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Lampung Natural Zeolite as a Green Solution: Heavy Metal Waste Treatment through Flotation-Filtration Method

Asep Setiawan
[1]Department of Chemical Engineering, University of Indonesia, West Java, Indonesia

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ABSTRACT

Purpose of the study: This study aims to evaluate and compare the effectiveness of flotation, filtration, and combined flotation–filtration processes in removing iron (Fe) and reducing Chemical Oxygen Demand (COD) from synthetic wastewater.

Methodology: This study employed flotation, filtration, and combined flotation–filtration methods using a ceramic membrane filtration unit, vacuum pump, air–ozone generator, and synthetic wastewater containing Fe, zeolite, Sodium Lauryl Sulfate (SLS), and Poly-Aluminum Chloride (PAC). Data were analyzed using concentration measurement and percentage removal efficiency calculations.

Main Findings: The combined flotation–filtration process showed the highest performance, achieving Fe removal efficiency of 94.74% with final concentration of 5.26 mg/L. Filtration and flotation showed lower efficiencies. COD reduction was more stable in filtration but more effective initially in flotation–filtration. Membrane fouling was lower in flotation–filtration, resulting in higher permeate volume compared to filtration alone.

Novelty/Originality of this study: This study presents a simultaneous flotation–filtration system integrated with air–ozone injection to enhance pollutant removal and reduce membrane fouling. It highlights the dual role of air–ozone as an oxidizing and cleaning agent, offering improved efficiency and membrane durability compared to conventional single-process methods.

Corresponding Author:
Asep Setiawan,
Department of Chemical Engineering, University of Indonesia, Jalan Majapahit No. 62, Dasan Agung Village, Selaparang District, Mataram City, West Nusa Tenggara, Indonesia
Email: apsetiawan95@gmail.com

1. INTRODUCTION

Environmental pollution from industrial wastewater containing heavy metals is a serious and growing problem [1], [2]. Metals such as iron, copper, and nickel are commonly found in wastewater from the electroplating, mining, and manufacturing industries [3], [4]. These heavy metals are toxic, non-biodegradable, and can accumulate in the food chain [5], [6]. Their impact not only damages aquatic ecosystems but also endangers human health. Therefore, effective and environmentally friendly wastewater treatment technologies are needed.

Various methods have been developed to address heavy metal pollution in wastewater, such as chemical precipitation, adsorption, filtration, and flotation [7], [8]. Each method has its own advantages and limitations in terms of efficiency, cost, and operational ease. Flotation is known to be effective in separating dissolved particles using air bubbles, while filtration is able to filter particles based on size [9], [10]. However, using a single method often fails to provide optimal results in reducing heavy metal levels to safe limits. Therefore, a combined approach is needed to improve the effectiveness of the treatment process [11], [12].

The combination of flotation and filtration is a promising alternative in wastewater treatment [13], [14]. Flotation can lift metal particles to the surface, while filtration serves as a secondary step to filter out remaining contaminants [15], [16]. The synergy of these two methods is expected to significantly increase heavy metal removal efficiency [17], [18]. Furthermore, this combined process also has the potential to reduce the use of additional chemicals. Therefore, this approach can be a more efficient and sustainable solution.

To support the effectiveness of this process, materials with high heavy metal binding capabilities are required. Natural zeolite is one such material that has been extensively studied due to its unique pore structure and good ion exchange capacity [19], [20]. Lampung's natural zeolite, in particular, holds significant potential due to its abundant availability and relatively low cost [21], [22]. Furthermore, this zeolite is environmentally friendly and easily applied in various waste treatment methods [23], [24]. Its use as a binding agent in the flotation-filtration process is an interesting innovation worthy of further study.

Although various studies have addressed the use of zeolite and waste treatment methods, most have focused on a single method [25], [26]. Research on the combination of flotation and filtration with the support of natural zeolite as a binding agent remains limited. Furthermore, there has been little comprehensive direct comparison between the combined method and a single method under similar conditions [27], [28]. This indicates a research gap that needs to be filled. Therefore, a study specifically comparing the performance of these three approaches is needed.

The novelty of this research lies in the integration of flotation and filtration methods with the use of Lampung natural zeolite as a binding agent in a single treatment system. This study not only tests the effectiveness of the combined method but also directly compares it with the separate flotation and filtration methods. This approach provides a clearer picture of the relative advantages of each method. Furthermore, the use of local resources, namely Lampung natural zeolite, provides added value in terms of sustainability [22], [29]. Thus, this research contributes to the development of more efficient and economical waste treatment technologies.

The urgency of this research is based on the increasing need for effective, affordable, and environmentally friendly waste treatment technologies. Industry requires solutions that are not only capable of significantly reducing heavy metal levels but are also easy to implement. The results of this study are expected to provide a more optimal technological alternative through a combined approach. Furthermore, this research can also serve as a basis for future industrial-scale development. Thus, this research is highly relevant in supporting environmental conservation and industrial sustainability efforts. Based on the above, the objective of this study was to compare the performance of the flotation-filtration process with that of flotation or filtration alone in liquid waste containing heavy metals.

2. RESEARCH METHOD

2.1. Tool Design

At this stage, a flotation, filtration, and flotation-filtration device will be designed. This device will be designed as a single device capable of performing all three processes, allowing it to be used for flotation or filtration alone, or for a combined flotation-filtration process. The device's circuitry can be seen in Figure 1 below.

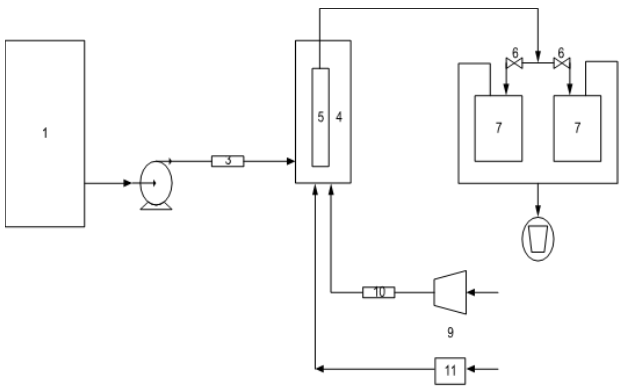

Figure 1. Flotation-Filtration Equipment Schematic

The equipment used in this study consists of several main components integrated into the processing system. The system begins with a mixing tank that serves as a homogenizer for the solution, supported by a water pump to circulate the fluid and a water flowmeter to control the flow rate. The solution is then channeled to a flotation-filtration tank, the main unit of the separation process. In the filtration stage, a ceramic membrane is used to filter particles and contaminants, while a valve regulates the fluid flow within the system. The filtration results are then collected in a permeate tank, assisted by a vacuum pump to accelerate the separation process.

To support the flotation process, the system is equipped with a compressor that produces compressed air and an air flowmeter to regulate the incoming air flow rate. Additionally, an ozonator is used to generate ozone, which can aid the oxidation process and increase separation efficiency [30], [31]. All of these components work in an integrated manner depending on the type of process being carried out, either separately or in a flotation-filtration combination. The device can be used for flotation, filtration, or flotation-filtration. Equipment such as a ceramic membrane, permeate tank, or vacuum pump is not required for the flotation process. Meanwhile, the compressor and ozonator are not activated during the filtration process. All equipment will be used during the flotation-filtration process.

2.2. Preparation of Process Materials

The materials used in this study included natural zeolite from Lampung, sodium lauryl sulfate (SLS), polyaluminum chloride (PAC), synthetic waste, and distilled water. Natural zeolite from Lampung requires pretreatment before use, while PAC, SLS, and distilled water can be used directly without special treatment. Synthetic waste, on the other hand, is not readily available and therefore requires prior preparation from suitable metal hydrate compounds.

The initial treatment of natural zeolite from Lampung involves reducing the particle size through a crushing process. Afterward, the zeolite is filtered using a sieve to obtain a uniform particle size, in the range of 0.35–0.4 mm. The filtered zeolite is then washed with distilled water to remove any adhering dirt or impurities. The zeolite is then heated in an oven at approximately 250 degrees Celsius for two hours, then cooled. After the heating process, the zeolite is stored in a desiccator to maintain its dryness before use in the processing process.

Synthetic waste is made by preparing a solution containing iron, copper, and nickel metals. Synthetic iron waste is made using the compound $FeSO4{\cdot}7H2O$, copper waste using $CuSO4{\cdot}5H2O$, and nickel waste using $Ni(NO3)2{\cdot}6H2O$. These three compounds are dissolved in water to produce synthetic waste with the desired metal content. This synthetic waste is then used as a sample in processing testing.

2.3. Hydrodynamic and Leakage Tests

At this stage, the designed equipment is tested for performance using water fluid to ensure the entire system functions as expected. Initial testing is carried out by checking for leaks in the equipment circuit. Given the continuous nature of the process, it is important to ensure the compatibility between the incoming water flow rate and the permeate flow rate sucked by the vacuum pump. Both flow rates must be balanced to ensure the fluid volume in the flotation-filtration tank remains stable, without excess or shortage. Next, the equipment is calibrated to obtain accurate flow rate values for both water and air. This calibration aims to ensure that the measuring instrument produces results that correspond to actual conditions. The calibrated devices include a liquid flowmeter and a gas flowmeter. This allows equipment performance to be controlled and optimized throughout the research process.

2.4. Mixing Process Materials

The prepared materials were then placed in a mixing tank for the homogenization process. The initial stage involved adding synthetic metal waste, Lampung natural zeolite at a concentration of 2 grams per liter, and Sodium Lauryl Sulfate at a concentration of 0.2 grams per liter. The mixture was then stirred for approximately ten minutes to ensure that all components were evenly mixed. Afterward, the pH of the solution was adjusted to a neutral value, namely pH 7, using sodium hydroxide or sulfuric acid solution. The next stage was the addition of Poly-Aluminum Chloride (PAC) at a concentration of 0.013 grams per liter to the mixture. The synthetic waste produced had a total volume of 15 liters with varying metal concentrations. The concentration variations used for each metal, namely iron, copper, and nickel, were 50 milligrams per liter, 100 milligrams per liter, and 150 milligrams per liter, respectively. These differences in concentration resulted in different compositions of the materials used in each solution. Details of the material composition for each concentration variation, especially for iron metal in 15 liters of distilled water, are presented in the following table:

Table 1. Composition of Synthetic Fe Waste and Additional Materials

Fe concentration (mg/L)	Lampung Natural Zeolite (gr)	SLS (gr)	PAC (gr)
50	30	3	0,195
100	30	3	0,195
150	30	3	0,195

The composition of the ingredients for the concentration of Cu metal in 15 liters of distilled water can be seen in Table 2.

Table 2. Composition of Synthetic Cu Waste and Additional Materials

Fe concentration (mg/L)	Lampung Natural Zeolite (gr)	SLS (gr)	PAC (gr)
50	30	3	0,195
100	30	3	0,195
150	30	3	0,195

The composition of the ingredients for the concentration of Ni metal in 15 liters of distilled water can be seen in Table 3.

Table 3. Composition of Ni Synthetic Waste and Its Additives

Fe concentration (mg/L)	Lampung Natural Zeolite (gr)	SLS (gr)	PAC (gr)
50	30	3	0,195
100	30	3	0,195
150	30	3	0,195

2.5. Flotation Process

At this stage, the wastewater treatment process containing iron metal at a concentration of 100 milligrams per liter was carried out. The flotation process was run continuously for ten minutes, with samples taken every two minutes. This experiment did not use any treatment variations because it aimed to evaluate the basic performance of the flotation process. The results obtained will later be used as a comparison to the performance of the combined flotation-filtration process. The experimental procedure began by flowing the synthetic iron waste mixture into the flotation tank until it reached a volume of five liters. Next, the water pump, compressor, and ozonator were activated simultaneously with a gas flow rate of 100 liters per hour. During the process, samples were taken every two minutes until the operating time reached ten minutes. After the process was complete, all equipment was turned off. The collected samples were then analyzed to determine the Chemical Oxygen Demand value and the remaining metal content.

2.6. Filtration Process

At this stage, waste containing iron metal at a concentration of 100 milligrams per liter was treated using a filtration method. The filtration process was carried out continuously for ten minutes, with samples taken every two minutes. This experiment did not use any treatment variations because it aimed to evaluate the basic performance of the filtration process. The results obtained were then compared with the performance of the combined flotation-filtration process. The experimental procedure began by flowing the synthetic iron waste mixture into the tank until the entire surface of the ceramic membrane was submerged. Next, the water pump and vacuum pump were operated simultaneously to support the filtration process. During the process, samples were taken every two minutes until the operating time reached ten minutes. In addition, the volume of the resulting permeate was also measured to determine filtration performance. After the process was completed, the equipment was turned off and the collected samples were analyzed to determine the Chemical Oxygen Demand value and the remaining metal content.

2.7. Flotation-Filtration Process

In this stage, waste containing iron metal at a concentration of 100 milligrams per liter was treated using a combined flotation-filtration method. The process ran continuously for ten minutes, with samples taken every two minutes. The initial experiment aimed to compare the performance of the combined method with separate flotation and filtration methods. The process began by flowing synthetic waste into a flotation-filtration tank until the entire ceramic membrane surface was submerged. Next, the water pump, vacuum pump, compressor, and ozonator were operated simultaneously, with an air flow rate of 100 liters per hour and the feed flow rate adjusted to the permeate flow rate. During the process, samples were taken periodically, the permeate volume was measured, then all equipment was turned off, and the samples were analyzed to determine the Chemical Oxygen Demand value and the remaining metal content.

The results of this experiment were then compared with those obtained from the separate flotation and filtration processes. If the combined method demonstrated superior performance, the study continued to determine the optimum conditions for the flotation-filtration process. Optimized parameters included the air flow rate and the initial concentration of metal waste. Furthermore, variations in the metal types used, namely iron, copper, and nickel, were conducted to determine the method's effectiveness against various contaminants. In the air flow rate variation stage, the process was carried out under the same conditions as before, but the air flow rate was varied to 100, 150, 200, and 250 liters per hour. The entire equipment system remained operating simultaneously, and the feed flow rate was adjusted to match the permeate flow rate. During the process, samples were taken every two minutes for ten minutes, and the permeate volume was measured. After the process was completed, the equipment was shut down, and the samples were analyzed to determine waste quality parameters. The results from this stage were used to determine the optimal air flow rate.

Next, variations in the initial concentration of metal waste were carried out using the previously obtained air flow rate as the optimum condition. The experiment began with synthetic iron waste at a concentration of 50 milligrams per liter, then continued with concentrations of 100 milligrams per liter and 150 milligrams per liter. The procedures remained the same: flowing waste into the tank until the membrane was submerged, operating all equipment, taking regular samples, and measuring the permeate volume. The next step was to conduct experiments with different metals, namely copper and nickel. Each metal was tested at the same concentrations: 50, 100, and 150 milligrams per liter. The experimental procedures used continued to follow the same steps as for iron waste treatment. This provided comprehensive data on the performance of the flotation-filtration method on various types and concentrations of heavy metals.

2.8. Sample Analysis

The collected feed and samples were then analyzed to determine water quality parameters, including metal content and Chemical Oxygen Demand values. This analysis aims to determine the difference in quality between the incoming water and the treated water. Thus, the effectiveness of the wastewater treatment process can be quantitatively evaluated based on changes in these parameters. Metal content analysis was conducted using atomic absorption spectroscopy with the aid of an Atomic Absorption Spectrophotometer. This method was chosen because it has a high level of accuracy and sensitivity in detecting metals in low concentrations. Metal content testing was conducted in the laboratory of the Faculty of Mathematics and Natural Sciences, University of Indonesia. Meanwhile, Chemical Oxygen Demand analysis was used to determine the amount of organic compounds contained in the water. A high Chemical Oxygen Demand value indicates poor water quality due to the large amount of dissolved organic matter. Conversely, a decrease in the Chemical Oxygen Demand value indicates improved water quality after the treatment process. Testing of these parameters was conducted in the laboratory of the Department of Chemical Engineering.

2.9. Data Processing

The data processing in this study consisted of data on the concentration of the metal waste to be processed. The results were in the form of a metal separation percentage, which can be calculated using the formula in equation 1:

$$\%Separation = \frac{KInitial\ concentration\ of\ metal - Final\ concentration\ of\ metal}{Initial\ metal\ concentration}\ x\ 100\% \ldots (1)$$

3. RESULTS AND DISCUSSION

In this method variation stage, a performance comparison was conducted between flotation, filtration, and a combination of flotation-filtration. The synthetic waste used was iron waste as a fixed variable, considering that iron metal is one of the most common contaminants found in water and is relatively easier to separate than other metals. All processes were conducted under identical operating conditions and run continuously for ten minutes. This approach aimed to obtain an objective comparison between the tested methods.

The comparison between the flotation and flotation-filtration processes was analyzed based on the final metal concentration and the Chemical Oxygen Demand value of the resulting permeate. Meanwhile, the comparison between the filtration and flotation-filtration processes not only considered these two parameters but also included aspects of membrane durability during the process. All three methods were then thoroughly evaluated to determine the most effective method for treating liquid waste containing iron metal.

3.1. Comparison of Flotation Process with Flotation-Filtration

The first comparison is in terms of Fe metal concentration. The results of these two methods can be seen in Figure 2.

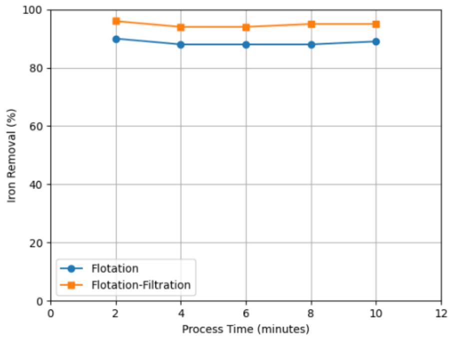

Figure 2. Comparison of Fe metal separation using the Flotation method and the Flotation-Filtration method

Figure 2 shows a comparison of the performance of the flotation process and the combined flotation-filtration process in treating ferrous metal waste. In the flotation process, the final iron metal concentration averaged 12.08 milligrams per liter, indicating that approximately 87.92 percent of the metal was successfully separated. Meanwhile, in the combined flotation-filtration process, the average final concentration decreased to 5.26 milligrams per liter, with a separation efficiency of 94.74 percent. These results indicate that the flotation-filtration method performed better than flotation alone. This increased efficiency is due to the simultaneous operation of two separation mechanisms. In the flotation process, air bubbles play a crucial role as a transfer medium for particle lift. These bubbles help float the formed flocs, allowing them to be separated from the liquid phase through surface extraction. However, this method has limitations because not all particles are lifted by the air bubbles. As a result, some contaminants remain in the solution.

The combination with the filtration process overcomes this limitation. Particles not removed during the flotation process can be retained by the ceramic membrane during the filtration stage. This filtration mechanism increases the efficiency of metal separation. The synergy between the flotation and filtration processes results in a more effective treatment system than either method alone. It should be noted that the two processes in the flotation-filtration method cannot be analyzed separately. This is because the flotation and filtration processes occur simultaneously and continuously within a single system. Therefore, the increase in efficiency cannot be interpreted as the partial contribution of each method. Instead, the results obtained are the combined effect of the interaction of the two processes as a whole.

Next is a comparison of the permeate COD which can be seen in Figure 3.

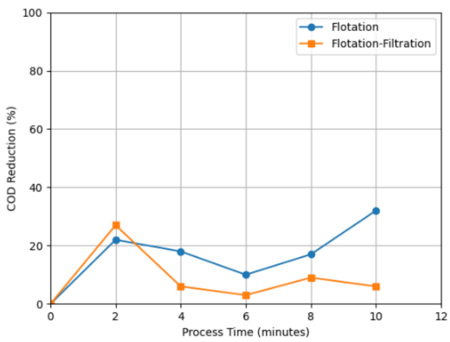

Figure 3. Comparison of COD in the Flotation method and the Flotation-Filtration method

Based on Figure 3, both methods demonstrated their ability to reduce the Chemical Oxygen Demand (COD) of wastewater. The COD value is significantly influenced by the presence of organic compounds in the solution, which in this case originates from sulfate ions from synthetic wastewater, as well as the use of surfactants. Surfactants play a crucial role in the flotation process as foam-forming agents that help maintain bubble stability, allowing contaminants to rise to the surface. However, the presence of surfactants also contributes to an increase in the COD value in the solution. The decrease in COD occurs because organic compounds in the wastewater are oxidized by air and ozone, then separated through flotation or a combination of flotation and filtration.

In the flotation process, the decrease in COD tends to increase over time. This is due to the oxidation of organic compounds by air and ozone, followed by separation through foam on the surface of the liquid. Some of the surfactant transforms into foam and is lifted along with the air bubbles, thereby reducing the organic content in the solution. Meanwhile, in the combined flotation-filtration process, the pattern of the decrease in COD shows a tendency to increase in the initial stage, then decrease again and remain relatively stable. This phenomenon is caused by the role of air and ozone, which not only act as oxidizing agents but also aid in the cleaning process of the ceramic membrane surface. Thus, in addition to increasing separation efficiency, this mechanism also maintains optimal membrane performance throughout the process.

3.2. Comparison of Filtration and Flotation-Filtration Processes

The first comparison is in terms of Fe metal concentration. The results of these two methods can be seen in Figure 4.

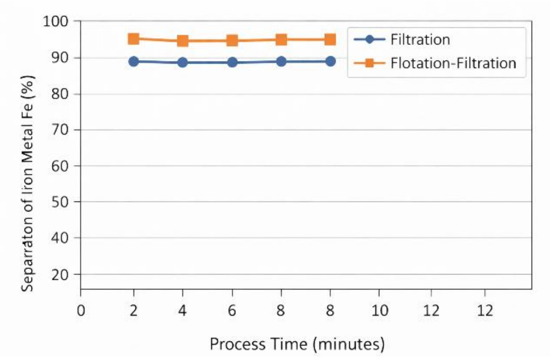

Figure 4. Comparison of Fe metal separation using the filtration method and the flotation-filtration method

Figure 4 shows a performance comparison between the filtration process and the combined flotation-filtration process in treating ferrous metal waste. In the filtration process, the final iron metal concentration averaged 11.89 milligrams per liter, indicating that approximately 88.11 percent of the metal was successfully separated. Meanwhile, in the flotation-filtration process, the final concentration averaged 5.26 milligrams per liter, with a separation efficiency of 94.74 percent. These results indicate that the combined method performed better than the single filtration method. This is because the flotation-filtration process utilizes two simultaneous separation mechanisms: flotation and filtration.

In both methods, the treated wastewater composition is similar: zeolite, sodium lauryl sulfate, and polyaluminum chloride. However, in the filtration process, the presence of these materials places an additional burden on the ceramic membrane, reducing separation efficiency. In contrast, in the flotation-filtration process, these materials play an active role in supporting the flotation process, such as floc formation and foam stabilization, thereby increasing the effectiveness of contaminant separation.

The quality of Chemical Oxygen Demand in both methods can be observed in Figure 4.5. In the filtration process, the Chemical Oxygen Demand value tends to be stable over time because the surfactant content in the solution does not undergo significant changes and is not raised to the surface. Conversely, in the flotation-filtration process, the Chemical Oxygen Demand value decreases, indicating an increase in the initial stage, then decreases again and tends to stabilize. This pattern is related to the role of the air and ozone mixture in the system.

In the initial stage of the flotation-filtration process, the membrane surface is still clean, allowing the air and ozone mixture to function optimally as an oxidizing agent capable of decomposing organic compounds, resulting in a decrease in the Chemical Oxygen Demand value. However, over time, the membrane surface begins to experience dirt buildup. Under these conditions, the air and ozone mixture acts not only as an oxidizing agent but also as a fouling preventative, both by cleaning the membrane surface and by reducing concentration polarization around the membrane. Thus, system performance is maintained throughout the process.

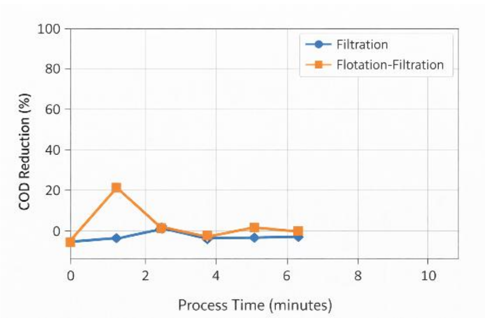

Figure 5. Comparison of COD in the Filtration method and the Flotation-Filtration method

The next comparison is in terms of permeate volume. This aims to determine the membrane's durability. The data from this study can be seen in Figure 6.

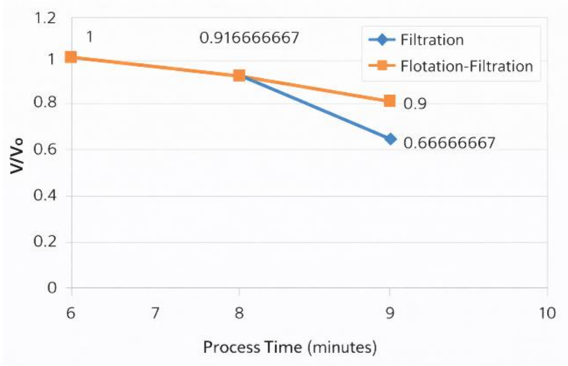

Figure 6. Comparison of permeate volume in the filtration method and the flotation-filtration method

Permeate volume comparisons were conducted to evaluate membrane durability, as a higher permeate volume indicates a longer lifespan. In both filtration and flotation-filtration processes, permeate volume decreased over time. This decrease was caused by fouling on the ceramic membrane surface. However, the decrease in permeate volume in the filtration process was more significant than in the flotation-filtration process. This was due to the flow of a mixture of air and ozone during the flotation-filtration process, which helped maintain the cleanliness of the membrane surface. This flow plays a role in reducing the accumulation of clogging particles, thus maintaining membrane performance better than in the single filtration process. In Figure 6, the permeate volume comparison analysis focuses on the sixth minute. This was done because during the first five minutes, the vacuum pump performance had not yet reached optimal conditions and was still fluctuating, resulting in unstable data for comparison. This condition was also observed throughout the study, where permeate volume actually increased in the initial stages. This instability of the vacuum pump was one of the challenges in the testing process that could affect the consistency of the results. The superior performance of the combined flotation-filtration method demonstrates a synergy of separation mechanisms that cannot be achieved by either method alone. Conceptually, flotation acts as a pre-treatment stage that reduces the load of suspended and dissolved particles before entering the filtration stage. Thus, filtration does not operate at maximum load conditions, increasing efficiency. This demonstrates that process integration can optimize the function of each operating unit within the treatment system.

From a mechanistic perspective, the presence of natural zeolite from Lampung makes a significant contribution to improving system performance [22], [32]. The zeolite's porous structure and ion-exchange capacity enable simultaneous heavy metal adsorption during the process. Furthermore, the interaction between the zeolite, coagulant (PAC), and surfactant (SLS) promotes the formation of more stable and easily separated flocs [33]. This combination enhances the effectiveness of flotation because larger, hydrophobic particles are more easily lifted by air bubbles.

The role of ozone and air in the system is not limited to the flotation process; they also provide additional effects in the form of organic compound oxidation. This oxidation process contributes to improved water quality by breaking down complex compounds into simpler, more easily separated forms [34], [35]. Furthermore, the gas flow in the system also functions as an in-situ cleaning mechanism on the membrane surface, thereby reducing the fouling rate [36], [37]. This is a crucial factor in maintaining stable filtration performance over the operating period.

From an operational perspective, single-stage filtration methods tend to be more susceptible to performance degradation due to particle accumulation on the membrane surface [38], [39]. This fouling can impede permeate flow and reduce overall process efficiency. Conversely, in a flotation-filtration system, most particles are removed early on, significantly reducing membrane load. This extends membrane life and reduces maintenance requirements.

The implications of these findings suggest that a combined approach not only improves separation efficiency but also offers advantages in terms of process sustainability. The use of local materials, such as natural zeolite from Lampung, supports economic and environmental aspects, while process integration reduces the need for additional chemicals and energy for system maintenance [40], [41]. Therefore, the flotation-filtration method has the potential to be further developed on an industrial scale as a more efficient and environmentally friendly waste processing technology.

This research has a significant impact on the development of more effective and sustainable wastewater treatment technology, particularly in reducing heavy metal levels and Chemical Oxygen Demand (COD). The results show that the combination of flotation-filtration methods with the support of natural zeolite can increase separation efficiency, reduce membrane fouling, and extend the operational life of the system [42], [43]. In addition, the use of local materials such as Lampung zeolite provides added value in terms of economic and environmental sustainability. However, this research still has several limitations, including the use of synthetic waste that does not fully represent real industrial waste conditions, limitations in the laboratory scale that does not reflect performance on an industrial scale, and instability in the performance of equipment such as vacuum pumps that can affect data consistency [44], [45]. Therefore, further research is needed with more complex waste conditions, broader optimization of operational parameters, and testing on a pilot or industrial scale to ensure the reliability and applicability of this method in practice.

4. CONCLUSION

This study concludes that the flotation–filtration method is more effective than single processes in removing heavy metals from wastewater. The integration of both methods improves separation efficiency, reduces membrane fouling, and enhances overall system performance. The use of natural zeolite further supports the process through adsorption mechanisms. This method shows strong potential as an efficient and environmentally friendly wastewater treatment technology. Further research is recommended using real industrial wastewater with more complex characteristics to test the effectiveness of the flotation–filtration method under more applicable conditions. Furthermore, pilot or industrial-scale development and optimization of operational parameters are necessary to improve system stability and ensure long-term performance sustainability.

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AUTHOR CONTRIBUTIONS

Conceptualization, A.S.; Methodology, A.S.; Software, A.S.; Validation, A.S.; Formal Analysis, A.S.; Investigation, A.S.; Resources, A.S.; Data Curation, A.S.; Writing – Original Draft Preparation, A.S.; Writing – Review & Editing, A.S.; Visualization, A.S.; Supervision, A.S.; Project Administration, A.S.; Funding Acquisition, A.S.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

Not applicable.

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