitation intensity, have a significant impact on the COD in DWW from the Mantaro River, specifically in the samples collected from the Pio Pata urban province. These findings suggest that the coagulation process is effective for reducing COD in domestic wastewater, and that the optimization of these parameters could further increase the treatment effectiveness. In the case of wastewater with high salt content, a remarkable removal was achieved through a combined coagulation and sedimentation process, conforming to a quasi-second order kinetics (Li et al. 2025). Similar results were reported by Meza-Leones et al. (2018), who analyzed the impact of Al2(SO4)3 and Moringa oleifera seed on water transparency in the Malambo swamp. To identify significant differences between treatment means, the Tukey statistical test was used, which allows to compare the treatment results.

To support the ANOVA assumptions and validate the results, the main statistical assumptions were verified using Minitab 19 software. The Shapiro-Wilk test was applied, obtaining a value of p = 0.034, indicating a slight deviation from normality. However, due to the small sample size (n = 16), this deviation is considered acceptable in the experimental context. Levene's test was significant (p < 0.001), indicating differences in variances. This context is common in experimental studies with few replicates, and does not invalidate the results, especially when supported by visual evidence.

Figure 1 shows the plot of standardized residuals vs. fitted values. The random distribution of the points around zero, with no definite patterns, supports the validity of the model and the independence of errors.

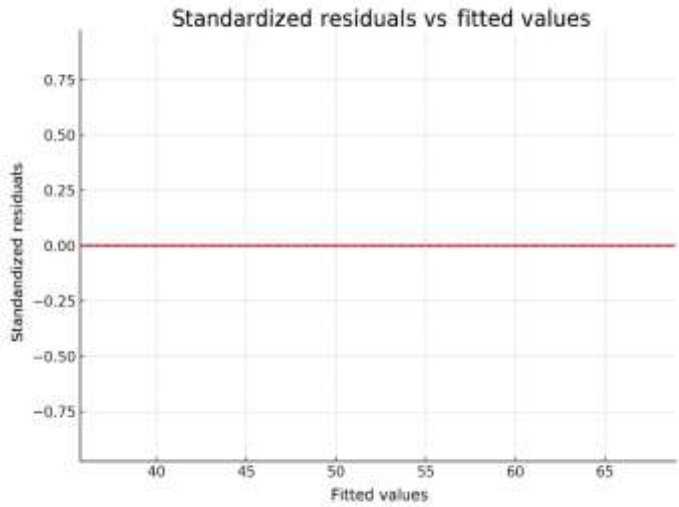

Figure 1: Graph of standardized residuals vs. adjusted values of the ANOVA model applied to COD reduction.

Note. Own elaboration from the residuals of the 4×2 factorial model adjusted with Minitab.

These results allow reasonable acceptance of ANOVA assumptions to evaluate the effect of poly aluminum chloride (PAC) on COD reduction in domestic wastewater.

Table 7 details the means corresponding to each treatment, where the means that do not share a similar letter indicate significant differences in coagulant dose, Al2(SO4)3 concentration, and agitation speed.

Table 7: Tukey comparison test 0.05.

Treatments (Concentration*Stirring intensity)	**N**	**Average**
21 (C2 V1) = Tr3	3	68.925a
12 (C1 V2) = Tr2	3	58.22b
31 (C3 V1) = Tr5	3	56.195c
22 (C2 V2) = Tr4	3	46.415d
11 (C1 V1) = Tr1	3	46.195d
32 (C3 V2) = Tr6	3	42.145e
42 (C4 V2) = Tr8	3	38.085f
41 (C4 V1) = Tr7	3	35.745g

C: Concentration. V: Stirring speed.

The results obtained using the Tukey statistical test ($p < 0.05$) indicate significant differences between the treatments, depending on the concentration of the coagulant agent and the intensity of agitation. Since PAC can pose health risks, it is recommended to limit its concentration to 20 mg/L, which has been shown to be effective in reducing water turbidity by 96% (Nti et al. 2021).

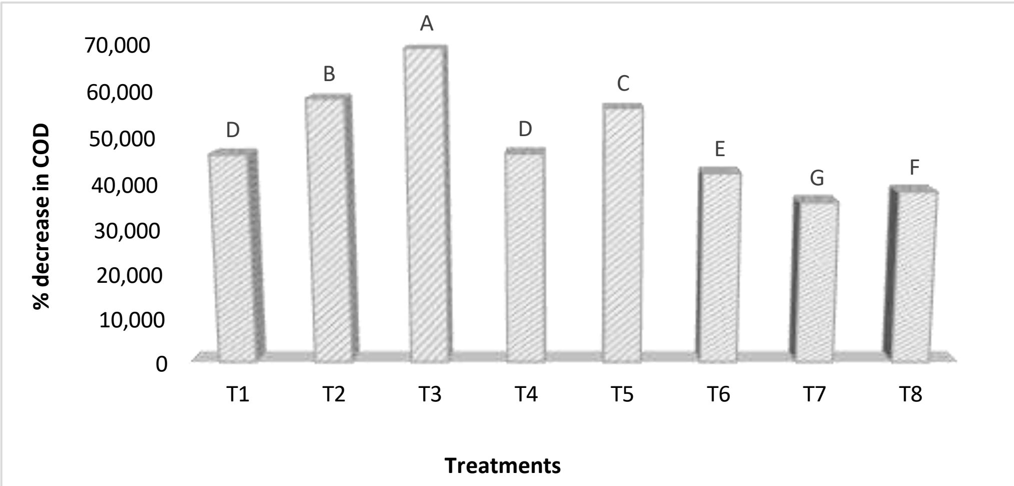

Figure 2: Percentage of COD reduction.

*A, B, C, D, E, F and G; These are statistical variations.

According to Medina-Valderrama et al. (2020), some treatments showed slight differences in efficacy, achieving COD removal exceeding 70%. In a comparative study, Gilpavas et al. (2018) reported a COD reduction from 420.00 to 195.00 mg/L in treated water from the textile industry, using a chemical coagulation approach combined with the Fenton process. Likewise, Diaz et al. (2021) achieved an efficient reduction of 81% in COD.

The high efficiency of PAC at 60 ppm may also be attrubuted to the formation of Al_{13}-type hydroxylated species, whose polynuclear structure allows a higher particle agglomeration capacity. These species prove to be more efficient than single monomers of aluminum sulfate, which explains the observed advantages of PAC in this study (Abu Bakar and Halim 2013; Daryabeigi Zand and Hoveidi 2015; Thom et al. 2024).

4. CONCLUSIONS

The present study represents a first documented effort to optimize the use of aluminum polychloride (PAC) as a coagulant for the removal of organic matter, expressed as COD, in domestic wastewater from the region of El Tambo, Huancayo. The results obtained show that the combination of 60 ppm PAC with an agitation of 100 rpm constitutes the optimum condition, reaching an efficiency of up to 68.93 % in COD reduction. This finding highlights the potential of PAC as a viable and effective alternative to improve water quality in local urban environments, provided it is used under controlled parameters. It also confirms that the effectiveness of the coagulation-flocculation process depends, to a large extent, on the proper selection of operating variables, mainly the coagulant dosage and mixing intensity. On the contrary, excessive doses, such as 100 ppm, resulted in a considerable decrease in efficiency, with removals below 36 %. This highlights the importance of avoiding overdosages that can generate adverse effects on the colloidal stability of the system. However, this work presents certain limitations, such as the limited number of samples and the short evaluation period, which restricts the possibility of extrapolating the results to other conditions or scales. Therefore, it is recommended for future research to replicate these tests in real treatment plants.

Author Contributions: Conceptualization, Lucia Pantoja-Tirado and Oliver Taype-Landeo; methodology, Susan Montes-Bujaico; software, Richerson Piscoche-Chinchay; validation, Wilson Mon-tañez-Artica, Lucia Pantoja-Tirado and Oliver Taype-Landeo; formal analysis, Lucia Pantoja-Tirado; investigation, Susan Montes-Bujaico; resources, Deyvid Cruz-Ventura; data curation, Richerson Piscoche-Chinchay; writing—original draft preparation, Deyvid Cruz-Ventura; writing—review and editing, Deyvid Cruz-Ventura; visualization, Oliver Taype-Landeo; supervision, Wilson Mon-tañez-Artica; project administration, Susan Montes-Bujaico; funding acquisition, Deyvid Cruz-Ventura. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

REFERENCES

1. Abdo, A. 2023. Treatment of mixed domestic–industrial wastewater by combined coagulation–sedimentation, biological processes and advanced oxidation. *Desalination and Water Treatment* 282, pp. 86–95. doi: https://doi.org/10.5004/dwt.2023.29173.
2. Abu Bakar, A.F. and Halim, A.A. 2013. Treatment of automotive wastewater by coagulation-flocculation using poly-aluminum chloride (PAC), ferric chloride (FeCl3) and aluminum sulfate (alum). *AIP Conference Proceedings* 1571(1), pp. 524–529. https://doi.org/10.1063/1.4858708.
3. Acarer, S. 2023. Microplastics in wastewater treatment plants: Sources, properties, removal efficiency, removal mechanisms, and interactions with pollutants. *Water Science and Technology* 87(3), pp. 685–710. http://iwaponline.com/wst/article-pdf/87/3/685/1172571/wst087030685.pdf.
4. Addich, M., Fatni, A., Bouzrour, S., El Baraka, N., Ousaa, A., Albrimi, Y.A. and Laknifli, A. 2024. Optimization of coagulation-flocculation in urban water treatment using Moringa oleifera. *Desalination and Water Treatment* 320, p. 100707. https://doi.org/10.1016/J.DWT.2024.100707.
5. Amiri, S., Vatanpour, V. and He, T. 2022. Optimization of Coagulation-Flocculation Process in Efficient Arsenic Removal from Highly Contaminated Groundwater by Response Surface Methodology. *Molecules* 27(22), p. 7953. https://www.mdpi.com/1420-3049/27/22/7953/htm.

6. Buslima, F.A., Abu Hasan, H., Sheikh Abdullah, S.R. and Othman, A.R. 2024. Water recovery from domestic wastewater using integrated biofilm-phytoremediation technology: A review. *Journal of Water Process Engineering* 65, p. 105875. https://doi.org/10.1016/J.jwpe.2024.105875.
7. Chen, Y., Chen, Z., Dong, Y. and Wu, H. 2024. Enhanced treatment performance and reduction of antibiotic resistance genes of biochar-aeration vertical flow constructed wetland for treating real domestic wastewater. *Process Safety and Environmental Protection* 189, pp. 11–20. https://doi.org/10.1016/j.psep.2024.06.041.
8. Corpus, R.M.B., Bayani, M.S., Aguilar, J.L., Aguilar, J.C.B. and Aguilar, H.B. 2024. Emerging pollutants in waste water: Challenges and advancements in treatment technology. *IOP Conference Series: Earth and Environmental Science* 1372(1), p. 012037. https://iopscience.iop.org/article/10.1088/1755-1315/1372/1/012037.
9. Daryabeigi Zand, A. and Hoveidi, H. 2015. Comparing Aluminium Sulfate and Poly-Aluminium Chloride (PAC) Performance in Turbidity Removal from Synthetic Water. *Journal of Applied Biotechnology Reports* 2(3), pp. 287–292. https://www.biotechrep.ir/article_69189.html.
10. Diaz, Y.J.R., Guevara, M.D.F., Diaz, O.D.B. and Armenta, L.H.M. 2021. Electrocoagulación como alternativa de tratamiento de aguas residuales mixtas originadas en la industria del procesamiento de lácteos y cárnicos. *Tecnura* 25(67), pp. 26–39. http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0123-921X2021000100026&lng=en&nrm=iso&tlng=es.
11. Galli, M., Sáringer, S., Szilágyi, I. and Trefalt, G. 2020. A Simple Method to Determine Critical Coagulation Concentration from Electrophoretic Mobility. *Colloids and Interfaces 2020, Vol. 4, Page 20* 4(2), p. 20. https://www.mdpi.com/2504-5377/4/2/20/htm.
12. Getahun, M., Asaithambi, P., Befekadu, A. and Alemayehu, E. 2024. Chemical oxygen demand removal from wet coffee processing wastewater using indigenous natural coagulants: Optimization through response surface methodology. *Desalination and Water Treatment* 317, p. 100217. https://doi.org/10.1016/j.dwt.2024.100217.
13. Gilpavas, E., Arbeláez-Castaño, P.E., Medina-Arroyave, J.D. and Gómez-Atehortua, C.M. 2018. Tratamiento de aguas residuales de la industria textil mediante coagulación química acoplada a procesos Fenton intensificados con ultrasonido de baja frecuencia. *Rev. Int. Contam. Ambie* 34(1), pp. 157–167. https://doi.org/10.20937/rica.2018.34.01.14.
14. Hidalgo, N.M.S., Crispin, K.X.M. and Marin, M.V. 2023. Comparison of flocculants and natural coagulants for wastewater remediation in South America in the last 10 years: a review of the scientific literature. In: *Proceedings of the LACCEI international Multi-conference for Engineering, Education and Technology*. https://doi.org/10.18687/laccei2023.1.1.584.

15. Hudson, H.E. 1965. Physical Aspects of Flocculation. *Journal - American Water Works Association* 57(7), pp. 885–892. https://doi.org/10.1002/j.1551-8833.1967.tb03453.x.
16. Jin, X. et al. 2025. Prolonged stirring pelleting coagulation for the enhanced treatment of fresh leachate: Removal performance and floc characteristics. *Separation and Purification Technology* 353, p. 128365. https://www.sciencedirect.com/science/article/abs/pii/S138358662402104X?via%3Dihub.
17. Kwon, H.J., Hidayaturrahman, H., Peera, S.G. and Lee, T.G. 2022. Elimination of Microplastics at Different Stages in Wastewater Treatment Plants. *Water (Switzerland)* 14(15), p. 2404. https://www.mdpi.com/2073-4441/14/15/2404/htm.
18. Li, E. et al. 2024. Synergistic enhancement of pollutant removal from high-salt wastewater using coagulation-flotation combined process. *Green Chemical Engineering*. https://doi.org/10.1016/J.GCE.2024.09.006.
19. Li, E. et al. 2025. Synergistic enhancement of pollutant removal from high-salt wastewater using coagulation-flotation combined process. *Green Chemical Engineering* 6(3), pp. 410–419. https://www.sciencedirect.com/science/article/pii/S2666952824000694.
20. Liu, C., Cai, W., Zhai, M., Zhu, G., Zhang, C. and Jiang, Z. 2021. Decoupling of wastewater eco-environmental damage and China's economic development. *Science of The Total Environment* 789, p. 147980. https://www.sciencedirect.com/science/article/abs/pii/S0048969721030515?via%3Dihub.
21. Liu, M. and Yu, W. 2022. Surface Chemical Groups of Flocs Are Key Factors for the Growth of Flocs in Sweep Coagulation: A Case Study of Surface Occupation by Humic Acid. *ACS ES and T Engineering* 2(12), pp. 2301–2310. https://doi.org/10.1021/acsestengg.2c00229.
22. Mayta, R. and Mayta, J. 2017. Chromium removal and chemical oxygen demand from tannery wastewater by electrocoagulation. *Revista de la Sociedad Química del Perú* 83(3), pp. 331–340. https://doi.org/10.37761/rsqp.v83i3.117.
23. Medina-Valderrama, C., Uriarte-Tirado, W., Cardenas-Vásquez, E. and Orrego-Zapo, S. 2020. Treatment wastewater of slaughterhouses through technology advanced oxidation: fenton process. *Revista Ingeniería UC* 27, pp. 165–174. https://www.redalyc.org/articulo.oa?id=70764230005.
24. Meza-Leones, M., Riaños-Donado, K., Mercado-Martínez, I., Olivero-Verbel, R. and Jurado-Eraso, M. 2018. *Evaluación del poder coagulante del sulfato de aluminio y las semillas de Moringa oleífera en el proceso de clarificación del agua de la ciénaga de Malambo, Atlántico*. https://www.redalyc.org/articulo.oa?id=553756965010.

25. Muniz, G.L., Silva, T.C.F. da and Borges, A.C. 2020. Assessment and optimization of the use of a novel natural coagulant (Guazuma ulmifolia) for dairy wastewater treatment. *Science of The Total Environment* 744, p. 140864. https://doi.org/10.1016/j.scitotenv.2020.140864.
26. Narayanan, M., Salmen, S.H., Chinnathambi, A., Natarajan, D., SD, P., Barathi, S. and Lee, J. 2025. Unlocking the potential of MgONPs for effective domestic wastewater treatment. *Journal of the Taiwan Institute of Chemical Engineers* 166, p. 105255. https://doi.org/10.1016/j.jtice.2023.105255.
27. Nti, S.O., Buamah, R. and Atebiya, J. 2021. Polyaluminium chloride dosing effects on coagulation performance: case study, Barekese, Ghana. *Water Practice and Technology* 16(4), pp. 1215–1223. http://iwaponline.com/wpt/article-pdf/16/4/1215/944042/wpt0161215.pdf.
28. Perez, M., Penalva, A., Simon, P. and Abellan, M. 2022. *Jar-testing and Measurement of Particle Size and Distribution for the Control and Optimization of Tertiary Treatment of a WWTP*. https://www.pamas.de/fileadmin/user_upload/download/press/spanish_publications/2022_Tecnoaqua_nr_53.pdf.
29. Shan, T.C., Matar, M. Al, Makky, E.A. and Ali, E.N. 2017. The use of Moringa oleifera seed as a natural coagulant for wastewater treatment and heavy metals removal. *Applied Water Science* 7(3), pp. 1369–1376. https://link.springer.com/article/10.1007/s13201-016-0499-8.
30. Shi, C. et al. 2023. Inorganic composite coagulant for wool scouring wastewater treatment: Performance, kinetics and coagulation mechanism. *Separation and Purification Technology* 313, p. 123482. https://doi.org/10.1016/j.seppur.2023.123482.
31. Singh, M.V. et al. 2024. Impact of Contaminated Water on Plants and Animals: Utilizing Natural and Chemical Coagulants for Treating Contaminated Water. *ES Energy and Environment* 23. https://doi.org/10.30919/ESEE1032.
32. Sun, H., Zhou, Y., Du, M. and Du, Z. 2024. Enhanced Removal of Refractory Organic Compounds from Coking Wastewater Using Polyaluminum Chloride with Coagulant Aids. *Water 2024, Vol. 16, Page 2662* 16(18), p. 2662. https://www.mdpi.com/2073-4441/16/18/2662/htm.
33. Tauseef, A., Mian, H.R., Khalid, H., Afzal, H. and Maqsood, H. 2023. Applicability of hybrid treatment to reduce the footprint of domestic and industrial wastewater of developing countries. *Journal of Water Process Engineering* 56, p. 104339. https://doi.org/10.1016/j.jwpe.2023.104339.

34. Thom, P.T., Khoi, N.T. and Bong, N.H. 2024. Comparative Study on the Effectiveness of Poly Aluminium Chloride (PAC), Aluminium Sulfate, and Iron Sulfate in Livestock Wastewater Treatment. *Asian Journal of Environment & Ecology* 23(11), pp. 96–106. https://journalajee.com/index.php/AJEE/article/view/625.
35. Vishali, S., Poonguzhali, E., Banerjee, I., George, S.S. and Srinivasan, P. 2023. Purification of domestic laundry wastewater in an integrated treatment system consists of coagulation and ultrafiltration membrane process. *Chemosphere* 314, p. 137662. https://doi.org/10.1016/j.chemosphere.2022.137662.
36. Wang, C., Alpatova, A., McPhedran, K.N. and Gamal El-Din, M. 2015. Coagulation/flocculation process with polyaluminum chloride for the remediation of oil sands process-affected water: Performance and mechanism study. *Journal of Environmental Management* 160, pp. 254–262. https://www.sciencedirect.com/science/article/abs/pii/S030147971530116X?via%3Dihub.
37. Wang, H.F., Qi, H.Y., Du, K., Ran, D. Di, Liu, W.H., Shen, X.F. and Zeng, R.J. 2022. Reinterpretation of the mechanism of coagulation and its effects in waste activated sludge treatment. *Separation and Purification Technology* 291, p. 120958. https://doi.org/10.1016/j.seppur.2022.120958.
38. Worku, A., Tibebu, S. and Kassahun, E. 2024. Phytoremediation potential of Duranta erecta in cascade hydroponics for effective domestic wastewater treatment. *Results in Engineering* 23, p. 102837. https://doi.org/10.1016/j.rineng.2024.102837.
39. Xiao, D., Nan, J., Zhang, X., He, W., Fan, Y. and Lin, X. 2024. Pilot-scale study of turbid particle evolutional/removal characteristics during coagulation-sedimentation-filtration (CSF): Effects of coagulant dosage and secondary dosing after breakage. *Journal of Water Process Engineering* 68, p. 106325. https://www.sciencedirect.com/science/article/abs/pii/S2214714424015575?via%3Dihub.
40. Youssef, H.H., Younis, S.A., El-Fawal, E.M., Ali, H.R., Moustafa, Y.M. and Mohamed, G.G. 2023. Synthesis of Polyaluminum Chloride Coagulant from Waste Aluminum Foil and Utilization in Petroleum Wastewater Treatment. *Separations 2023, Vol. 10, Page 570* 10(11), p. 570. https://www.mdpi.com/2297-8739/10/11/570/htm.
41. Yu, J., Xu, H., Yang, X., Sun, H., Jin, Z. and Wang, D. 2022. Floc formation and growth during coagulation removing humic acid: Effect of stirring condition. *Separation and Purification Technology* 302, p. 122084. https://www.sciencedirect.com/science/article/abs/pii/S1383586622016392?via%3Dihub.

42. Zhang, Y. et al. 2023. Efficient treatment of the starch wastewater by enhanced flocculation–coagulation of environmentally benign materials. *Separation and Purification Technology* 307, p. 122788. https://doi.org/10.1016/j.seppur.2022.122788.
43. Zhang, Z., Zhao, L., Li, Y. and Chu, M. 2015. A Modified Method to Calculate Critical Coagulation Concentration Based on DLVO Theory. *Mathematical Problems in Engineering* 2015(1), p. 317483. https://doi.org/10.1155/2015/317483.