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Reduction of pollution of vegetable oil refinery effluents by flotation: Case of phenol, detergents, ammonium, nitrates, and total phosphorus

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ABSTRACT

Wastewater from vegetable oil refineries is toxic due to contaminants such as phenols, surfactants, nitrates, ammonium ions, and total phosphates, which pose a serious environmental threat. These pollutants are detrimental to aquatic life, destroying biodiversity and affecting water sources, hence the need for proper treatment methods. Among the possible methods, flotation is an effective method to minimize environmental pollution. It offers significant advantages, particularly its high efficiency in removing pollutants, especially from industrial wastewater with high oil and grease content.The effectiveness of flotation in treating two types of wastewaters generated by vegetable oil refineries, namely process wastewater (PWW) and acidic wastewater (AWW), was evaluated in this study. The wastewater samples were collected at three different times of the year to determine the effect of temperature, pH, and pollution concentration on the efficiency of natural flotation. The results showed that wastewater with an acidic pH is more effective in natural flotation than other types of wastewaters, particularly in autumn when the temperature and production rate are moderate. This optimization resulted in average removal rates of 70% for phenol, 82% for detergents, 77% for organic matter, 85% for nitrates, 90% for ammonium ions, and 97% for total phosphorus. At an industrial scale, flotation as a pretreatment step upstream of wastewater treatment plants has proven necessary to reduce the environmental impact of vegetable oil refinery discharges. This approach improves pollutant removal efficiency, lowers energy costs, and eliminates the need for chemical reagents while preserving the regular operation of treatment plants. As such, it can be considered a sustainable and economically viable solution.

Keywords: process wastewater, acidic wastewater, flotation treatment, impact environmental, vegetable oil refinery effluents.

INTRODUCTION

Vegetable oil refineries consume large quantities of water and produce wastewater contaminated with various organic and inorganic pollutants. These contaminants include phenolic compounds and detergents (Hartal et al., 2024). These highly toxic pollutants can harm aquatic life and ecosystems if discharged without proper treatment (Achak et al., 2019). Additionally, vegetable oil refining equipment discharges two wastewaters: acidic or alkaline. The acidity of vegetable oil refinery wastewater primarily stems from sulfuric acid added during soap manufacturing (Kaya and Hung, 2021). These discharges can harm wastewater treatment facilities, mainly by disrupting biological processes (Yakamercan and Aygün, 2024), necessitating preliminary steps to reduce their environmental impact (Kastali et al., 2021).

Several studies have been conducted on the biodegradability of pollutants from vegetable oil refineries using anaerobic biodegradation (Tomei et al., 2021), biodegradation by the bacterial strain Acinetobacter (Liu et al., 2016), and biodegradation by Pseudomonas (Yang et al., 2020). Phenols and detergents disrupt the normal functioning of treatment plants by causing foaming in activated sludge reactors, inhibiting biomass development, and promoting the growth of filamentous bacteria in clarifiers (Lahsaini et al., 2018). Furthermore, phenolic compounds and detergents are poorly biodegradable and often need a combined treatment strategy.

Effluents from vegetable oil refineries also contain other pollutants, such as nitrates, ammonium ions, and phosphates, which pose environmental risks. These substances can lead to water pollution, encourage eutrophication, and harm human health (Berkessa et al., 2019). At present, Several technologies, including biological treatment (Carrasquero-Ferrer et al., 2025), chemical precipitation (Huang et al., 2017), and adsorption (Nir et al., 2024), are used to treat these pollutants. In addition, Kyzas and Matis (2019) reported several techniques for treating industrial wastewater, including flotation and adsorption, as effective ways of contaminant reduction in industrial wastewater. Dkhissi et al. (2020) showed that treatment of vegetable oil wastewater by coagulation-flocculation with industrial waste rich in $FeCl_3$ and natural coagulants led to 78% phenol removal, 90% detergents removal, and 99% turbidity removal. In its various forms, flotation has become a highly effective separation method for reducing toxic substances (Sony et al., 2020). Compared to conventional physicochemical treatment, flotation can effectively reduce poisonous pollution. It is based on removing pollutants by bringing them to the surface without needing energy or chemical reagents (Kastali et al., 2021). Furthermore, natural flotation remains highly attractive for refineries to reduce pollution related to phenolic compounds and surfactants in oily wastewater with low operating costs (Kastali et al., 2021).

Production in a vegetable oil refinery depends on raw material availability and market demand, leading to seasonal variations. There is a high production during the oilseed harvest, especially of sunflower, soybean, or rapeseed. Natural flotation is a cost-effective and efficient method for controlling contaminants (Hajam et al., 2024). This study examines the impact of seasonal variations on wastewater volume and composition and their influence on natural flotation efficiency. Additionally, the study seeks to identify the optimal pH conditions for pollutant adsorption, particularly oil particles and organic matter, across variable production conditions. Treating wastewater before sending it to an industrial wastewater treatment plant considerably reduces treatment costs and the energy consumption associated with chemical reagents, which is particularly advantageous for companies that operate 24 hours a day. This innovative approach minimizes operating costs and meets the environmental sustainability goals. Natural flotation does not require energy or chemical substances to function, thus making it an environmentally friendly option.

MATERIAL AND METHODS

Production process and wastewater treatment plant

Lesieur Cristal is a vegetable oil refinery based in Casablanca, which has recently implemented a wastewater treatment plant to reduce the environmental impact of its discharges. The company focuses on eliminating pollutants using biological methods within a sequential batch reactor (SBR). During the oil refining, Lesieur Cristal consumes significant amounts of potable water, generating acidic and alkaline effluents and various types of wastewater from producing edible oils, cosmetics, soaps, and decolorizing agents.

As part of this research, untreated wastewater samples were collected. This study is conducted within an existing collaboration to strengthen joint initiatives to develop innovative and sustainable solutions for treating industrial wastewater.

Sampling method

Two types of wastewaters were selected for characterization and natural flotation tests:

- Process wastewater (refining and soap wastewater) (PWW),
- Acidic wastewater from the soap separation process (AWW).

This selection was made because both wastewater types are rich in oils and greases and have significant flow rates. Reducing the oil content through natural flotation before directing the wastewater to treatment plants is highly beneficial (Junior et al., 2025).

Wastewater samples were stored at 4 °C and warmed to room temperature before testing (Ahmed et al. 2020). The samples were collected in Ain Harrouda, Casablanca, at a flow rate of 5 liters per hour during working hours, resulting in a composite sample of 40 liters. Additionally, three samples of both wastewater types were collected at different times of the year to account for seasonal variations in their composition (winter, summer, and autumn). The sampling was conducted in the middle of each season – on February 5 for winter, August 5 for summer, and November 5 for autumn. This approach ensured a representative characterization of the wastewater.

All samples were then analyzed for physico-chemical parameters following the procedures outlined in the Standard Methods for the Examination of wastewater.

Pilot system used in laboratory experiments

Figure 1 illustrates the pilot system used for laboratory flotation experiments. The wastewater collected over a day was carefully mixed to obtain a homogeneous sample before being used for natural flotation tests in a 30-liter reactor. After sampling the treated water, several parameters were analyzed, including pH, conductivity, turbidity, COD, BOD_5, oils and greases, surfactants, phenols, absorbance at 254 nm, nitrates (NO_3^-), ammonium (NH_4^+), and phosphorus. The flotation process was monitored over 24 hours to determine the optimal time for maximum efficiency (Ziar et al., 2021). The presence of phenols, surfactants, ammonium, nitrates, and phosphorus was compared before and after treatment.

Analysis of physico-chemical parameters

Wastewater analysis covers the fundamental groups of the physico-chemical and chemical parameters defined by the current regulation on the conditions for discharging wastewater into the public sanitation system.

- Phenolic compounds were measured using the colorimetric method Folin-Ciocalteu (FC) based on the method reported by Singleton & Rossi (Singleton and Rossi, 1965).
- Determination of surfactant: The determination of surfactant is based on forming a soluble complex in toluene between the surfactant, an anionic compound, and methyl violet, a cationic compound. The reading is carried out at the spectrometric wavelength of 615 nm (Motomizu et al., 1982).
- The nitrate was determined by the spectrometric method in the presence of sulfosalicylic acid according to EN ISO 78-90 January 1997 (T 90-045) (AFNOR, 1999)
- The spectrophotometric method indophenol blue determined the NH_4^+ ammonia nitrogen according to AFNOR NF T 90-015 January 1997. (AFNOR, 1999)
- Phosphorus was analyzed using the ascorbic acid technique by spectrophotometer at 700 and 880 nm according to NFT 90-023(AFNOR, 1999)

RESULTS AND DISCUSSION

Physico-chemical characteristics of wastewater

Industrial development and the use of oils and greases are worsening environmental pollution (Erfani et al., 2024). Therefore, finding a cost-efficient method to remove these contaminants from polluted water is essential (Wang et al. 2024). The

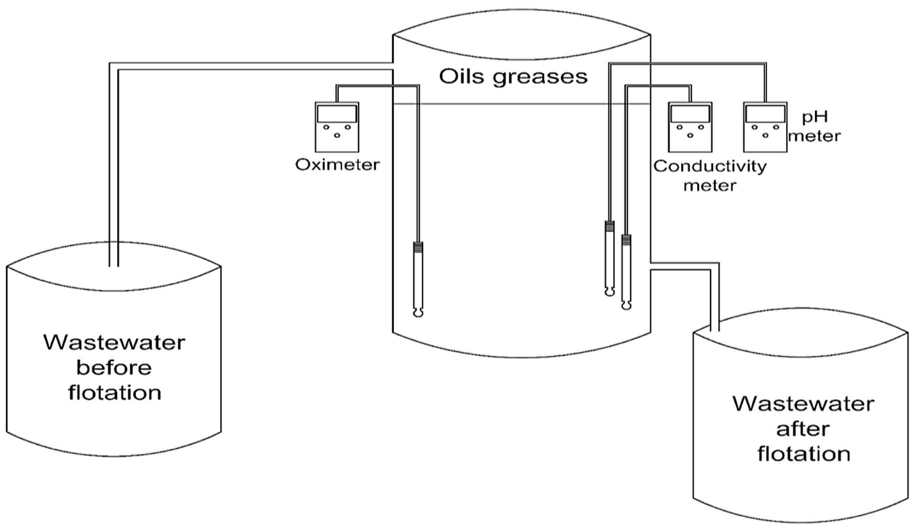

Figure 1. The reactor used for monitoring natural flotation

physicochemical parameters of AWW and PWW Wastewater during different periods (autumn, summer, and winter) are presented in Table 1.

Acidic wastewater has a pH between 1.5 and 6.1, while process wastewater has a basic pH. The acidity of acidic wastewater in this industry mainly results from adding sulfuric acid during the separation of free fatty acids from soap (Saleem et al., 2024). Studies reveal that both types of industrial wastewater exhibit a high organic load, with COD values ranging from 181 g/L to 32 g/L. The BOD_5 concentration is 13.6 g/L for acidic wastewater (AWW) and 5.4 g/L for process wastewater (PWW).

Additionally, acidic discharges have an oil and grease concentration of around 57 g/L, significantly higher than that of process wastewater, which has a value of approximately 19 g/L. The suspended solids content for acidic and process effluents is 365 mg/L and 570 mg/L, respectively, with turbidity around 4000 NTU for both discharges, indicating a high amount of dissolved organic matter and inorganic salts. Similar values were reported by Dkhissi et al. (2018).

Moreover, both types of wastewaters are heavily loaded with phenols, detergents, nitrates, ammonium, and phosphorus, which could cause severe environmental issues and operational challenges for wastewater treatment plants due to foam formation. This foam can interfere with activated sludge treatment processes (Burzio et al. 2024). Furthermore, Cisterna-Osorio and Arancibia-Avila (2019) demonstrated that fats strongly influence the biodegradability of organic pollutants in vegetable oil industrial effluents. As biodegradability evolves over time, it significantly impacts the efficiency and saturation of treatment systems (Dhanke et Wagh 2020).

Effects of various surfactants in wastewater on flotation performance

Figure 2 illustrates the variation in surfactant concentration as a function of the time of year, both before and after flotation. Flotation is a separation process used for mineral and organic matter, particularly for removing oils, greases, and surfactants (Zhang et al. 2024).

The results demonstrate that natural flotation can significantly reduce the amount of surfactants present. The removal rate ranges from 50% to 82% for acidic wastewater.

Treatment efficiency varies significantly between seasons, with the highest performance observed in autumn, while summer and winter show lower efficiency. The pollutant removal rate is highest in the treated effluents in autumn when production is relatively low. The effluents are also less acidic during this period, which helps improve the flotation process's efficiency by facilitating particle separation. Higher production increases surfactant concentration during summer, reducing flotation efficiency to 60%. A study by Chatoui et al. (2017) and Dkhissi et al. (2020)

Table 1. Physicochemical characteristics of the wastewater used for the study (acidic wastewater AWW, process wastewater PWW (1-autumn, 2-summer, 3-winter)

Parameter	AWW1	PWW1	AWW2	PWW2	AWW3	PWW3
Temperature	20	21	38	31	15	12
Air temperature	19	19	23.2	23.2	16.3	16.3
pH	2.8	8	1.6	7.2	6.2	11.2
Conductivity, µs/cm	54	3.2	25	5.2	20	6.5
Turbidity	3950±0.03	3810±0.07	4000±0.03	3500±0.07	3800±0.03	3857±07
TSS, mg/l	356.4±1.05	570.2±1.08	-	9OOO±1.05	-	-
COD, g/L	32.1±0.8	9±0.09	181±0.8	16.9±0.09	57±0.8	9.8
BOD_5, g/L	13.6±0.05	5.4±0.02	-	9	-	-
Oil and greases, g/L	56.8±0.6	16±0.3	39±0.6	-	43±0.6	19±0.3
Surfactant, mg/L	340±0.7	162±0.8	370±0.7	300±0.7	40±0.7	10±0.7
Phenol, mg/L	200±0.08	62.55±0.06	380±0.08	13.2±0.06	60±0.07	10±0.04
Abs 254	0.9±0.03	0.32±0.02	0.8±0.01	2.5±0.02	0.7±0.05	0.29±0.04
NO_3^-, mg/L	140±0.07	150±0.03	200±0.03	350±0.03	70±0.03	35.5±0.03
NH_4^+, mg/L	27.2±0.02	65.2±0.07	60±0.02	75±0.02	8±0.02	10±0.03
Phosphorus, mg/L	65±0.3	181±0.6	150±0.3	250±0.6	50±0.3	41.9±0.2

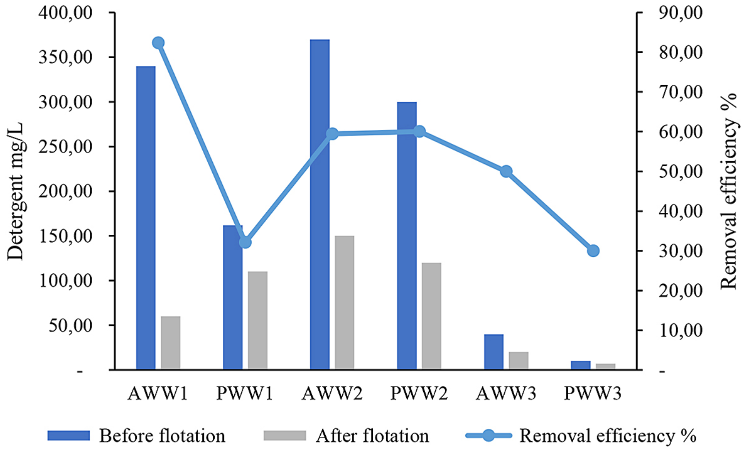

Figure 2. Variation of surfactants before and after flotation

revealed that the high production of surfactants coupled with dry climatic conditions worsens the concentration of these pollutants in wastewater and, therefore, their removal.

Finally, although yields are lower in winter, the elimination efficiency remains around 50%. The lower efficiency could be ascribed to low temperatures and more acidic wastewater in winter, which deteriorates the flotation treatment's performance. Nevertheless, pollutant removal is still high during the year, but the treatment efficiency differs at different times and is lower in winter and summer. Moreover, process wastewater has a removal efficiency of 32–62%. For process wastewater, surfactant reduction is mainly attributed to sedimentation and flotation mechanisms (Fig. 2). These results indicate that surfactants are more effectively removed during natural flotation of acidic wastewater than process wastewater. Indeed, under acidic pH conditions, the surface properties of particles and surfactants promote their separation by flotation, enhancing their adhesion to air bubbles and facilitating their removal (Houssam & Eddine, 2023).

During flotation, negatively or neutrally charged surfactants can be adsorbed onto the formed flocs, which may facilitate their removal. Chatoui et al. (2017) demonstrated that fats formed during flotation could adsorb various pollutants. The combination of flotation with advanced oxidation using the Fenton reaction has shown remarkable destruction of phenolic content in refinery wastewater, reaching up to 99.9% removal (El-Awady et al., 2015).

Flotation can effectively reduce organic and metallic pollutants in wastewater, as demonstrated by Kyzas & Matis (2019). Although the volume of acidic wastewater is relatively low, its pollutant load is higher than that of other wastewater. This could pose significant environmental challenges, particularly in wastewater treatment plants' biological processes (Zhao et al., 2024).

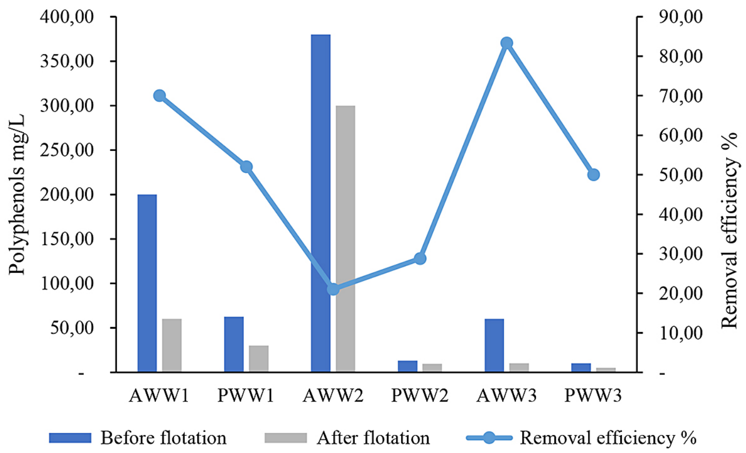

Figure 3. Variation of phenols before and after flotation

Study of flotation performance on phenol concentration reduction

Figure 3 illustrates the variation in phenol concentration before and after flotation during three different periods: autumn, summer, and winter.

The results indicate that natural flotation can significantly reduce the phenol content in wastewater. However, the efficiency of the process is strongly influenced by the initial concentration of contaminants, which depends on seasonal production volumes (Asgari et al., 2024).

In autumn, the phenol removal rate reaches 70%, considered moderate. This performance is attributed to the relatively low pollutant load, allowing for better adsorption of phenols via the flocs formed during the flotation process. During the winter season, the ability to remove phenol from samples was 83%, but in summer, when output was at its highest, the efficiency decreased notably to 20% for heavily tainted samples. This decline is attributed to the fact that phenols are more soluble at concentrations, which makes them less prone to being absorbed by the flocs (Slimani et al., 2024). Furthermore, the initial phenol content in the samples was correlated with the percentage of phenolic compounds' removal in the process water, which was between 52% and 30%. These results support the notion of the initial pollutant load as a key determinant of overall treatment efficiency. However, it is crucial to mention that the phenolic compound content in process water is typically relatively low, according to Chatoui et al. (2017) and Dkhissi et al. (2018).

However, natural flotation is an effective and economical pollution control method that does not require much energy and reagents, as Kastali et al. (2021) stated. According to Khalidi-Idrissi et al. (2024), flotation combined with coagulation-flocculation using ferric chloride and Amerfloc can remove essential pollutants. Chatoui et al. (2016) reported that flotation treatment is also a crucial preliminary step to decrease the fat and phenol content of the water. Louhichi et al. (2019) observed that flotation is most helpful in treating wastewater rich in oils and greases.

Study of flotation performance on 254 nm concentration reduction

Figure 4 illustrates the variation in absorbance 254 nm before and after flotation across three seasons: autumn, summer, and winter.

Figure 4 highlights the evolution of phenolic compound concentration (Abs 254 nm) before and after flotation across three seasons (autumn, summer, and winter). The results show that when the organic matter content is moderate in autumn, acidified wastewater's removal rate reaches approximately 80%. In contrast, for process wastewater, where the pH is high, this efficiency drops to 20% in summer, when industrial production is at its peak. The results obtained are superior to those reported by Prazeres et al., 2020 who studied wastewater treatment from olive oil mills. This study showed that chemical precipitation with HCl, H_2SO_4, HNO_3, NaOH, and Ca $(OH)_2$ allows a reduction in absorbance at 254 nm, with removal rates of 12.5 to 23.5% for HCl, 10.9 to 22.9% for H_2SO_4, 40.5 to 72.0% for HNO_3 and 18.5 to 45.9% for Ca $(OH)_2$. However, in acidified wastewater during

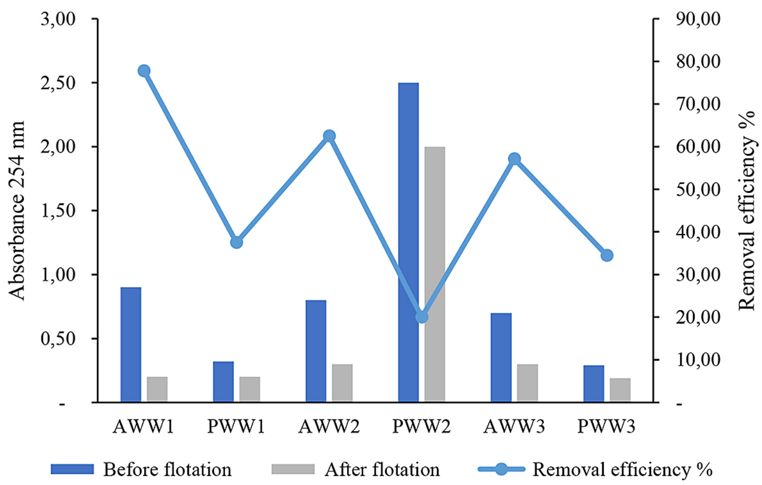

Figure 4. Analysis of phenolic compounds abs 254 nm before and after flotation

summer, removal rates reached 60%, emphasizing the significant impact of pH on process efficiency. Higher acidity enhances the availability of organic matter to the air bubbles, hence their more straightforward encapsulation and removal from the water. These results, therefore, confirm the necessity of controlling the acidity of wastewater to enhance the natural flotation process, especially when there is a high load of industry effluents that require treatment, for example, during the summer season.

Hartal et al. (2023) found that the flotation treatment of vegetable oil refinery wastewater reduced the absorbance at 254 nm (ABS254). The results showed a high degree of fatty matter reduction of 90.8% in acidic conditions as opposed to 64.7% in essential conditions. These data show that phenolic compounds are easier to remove in an acidic environment; therefore, acidic flotation is suitable for fighting industrial wastewater pollution. Khalidi-Idrissi et al. (2024) have further established that natural flotation is very efficient in flotation phenolic compounds from wastewater, using 254 nm absorption. The removal rate was 69% when combined with coagulation-flocculation using Amerfloc and Drewfloc 2448. This emphasizes the importance of natural flotation in enhancing wastewater treatment and its possibility as a simple yet effective measure for organic pollution control in industrial effluents.

In summary, the phenolic compounds absorbed at 254 nm in the vegetable oil refinery wastewater make the treatment in sequencing batch reactors (SBR) difficult. These substances can slow down microbial activity and decrease the efficiency of biological processes, leading to sludge formation (Singh & Shikha, 2019). If natural flotation is employed as a pretreatment step before SBR treatment, this could decrease this organic load, enhance purification efficiency, and decrease environmental impact.

Study of flotation performance on the ammonium nitrates and total phosphorus reduction

Flotation technology is applied widely across various industrial sectors to remove pollutants like ammonium, nitrates, and phosphates from treated Wastewater (Mao et al., 2024). Figures 5, 6, and 7 demonstrate the variation in nitrate, ammonium, and phosphorus concentration before and after flotation in three seasons: autumn, summer, and winter.

Figures 5 and 6 show the reduction of nitrate and ammonium ions during the natural flotation process during three seasons. The results show a very high decrease of about 85% for nitrates and 90% for ammonium after natural flotation. These results show that the process is good at removing these pollutants. In addition, flotation is an approach that has the advantage of requiring no energy, chemical reagents, or qualified personnel, making it an economical and easily applicable solution. The results obtained are almost identical to those reported by Haddaji et al. (2023), who demonstrated the effectiveness of an OA-SBR (aerobic-anoxic sequential batch reactor) system for the simultaneous removal of carbon, nitrogen, and phosphorus from wastewater from vegetable oil refining by modulating cycle times, achieving 96% removal of NH_4^+-N. Sazan et al. (2024) treated oily wastewater using dissolved air flotation (DAF) and moving bed biological reactors (MBBR). The experiments were designed and analyzed using response surface methodology (RSM). The optimum conditions obtained by RSM for DAF were a flotation time of 10 minutes and an airflow rate of 72 L/min, making it possible to achieve removal rates of 45.93% for ammonium.

Bolto and Xie (2019) state that natural flotation can be used on its own or in conjunction with coagulation-flocculation to improve the removal of colloids, which can hold a significant portion of charged ions in wastewater treatment plants. Moreover, the pH is an essential factor that determines the efficiency of this process. Flotation works best in acidic conditions since low pH favors the interaction between the charges in ions and flocs, resulting in better pollutant removal. Hence, flotation achieves maximum removal at acidic conditions since, in low pH, the charges in ions and flocs have a better tendency to interact and remove the pollutants effectively. Research conducted by Hartal et al. (2023) demonstrated that flotation in an acidic environment resulted in a remarkable nitrate removal rate of up to 97%.

Furthermore, flotation is very efficient in removing phosphorus, with the percentage of total phosphorus removed between 25% and 97% (Fig. 7). The initial phosphorus concentration influences the reduction efficiency in the wastewater, the acidic nature of the flocculant used (under acidic pH conditions), and the characteristics of the process water (under basic pH conditions). However, flotation is particularly suitable

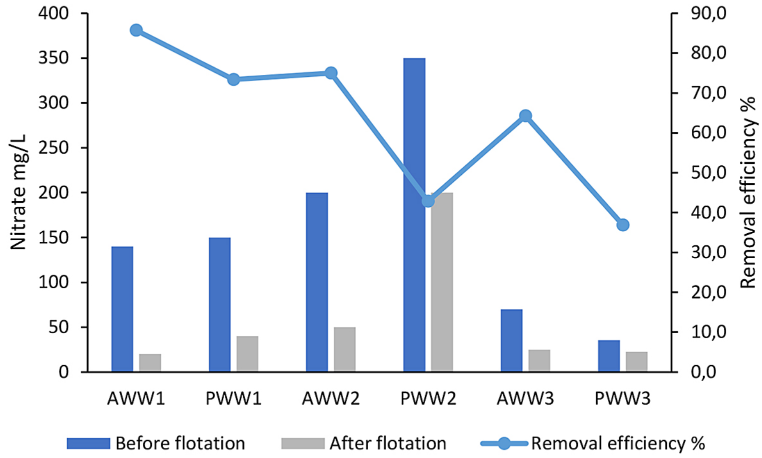

Figure 5. Variation of NO_3^- before and after flotation

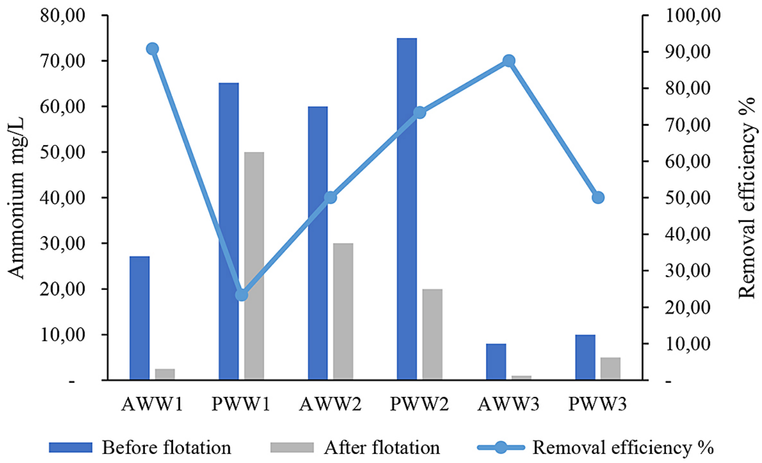

Figure 6. Variation of NH_4^+ before and after flotation

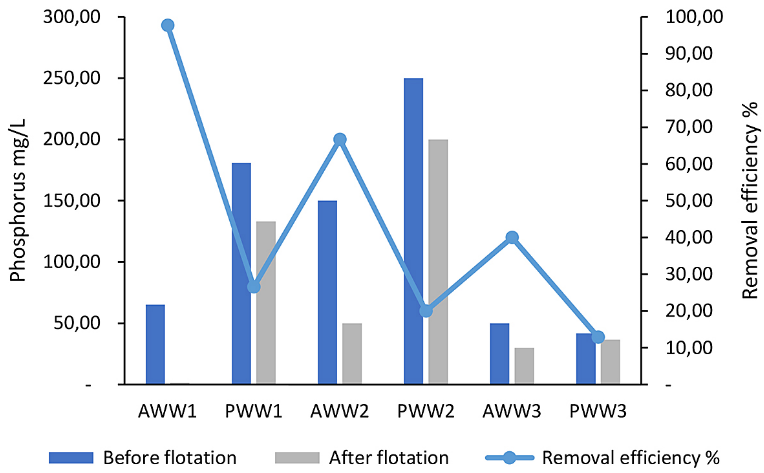

Figure 7. Variation of total phosphorus before and after flotation

for eliminating soluble ionic species that may be toxic. The process relies on adsorption, allowing ions to be captured or trapped before separating charged particles from the water.

The total phosphorus removal capacity is significantly enhanced in acidic environments, reaching up to 95%. This highlights the importance of pH in improving flotation effectiveness.

pH levels assist in ion adsorption and particle separation processes. This enhances the efficiency of removing contaminants and decreasing wastewater toxicity before treatment (Berdakh et al., 2024; Xu et al., 2024). Hartal et al. (2023) also reported that flotation in acidic environments can achieve an impressive phosphorus removal rate of 99.8%, further underscoring its potential as a powerful pretreatment method for industrial wastewater.

Moreover, the flotation method has proven to be highly effective in removing total phosphorus, with reduction rates ranging from 25% to 97% (Fig. 7). The removal efficiency is influenced by the initial concentration of total phosphorus in wastewater, the acidic nature of the flocculant used (at low pH), and the process water conditions (at high pH). The flotation method effectively removes ionic substances (Yu et al., 2024). This technique uses adsorption to capture ions beforehand and separate charged particles and ions.

Acidic conditions enhance the phosphorus removal efficiency up to 95%. This emphasizes the importance of pH in flotation treatment efficacy by improving ion adsorption at low pH and particle separation. Therefore, this makes the process more efficient in removing pollutants and decreasing the toxicity of the wastewater before further treatment. Flotation processes in acidic conditions can also thoroughly remove all phosphorus, according to Hartal et al. (2023), with a remarkable removal rate of 99.8%.

STATISTICAL STUDY

The correlation matrix Pearson in Table 2 presents a complete analysis of PCA applied to several variables tracked during the flotation treatment process. Figure 8 also illustrates the variables examined in addition to the graphical representation.

Such an approach was selected because it reduces the number of variables without losing essential information. The first two principal components (PC1 and PC2) explained 89% of the total variance, indicating that this approach is valid and appropriate, as Hartal et al. (2024) supported.

Table 2. Pearson correlation of physicochemical parameters

Correlation	pH	Detergent	Phenol	Abs254	Nitrate	Ammonium	Phosphorus
pH	1.000						
Detergent	-.793	1.000					
Phenol	-.876	.687	1.000				
Abs254	-.142	.492	-.144	1.000			
Nitrate	-.290	.710	.102	.884	1.000		
Ammonium	-.227	.651	.197	.533	.860	1.000	
Phosphorus	-.069	.519	-.020	.673	.907	.963	1.000

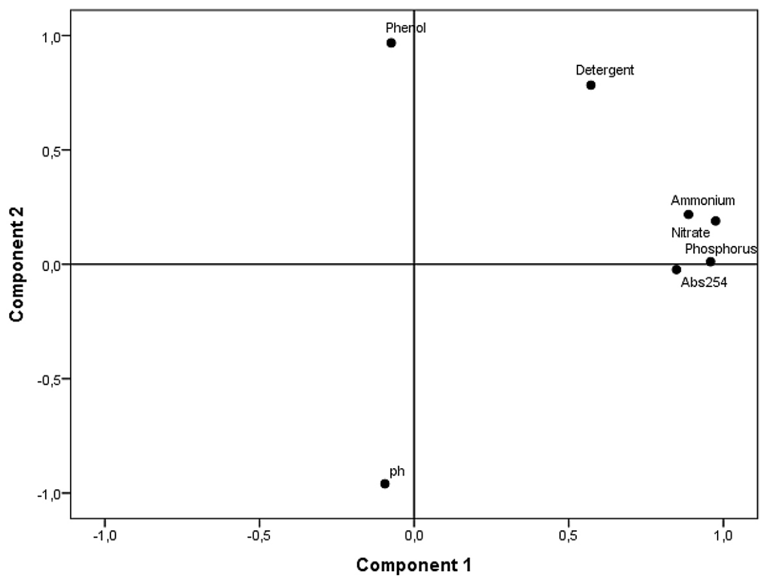

Figure 8. Diagram of PCA components of physicochemical parameters

The first principal component (PC1), which explains 53.1% of the variance, showed a significant positive correlation with nitrates, ammonium, total phosphorus, and absorbance concentrations at 254 nm. These highly interconnected parameters showed that natural flotation could reduce them concurrently, even with seasonal variations. This synergy is ascribed to the exact mechanisms, such as the pollutants' adsorption on the formed flocs and their separation at the surface. Furthermore, the high efficiency seen in acidified waters indicates that pH is an essential factor in the interaction between pollutants and air bubbles, thus enhancing the retention of the contaminants. Khattabi et al. (2022) have also shown a strong correlation between ammonium and phosphorus and their concomitant elimination during wastewater treatment.

The second principal component (PC2), which explains 36.5% of the variance, was also correlated with more specific correlations. It emphasized that the correlations of parameters related to pH and concentrations of phenols and surfactants have a distinct influence on treatment efficiency. One of the differences is that, while nitrates and ammonium do not require optimal operational conditions, these parameters do, specifically a strongly acidic pH, to be effectively removed. This observation confirms that due to their chemical nature, phenols are more challenging to remove when present at high concentrations, especially during summer, when industrial production increases.

Furthermore, the correlation matrix revealed that nitrates and total phosphorus are the pollutants most sensitive to natural flotation treatment, with correlation coefficients close to 1. This indicates that their reduction can be predicted with high accuracy, facilitating the optimization of industrial processes. In contrast, surfactants and phenols showed weaker correlations with other parameters, suggesting that they require specific approaches to maximize their elimination.

CONCLUSIONS

This research highlights the advantages of natural flotation as a pretreatment for vegetable oil refinery wastewater. This technique removes critical pollutants such as phenols, detergents, nitrates, ammonium, and total phosphorus. This study confirms that wastewater treatment efficiency is influenced by pH, temperature, and seasonal variations. Natural flotation effectively removes pollutants such as phenols (70%), surfactants (82%), nitrate (85%), ammonium (90%), phenolic compounds (77%), and total phosphorus (97%) from vegetable oil refinery wastewater. The process is particularly efficient under acidic conditions and during autumn when production rates are moderate. These findings confirm that flotation is a sustainable and cost-effective pretreatment method for managing wastewater in the vegetable oil industry.

The statistical analysis based on these observations supported the findings by revealing the significant correlations between key parameters like pH, organic load, and nutrient concentration. These results are important because they show that it is possible to fine-tune operational parameters to enhance flotation efficiency as a function of season and effluent type. When this method is applied in conjunction with a holistic wastewater treatment system, refineries will be able to enhance their sustainability and comply with the ever-increasing social and environmental responsibilities in the management of water resources. These results also open up the prospect for an environmentally friendly, cost-effective industrial-scale optimization method tailored to the needs of vegetable oil processing industries. Additionally, developing combined methods such as flotation combined with coagulation and flocculation is possible and may result in better treatment performance by concurrently acting against various kinds of pollutants.

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