

# Performance Evaluation Of Polyacrylamide (Pam) In Flocculation: A Study Of Pollutant Removal From Wastewater And Leachate

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## Abstract

Water pollution from municipal wastewater and landfill leachate represents a growing global challenge. This study evaluated the efficiency of synthesized polyacrylamide (PAM) as a flocculant for wastewater treatment in Mascara, Algeria. PAM was obtained via free-radical polymerization and characterized by FTIR, XRD, and zeta potential analysis, confirming its structural integrity and amorphous nature. Coagulation–flocculation experiments were conducted using aluminum sulfate as a coagulant, with operational optimized parameters

Results demonstrated that the optimal conditions, significantly improved effluent quality. Wastewater treatment reduced BOD and COD, and conductivity dropped. Leachate treatment decreased BOD, with minimal impact on conductivity. Heavy metal fixation was highest for Fe (~95%) and moderate for Ca, Mg, and Pb, while K and Zn showed low removal efficiency.

Overall, PAM proved to be an effective and low-cost flocculant for pre-treatment of wastewater and leachate,

**Keywords:** Polyacrylamide; coagulation–flocculation; wastewater; leachat; heavy metals;

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## INTRODUCTION

Water scarcity and pollution remain critical challenges driven by urbanization, climate change, and population growth<sup>1</sup>. Clean drinking water access is increasingly constrained, with anthropogenic activities such as agricultural runoff, industrial effluents<sup>2</sup>, and urban wastewater—emerging as dominant sources of water pollution<sup>3,4</sup>. Pollutants, defined as substances altering water's physical, chemical, or biological properties<sup>5</sup>, accumulate in freshwater and coastal systems, threatening aquatic ecosystems worldwide<sup>6</sup>.

Beyond environmental consequences, water pollution exacts a severe human toll—contributing to millions of illnesses and premature deaths annually. Chemical contaminants alone were linked to approximately 9 million premature deaths in 2019, including 5.5 million from cardiovascular diseases attributable to water pollution<sup>7</sup>. These stark figures underscore the imperative for optimized water treatment strategies.

Essential treatment stages include coagulation and flocculation, critical for removing suspended solids and colloidal contaminants. Coagulants such as aluminum sulfate ( $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ ) neutralize the negative surface charge of particles, enabling their aggregation into

microflocs<sup>8,9</sup>. Subsequent flocculation promotes floc growth via gentle mixing, influenced by coagulant dosage, mixing intensity, residence time, and temperature<sup>8</sup>. Recent studies highlight advancements in flocculant technology and process optimization.<sup>10</sup> optimized UV-initiated cationic PAM formulations via response surface methodology, significantly improving flocculation efficiency in wastewater treatment applications<sup>11</sup>

Degradation effects on CPAM have also been examined found that CPAM degradation can alter floc morphology, reduce required dosages, and improve kinetics of aggregation and dewatering<sup>12</sup>

Additionally, hybrid and biodegradable flocculants such as starch-based or plant derived polymers are emerging as eco-friendly alternatives with promising performance across a broader temperature and pH range<sup>13</sup>

This study aims to evaluate polyacrylamide (PAM) efficacy in wastewater treatment by examining operational variables including coagulant dose, mixing speed, and temperature. Emphasis is placed on temperature's impact

on floc growth, stability, and sludge dewaterability. Insights from this work may inform the optimization of coagulation–flocculation processes and support the development of sustainable flocculant technologies.

## MATERIALS AND METHODS

### 1. Chemicals

Aluminum sulfate ( $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ , coagulant), acrylamide monomer, N,N'-methylenebisacrylamide (crosslinker), and benzoyl peroxide (initiator) were obtained from Sigma-Aldrich.

### 2. Synthesis of PAM (free-radical polymerization)

In a 250 mL round-bottom flask with mechanical stirring, 5 g acrylamide, 0.05 g N,N'-methylenebisacrylamide, and 0.01 g benzoyl peroxide were dissolved in 10 mL tetrahydrofuran (THF). The mixture was refluxed at 60 °C for 24 h, then precipitated into 50 mL heptane under vigorous stirring. The precipitate was filtered, washed, dried, and ground to a fine white powder. The resulting polyacrylamide (PAM) was collected by vacuum filtration, washed thoroughly, and dried in air. After complete drying and grinding, a fine white crystalline powder of PAM was obtained.

### 3. Characterization

#### 3.1. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

FTIR spectra were obtained using a [Thermo Scientific Nicolet iS50] Fourier Transform Infrared Spectrometer, equipped with a [Mercury-Cadmium-Telluride (MCT)] detector. The spectrometer operates in the range of 4000  $\text{cm}^{-1}$  to 400  $\text{cm}^{-1}$ , with a spectral resolution of [4  $\text{cm}^{-1}$ ]. Samples were analyzed in solid/liquid form using direct absorption. Data were processed using Fourier Transform to generate absorption spectra.

#### 3.2. X-ray Diffraction (XRD) Analysis

X-ray Diffraction (XRD) Analysis: To investigate the crystallographic structure of the synthesized sample, X-ray diffraction (XRD) measurements were conducted at the Synthesis and Catalysis Laboratory, Department of Physics, Ibn Khaldoun University of Tiaret. The analysis was performed using a MiniFlex 600 W X-ray diffractometer.

#### 3.3. Zeta Potential Measurement of Wastewater Samples

Zeta potential measurements were performed on wastewater samples using a Zetasizer (Malvern Instruments, UK) to assess particle surface charge. The samples were analyzed at 25 °C without further

### 4. Sampling

Wastewater samples were collected at Mascara (northwestern Algeria) municipal wastewater was collected through a partially developed sewage network, with limited coverage in rural areas. Incomplete infrastructure leads to the discharge of untreated domestic effluents into the environment, impacting water quality.

Leachate from local landfills, especially during the rainy season, contains high levels of organic pollutants, ammonia, and heavy metals. It is typically collected via bottom drainage systems and stored in retention basins. However, treatment remains insufficient, increasing the risk of environmental contamination.

Representative wastewater and leachate samples were collected from urban areas and landfill sites in Mascara for analysis and treatment evaluation using coagulation–flocculation processes. Raw wastewater: Collected from the influent of the municipal wastewater treatment plant (Mascara, Algeria), stored at 4 °C, and used within 24 hours

#### 4.1. Coagulation–Flocculation Procedure

The coagulation–flocculation experiments were conducted using the standard jar-test method to simulate wastewater treatment at laboratory scale. All tests were carried out at room temperature ( $25 \pm 2$  °C), based on APHA (2017) guidelines and recent optimizations reported from several studies<sup>10,11</sup>.

#### 4.2. Jar Test Procedure

1) Each test was performed on 100 mL of wastewater placed in 1-liter beakers. The coagulation–flocculation process involved the following steps:

Coagulant dosage: Aluminum sulfate was added at different masses (0.08, 0.16, 1 g) to determine the optimal dose.

2) The rapid mixing: Samples were stirred at 150, 300, 600, rpm for 24 h to ensure uniform dispersion of the coagulant. In selected tests, PAM (flocculant) was added at different masses to optimize the procedure test at a dose of 4, 6, 10, 15 g in 100 mL of wastewater after the rapid mixing phase, and gently mixed during the flocculation step. The supernatant was collected after 24 h of test: A volume of clarified water was collected from 2 cm below the surface and analyzed immediately.

3) Determination of Heavy Metal Concentration

The concentrations of heavy metals—Potassium (K), Calcium (Ca), Magnesium (Mg), Iron (Fe), Copper (Cu), Zinc (Zn), Cadmium (Cd), and Lead (Pb)—were determined using Atomic Absorption Spectrophotometry (AAS). The analysis was performed using a [insert model and manufacturer of the AAS device following standard methods (e.g., APHA 3120 B). Before measurement, calibration curves were established using standard solutions for each metal. Each sample was analyzed in triplicate, and the average values were recorded

## RESULTS AND DISCUSSION

### 1. Polymer characterization

Acrylamide appears as white, glittering, and odorless crystals that sublime slowly at room temperature .

#### 1.1. Fourier Transform Infrared (FTIR) Spectroscopy Analysis

PAM was characterized by ftir (Figure1) presents an infrared spectrum displaying five distinct bands at different frequencies.

The FTIR spectrum (Figure1) of polyacrylamide exhibits characteristic absorption bands confirming the presence of functional groups specific to amides. The broad band around  $3193\text{--}3340\text{ cm}^{-1}$  corresponds to N-H stretching, while the peak at  $2947\text{ cm}^{-1}$  is attributed to C-H stretching vibrations. The strong absorption at  $1662.5\text{ cm}^{-1}$  is assigned to the C=O stretching of the amide I band. CH<sub>2</sub> bending appears at  $1454.2\text{ cm}^{-1}$ , and the C-N stretching vibration (amide III)

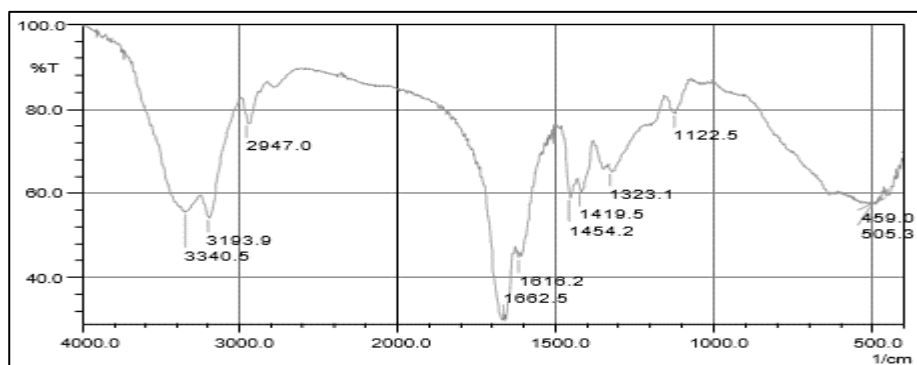


Figure 1 : FTIR Spectrum of Synthesized Polyacrylamide (PAM)

#### 1.2. XRD Analysis

The X-ray diffraction (XRD) (Figure 2) pattern of synthesized polyacrylamide (PAM) shows a broad diffraction peak centered around  $2\theta \approx 19^\circ$ , characteristic of an amorphous structure. The absence of sharp and well-defined peaks confirms the non-crystalline nature of PAM. This amorphous profile is typical for polymeric materials due to the irregular arrangement of polymer chains is observed at  $1323\text{ cm}^{-1}$ .

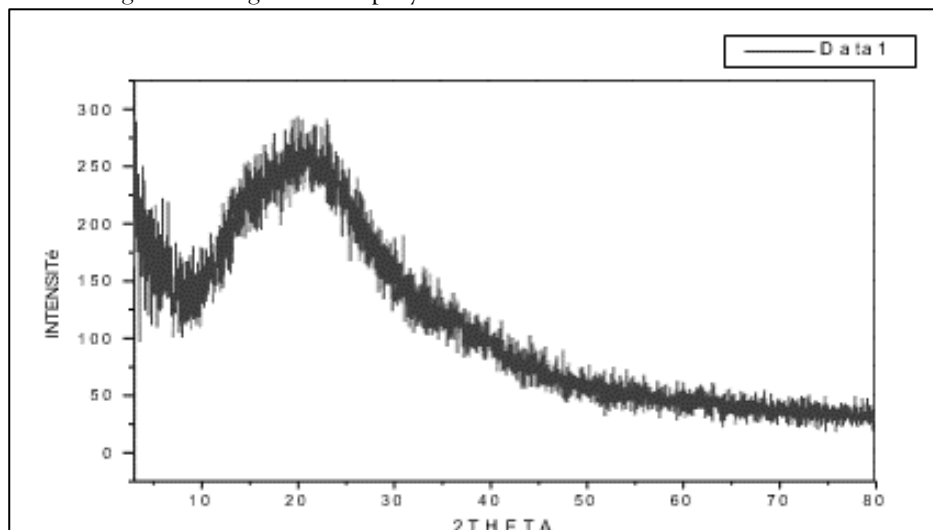


Figure 2 : XRD diffractogram of Synthesized Polyacrylamide (PAM)

### 2. Process optimization

Comparative Analysis of Flocculant Efficiency Using ,0.08,0.16,1 g of  $\text{Al}_2(\text{SO}_4)_3$

Among the three conditions tested, Experiment 2 (600 rpm, 1 h) produced the highest flocculant mass (0.330 g) and maximum sedimentation height (2.0 cm), confirming the positive impact of prolonged and vigorous agitation on floc formation and separation efficiency.

Experiment 3 (300 rpm, 30 min) yielded intermediate results (0.166 g), demonstrating that moderate agitation can be effective when well-optimized. Experiment 1 (600 rpm, 30 min) showed the lowest performance, according to the results. The Experiment 2 is the most effective setup, offering superior flocculant production and sedimentation, and is therefore recommended for optimal treatment performance (Table 1)

**Table 1:** comparison of the effect of flocculant mass

Experiment	Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> mass	Best Condition	Time	Speed (rpm)	M (g)	Sedimentation (cm)	pH	T (°C)
01	0.08g	High flocculation	30 mn	600	0.142	1.4	6.69	11.2
02	1g	Very high efficiency	1 h	600	0.330	2.0	4.70	18.5
03	0.16g	Consistently good floc yield	30 mn	300	0.166	1.3	5.76	15.1

## 2.1 Effect of flocculant Mass

Table 2 illustrates the variation in pH, conductivity (X), and temperature (T) over seven days of treatment using different doses of polyacrylamide (PAM) as a flocculant (4 g, 6 g, 10 g, and 15 g). The analysis of these physicochemical parameters provides insights into the efficiency of coagulation–flocculation treatment for wastewater purification.

Electrical conductivity increased with both flocculant dose and treatment duration, indicating progressive ion release due to colloidal destabilization in wastewater [15] compaction. Among all conditions, we noted at high doses (15g and 10g) a gelling of the medium is due to the high mass used.

The mass of, 4 g of PAM dose (m1) showed the most balanced performance, with significant conductivity increase, stable pH, and moderate temperature rise. This suggests it is the optimal dose for effective coagulation–flocculation, whereas the 15 g and 10g dose may indicate overdosing, potentially leading to particle restabilization or residual polymer accumulation.

**Table 2 :** Evolution of Physicochemical Parameters of Wastewater with a treatment as a Function of Flocculant Mass (FX)

Mass of PAM	m1=4g			m2=6g			m3=10g			m4=15g		
	pH	χ	T	pH	χ	T	pH	χ	T	pH	χ	T
0 Day	6.5	2.05	19	6.5	2.05	19	6.5	2.05	19	6.5	2.05	19
1 Day	4.16	14.07	22.3	4.15	14.15	22.5	3.97	14.51	24.3	3.95	14.91	26.2
2 Days	4.47	6.49	22.9	4.38	8.28	22	4.1	10.94	27.2	4.00	11.70	25.8
3 Days	4.27	6.14	23.8	4.31	6.22	24.1	3.95	11.73	28.6	3.86	14.19	28.7
4 Days	4.98	12.66	24.4	4.61	9.86	24.5	4.43	12.18	26.9	4.33	13.40	29.9
7 Days	4.58	6.77	25.2	4.36	9.16	24.5	4.16	13.79	29.7	4.1	14.66	30.5

X conductivity, T temperature, PAM: polyacrylamide

### 3. Treatment performance

The table shows the optimization of the physicochemical treatment parameters of the tests carried out on wastewater and leachate.(Table3)

**Table 3:** optimized leachate treatment parameters

Coagulant Mass(g)	Floculant mass(g)	Speed (Rpm)	Volume of the essay(ml)
1	4 maxima	600	100

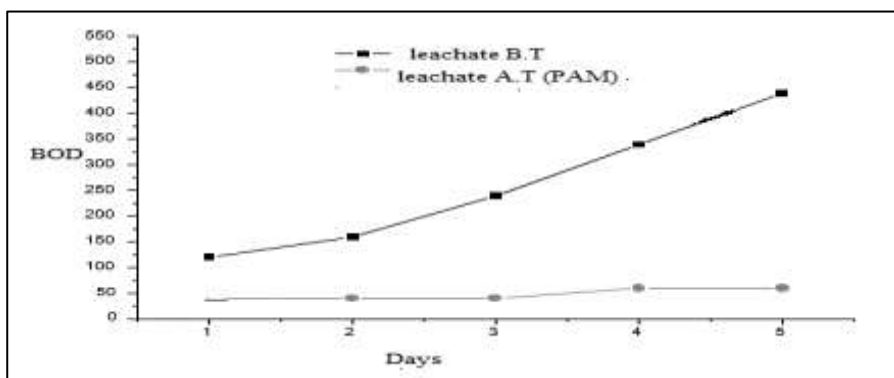
after having fixed the mass of the coagulant and the flocculent, we proceeded with the treatment of the wastewater by adding 2g of PAM for the wastewater and 4g for the leachate, and 1g of coagulant under agitation of 600 tr:m, we measured the conductivity before and after treatment of the wastewater and leachate, the results are represented in the Table 4.

The treatment process applied to both wastewater and leachate (Table 4) exhibited significant improvements in water quality parameters. In the case of wastewater, the BOD level decreased from 200 mg/L before treatment (B.T) to 80 mg/L after treatment (A.T), indicating a high reduction in biodegradable organic matter. Similarly, electrical conductivity dropped from 1739  $\mu\text{S/cm}$  to 100  $\mu\text{S/cm}$ , reflecting effective removal of dissolved ions. For leachate, the BOD decreased from 440 mg/L to 60 mg/L, showing a substantial improvement in organic load reduction. The slight increase in conductivity from 13.37  $\mu\text{S/cm}$  to 14.51  $\mu\text{S/cm}$  is negligible and remains well below the standard limit ( $\leq 35 \mu\text{S/cm}$ ), confirming the absence of significant ionic contamination (Figure3)

**Table 4 :** BOD and Conductivity Results of treatment by PAM

Results	Wastewater Treatment				Leachate Treatment			
	B.T	A.T	B.T	A.T	B.T	A.T	B.T	A.T
BOD	200	80			440	60		
Conductivity			1739	100			13.37	14.51
conductivity Standard limit( $\mu\text{S/cm}$ )	$\leq 2800$				$\leq 35$			
BOD Standard Limit (mg/L)	13-143				$20 \geq \text{BOD} \leq 57000$			
interpretation	Significant reduction in ion content and BOD levels; treatment is highly effective				Slight ion increases but well within acceptable range; high BOD removal efficiency.			

B.T: before Treatment, A.T: After Treatment



**Figure 3:** monitored BOD of wastewater and leachate

#### 3.1 Biodegradable nature of wastewater effluents

##### 3.1.1. Evaluation of COD of Westwater

The effectiveness of PAM in reducing the chemical oxygen demand (COD) of wastewater was clearly demonstrated. As shown in the table, the COD of raw wastewater before treatment was 4992 mg/L. After treatment with PAM, the COD was significantly reduced to 182 mg/L, indicating remarkable removal efficiency. This substantial decrease confirms the potential of PAM as an effective coagulant in wastewater treatment processes.(table5)

**Table 5 :** Results of COD of waste Water

Sample	COD before traitement before treatment whithPAM	COD before traitement after treatment whithPAM
Waste Water	4992	182

### 3.1.2. Ratio of COD/BOD

The ratio between COD and BOD5 is often very different from that of urban wastewater. It evolves in various stages of treatment. The COD value is always higher than that of the BOD5 [14], the COD/BOD5 ratio is the index of the biodegradability, of a water, For a pollution to be degradable, the ratio must be less than 2.5 [15], For industrial effluents, which may contain a significant fraction of non-biodegradable compounds, it can be considered according to the COD / BOD5 ratio that the ability to biodegrade is more, or less favorable to biological treatment, the following rules generally being retained (Table 6)

- COD/BOD < 3 ; easily biodegradable effluent
- 3 <COD/BOD< 5 moderately. biodegradable effluent
- COD/BOD > 5. Hardly biodegradable effluent

In order to demonstrate the effectiveness of the polymer, we carried out a kinetic monitoring of bod and the results are shown on the following graph(figure3), we note, that BOD levels in untreated leachate (B.T) increased steadily from day 1 to day 5, reaching over 400 mg/L, indicating continuous organic load accumulation. In contrast, leachate treated with PAM (A.T) maintained consistently low BOD values (below 60 mg/L) throughout the same period, demonstrating the polymer's high efficiency in reducing biodegradable organic matter

**Table 6 :** percentage of biodegradability of Waste Water

Sample	Wastewater+PAM before treatment	Wastewater+PAM after treatment
COD/BOD	DCO/DBO5 > 5	COD/BOD < 3
Results	Hardly biodegradable effluent	easily biodegradable effluent

### 3.1.3. Zeta Potential Analysis of Wastewater Before and After PAM Treatment

The zeta potential analysis provides insight into the stability and surface charge of colloidal particles in wastewater. In Figure III.20, the raw wastewater exhibited a zeta potential of +11.3 mV, with a high deviation (8.17 mV), suggesting the presence of unstable and highly dispersed particles, generally indicates a low electrostatic repulsion between particles, which favors aggregation and explains the poor colloidal stability of untreated effluent [16] (Figure 4).

In contrast, (Figure 5) shows a significant reduction in zeta potential to +1.73 mV after treatment with PAM (polyacrylamide). This sharp decrease, combined with a narrower peak and lower deviation (4.00 mV), reflects the neutralization of surface charges and the aggregation of particles, leading to improved flocculation. The increase in conductivity (from 1.67 to 3.05 mS/cm) further supports the addition of ionic species through coagulant action.

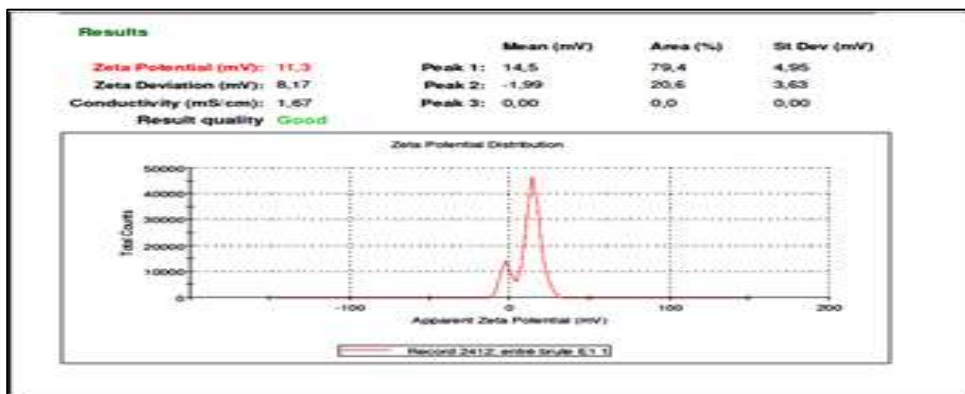


Figure 4: zeta potential of raw wastewater before treatment,

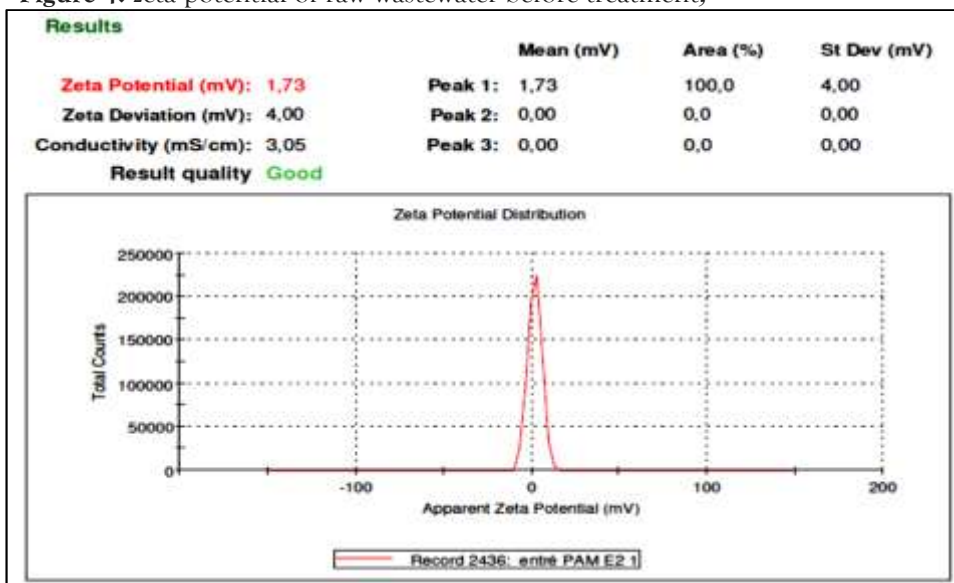


Figure 5: Zeta potential of raw wastewater after treatment with PAM,

#### 4. Metal ,Ca ,Mg ,K ,fixation

The percentage fixation data (Figure 2) Table 6 highlight that PAM demonstrated the highest affinity for Fe (~95%), followed by Ca (~60%) and Mg (~45%). Moderate fixation was observed for Pb (~30%) and Cu (~25%), whereas K (~8%) and Zn (~5%). (Table5) showed minimal interaction with the polymer. The absence of Cd in both treated and untreated samples indicates concentrations below detection limits. The marked removal of Fe and divalent alkaline earth metals suggests that PAM preferentially binds higher-valence cations and those prone to hydrolysis, forming stable flocs.

Combining the organic matter and heavy metal removal results (Figure 6), PAM treatment appears to be an effective step in leachate pre-treatment, particularly for reducing BOD and selected transition metals such as Fe and Cu. However, elements with low fixation rates, K, Zn) may require complementary treatment processes (, ion exchange, chemical precipitation). Optimization of PAM dosage, pH, and contact time could further enhance removal efficiencies for less reactive species.

Table 7: Results of fixation of raw metal by treated leachate

Parameter	Raw leachate	Treated leachate (PAM)
K (ppm)	61.22	55.74
Cr (ppb)	163.73	162.80
Mn (ppb)	187.51	175.41
Fe (ppb)	687.37	419.54
Cu (ppb)	39.21	17.05

Zn (ppb)	37.27	33.54
Cd (ppb)	0.00	0.00
Pb (ppb)	11.72	9.07

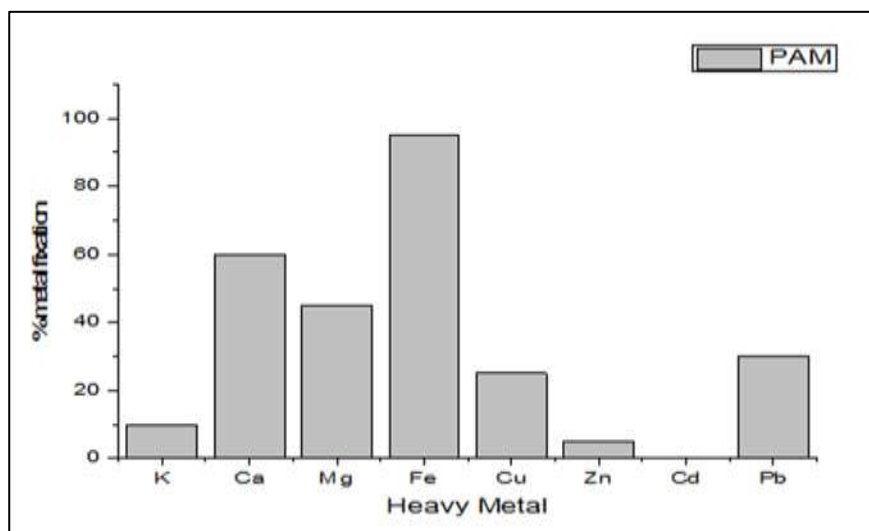


Figure 6 : percentage of reduction of Metals by PAM

## 5. DISCUSSION

The FTIR analysis confirmed the successful synthesis and structural stability of polyacrylamide (PAAm), with characteristic absorption bands corresponding to N-H, C-H, C=O, CH<sub>2</sub>, and C-N groups. These results are in good agreement with previously reported spectra of polyacrylamide-based hydrogels and films<sup>14</sup>, validating the chemical integrity of the synthesized material.

Application of PAAm in leachate treatment demonstrated a significant influence of polymer dosage on the physicochemical properties of the effluent. The optimal dosage was essential for maintaining pH stability, promoting ionic dissociation (as shown by conductivity measurements), and ensuring thermal safety during the treatment process<sup>16,17</sup>. This underlines the critical role of dosage optimization in achieving efficient treatment performance.

In terms of pollutant removal, the results highlighted the efficiency of PAM in reducing both organic load (BOD) and certain transition metals such as Fe and Cu. These findings are consistent with earlier studies that reported the high affinity of polyacrylamide for multivalent cations through complexation and charge neutralization mechanisms<sup>18</sup>. Nevertheless, the relatively low fixation rates observed for more mobile elements such as K and Zn suggest that additional processes—such as ion exchange or chemical precipitation—may be required to achieve higher removal efficiencies for these species.

Overall, the treatment process using PAM significantly improved leachate quality by lowering organic and inorganic pollutant levels to values compatible with discharge standards. The results not only confirm the efficiency of polyacrylamide in wastewater remediation but also emphasize its potential as a cost-effective and scalable pre-treatment strategy. When combined with complementary technologies, PAM-based treatment could represent a sustainable solution for integrated leachate management.

## CONCLUSION

This study demonstrated the successful synthesis and application of polyacrylamide (PAM) as an efficient flocculant for wastewater and landfill leachate treatment. The characterization confirmed the structural integrity and amorphous nature of the polymer, while coagulation-flocculation experiments highlighted its capacity to significantly reduce BOD, COD, conductivity, and heavy metal concentrations. Optimal operational parameters (coagulant dosage, flocculant concentration, and mixing conditions) were identified, ensuring maximum pollutant removal without overdosing effects. The results indicate that PAM treatment effectively transforms hardly biodegradable effluents into easily biodegradable ones, enhancing their suitability for subsequent biological treatment. However, limited fixation of certain metals (K, Zn) suggests the need for complementary

processes such as ion exchange or precipitation. Overall, PAM represents a promising, cost-effective, and scalable solution for improving wastewater and leachate quality, supporting sustainable environmental management.

#### Nomenclature and Units

All quantities reported in SI units. Abbreviations follow IUPAC/NIST recommendations. BOD: biochemical oxygen demand ; COD : chemical oxygen demand ;  $\kappa$  : conductivity.

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#### Conflicts of Interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

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