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Evaluation of Palm Oil Mill Effluent Using ROKAS Adsorption Column for Wastewater Treatment

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ABSTRACT

This paper assesses the effectiveness of the ROKAS adsorption column for wastewater treatment, particularly in the treatment of industrial wastewater, such as palm oil mill effluent (POME). This design was developed for participation in the Innovative and Creative Group (KIK) competition in Malaysia. It integrates both adsorption and membrane filtration components; however, for the purpose of this study, only the adsorption component was evaluated. The removal of primary pollutants using activated carbon (AC) and a mixture of AC and a commercial adsorbent (ammonia reducer (AR)) via the adsorption process was conducted to treat POME. The study emphasizes the effect of pH and contact time on the removal efficiencies of pollutants. The results showed that AC achieved the optimal percentage of color removal removal of 98% in 24 h at pH 8. This study showed that the introduction of AR significantly reduced about 71% of the initial ammonia content. These findings support the feasibility of adsorption-based systems of decentralized, cost-effective, and sustainable wastewater treatment. Future research recommendations include a continuous flow system design, operational enhancement, and the evaluation of the effectiveness of bio-alternative adsorbents.

1. Introduction

Industrial wastewater is the aqueous effluent generated from substances dissolved or suspended in water, usually during industrial manufacturing processes or related cleaning activities. Proper management of wastewater is crucial for public health and environmental sustainability. As industries expand, the volume of wastewater produced can increase significantly. Water resources, human health, and ecosystems are seriously threatened by untreated or inadequately treated wastewater. Therefore, efficient wastewater treatment technologies are necessary to support sustainable industrial operations and comply with strict environmental requirements.

One of the most extensively used measures for water quality assessment is biochemical oxygen demand (BOD). It provides information about the readily biodegradable portion of the organic load in water [1]. However, industrial wastewater systems typically use chemical oxygen demand (COD) because it offers a broader assessment than BOD [2]. In addition, the standard method for

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determining COD is simple and fast, and the analysis time is only 2 h, which is significantly shorter than that required for BOD [3].

Numerous technologies have been developed for treating industrial wastewater. Each technology offers unique benefits and drawbacks. Conventional methods for wastewater treatment include physical treatment (filtration and adsorption), chemical treatment (coagulation), and biological treatment (activated sludge). However, these methods often require extensive infrastructure and are energy-intensive, making them unsuitable for small-scale or remote industries. Consequently, there is growing interest in more affordable, portable, and sustainable treatment options. Membrane technologies of reverse osmosis, ultrafiltration, and nanofiltration offer high efficiency in the removal of pollutants in a compact approach, although fouling and operational costs remain challenges. Electrochemical treatments, including electrocoagulation and electro-oxidation, effectively remove contaminants with reduced chemical consumption, making them suitable for decentralized applications. Advanced oxidation processes, such as Fenton oxidation, ozonation, and photocatalysis, generate highly reactive species during the degradation of complicated pollutants; hence, they are ideal in industries dealing with recalcitrant organic compounds.

In this research, a new wastewater treatment system was introduced: the ROKAS portable wastewater treatment system. This system proved valuable in the laboratory for experiential learning, allowing students to investigate adsorption kinetics, pollutant removal, and process optimization under controlled conditions. The incorporation of eco-friendly bio-adsorbents and solar energy into the design makes the technology relevant to sustainability objectives and demonstrates practical applications of renewable energy in wastewater treatment. Besides, the laboratory-scale setup generates data useful for scaling up to industrial levels, thereby bridging the gap between theory and practice. This approach addresses the need for low-cost, portable, and sustainable treatment technologies and offers an alternative to conventional methods for industries with limited infrastructure.

2. Experimental Section

2.1 Materials

The wastewater used in this study is palm oil mill effluent (POME) collected in Kuala Nerang, Kedah. The adsorbent used in this study is activated carbon (AC), which was obtained from a previous research group under Dr. Khairuddin. Meanwhile, the commercial material (ammonia reducer (AR)) was purchased from LG Agricare Sdn. Bhd.

2.2 Instrumentation

This study utilized the ROKAS portable wastewater treatment system (Malaysia) to treat POME (Figure 1). The rotational speed was set between 120 and 250 rpm to ensure adequate mixing and, consequently, effective removal of contaminants from the wastewater. To evaluate treatment performance, ammonia content was measured using a spectrophotometer, which provided accurate measurements of absorbance related to pollutant reduction. This approach enables an effective evaluation of the system's performance in wastewater treatment and contributes to the development of sustainable, portable treatment options for industrial applications.

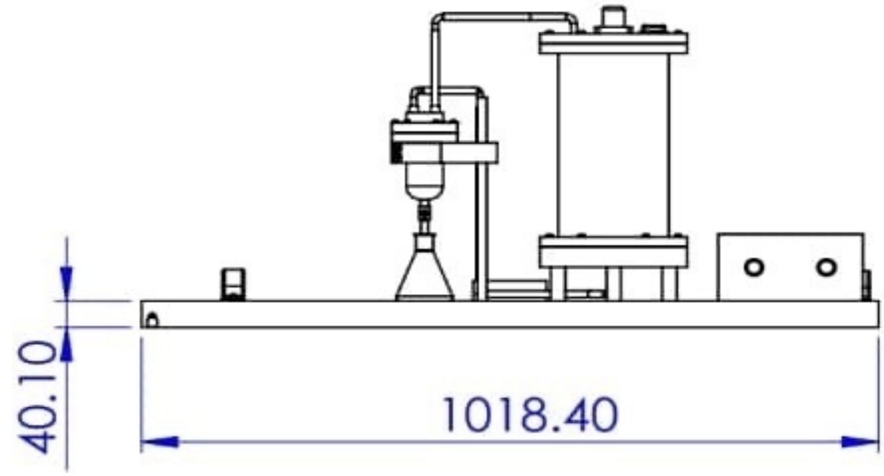

Fig. 1. Diagram of ROKAS design

2.3 Wastewater Characterization

The quality of the raw materials and the method used to produce crude palm oil determined the characteristics of POME [4]. Mahmod *et al*. [5] reported that POME is a thick, brown liquid discharged at high temperatures (80–90 °C) and low pH levels (3.3–5.7). Its high levels of BOD (10,250–43,000 mg/L), COD (15,000–100,000 mg/L), and oil and grease (130–18,000 mg/L) make it a significant environmental problem.

2.3.1 Sampling of POME

The POME sampling was carried out to collect representative samples to analyze their physicochemical properties. In this study, special attention was given to the observation of ammonia content and COD, as these parameters serve as the main indicators of nitrogen concentration and organic overload in effluent. Accurate determination of these values is essential for evaluating the environmental impact of the discharge and for selecting appropriate treatment methods.

To avoid contamination and dilution, all sampling bottles were thoroughly cleaned with distilled water and quickly rinsed with effluent before collecting the samples. The samples were then sent to the laboratory on time and stored in a chiller at a temperature of 6 °C to preserve their original condition for further analysis. The analysis of ammonia and COD was conducted within 24 h of sample collection to prevent significant changes in composition due to microbial degradation or chemical alteration, as proposed by Hossen *et al.* [6]. This sampling and preservation procedure adhered to internationally recognized best practices in industrial wastewater monitoring.

2.3.1.1 Ammonia Analysis

As ammonia is a common component of many aqueous streams, it must be strictly controlled due to its toxicity and potential to cause eutrophication. In addition to irritating the eyes, throat, and nasal mucosa, excessive exposure to ammonia in the air can result in severe harm or even death [7]. In the context of industrial wastewater, it has been observed that POME contains high nitrogen levels, with ammonia accounting for a significant portion of this nitrogen content [8]. Babu *et al.* [9] reported that the typical ammonium concentration in POME ranged between 35.2 and 631 mg/L, depending on the processing practices and wastewater management systems employed.

In this study, ammonia levels were assessed using Nessler's reagent spectrophotometry. A sample of POME was mixed with Nessler's reagent and incubated for approximately 10 min to allow color development. After incubation, the color intensity of the solution was measured at 425 nm using an ultraviolet-visible (UV-Vis) spectrophotometer. The ammonia concentration in the sample was then determined by comparing the absorbance values against a calibration curve constructed from standard ammonium solutions [7]. This method proved effective for routine monitoring of ammonia levels in POME, which remained important due to the harmful effects of excessive ammonia concentrations on both the environment and human health.

2.3.1.2 Chemical Oxygen Demand Analysis

Chemical oxygen demand is recognized as a crucial parameter for measuring the concentration of reducing pollutants in wastewater and serves as a direct indicator of the level of organic pollution. In this study, the method used to measure COD followed a procedure similar to that of ammonia analysis in terms of equipment, utilizing UV-Vis spectrophotometry for absorbance measurement.

The experiment began with the preparation of the digestion reagent by dissolving 4.9 g of potassium dichromate in 50 mL of concentrated sulfuric acid. Subsequently, approximately 10–25 mL of POME samples was pipetted into COD digestion tubes. Depending on the expected COD value, 1–2 mL of the prepared digestion reagent was added to each sample. The mixture was then heated in a water bath or digestion block at 150 °C for 2–3 h to ensure complete oxidation of organic compounds present in the sample. During the digestion process, the solution changed to a yellow or green color, indicating the extent of oxidation [10].

Following digestion, the samples were cooled and neutralized, typically with the addition of sodium bicarbonate, to achieve a neutral pH. The absorbance of the resulting solution was measured using a UV-Vis spectrophotometer at a wavelength of approximately 600 nm. A calibration curve was prepared using standard solutions with known COD values, and the COD concentration of the samples was determined by comparing their absorbance values with those of the standards. This method provides a rapid, reliable, and efficient means of quantifying the amount of oxidizable organic material present in POME by measuring the corresponding oxygen demand.

2.4 Wastewater Treatment

In this study, the SMART portable wastewater treatment system was utilized to treat POME. This system operates based on the adsorption mechanism, which functions as a tertiary wastewater treatment method designed to reduce residual contaminants following preliminary and secondary treatments.

Initially, raw POME samples were collected from the processing site and filtered to remove large suspended solids and debris. The commercial adsorbents, comprising AC and a selected commercial material (AR), were oven-dried, ground, and prepared prior to use to achieve a uniform particle size distribution and consistent surface characteristics. Batch adsorption experiments were performed by adding 10 g of adsorbent into 1,000 mL of POME contained within a laboratory-scale reactor. Throughout each experimental run, operational parameters such as contact time, stirring speed, and temperature were precisely controlled to maintain the consistency and reliability of the experimental conditions.

The removal efficiencies of ammonia and COD were calculated to evaluate the treatment performance under different operational settings. Furthermore, variables including adsorbent dosage and solution pH were systematically varied and optimized to determine the optimum treatment conditions for maximum pollutant removal. The data obtained from these experiments provide valuable insights into the adsorption behavior and efficiency of the selected adsorbents when applied for POME treatment within a portable, decentralized wastewater treatment system.

2.5 Adsorption Experiments

The adsorption experiments of POME were conducted using two types of adsorbents: AC and AR. The effects of several operational parameters, including contact time, adsorbent dosage, and pH, were examined to evaluate their influence on the removal efficiency of ammonia and COD. The AC sample was obtained from a previous research group within the institution, ensuring consistency in preparation and characteristics. Meanwhile, the commercial adsorbent material was purchased from a certified supplier to meet laboratory-grade specifications suitable for wastewater treatment applications.

2.5.1 Effect of pH

The surface characteristics of adsorbents are influenced by the initial pH of the solution, as pH directly affects the surface charge of the adsorbent and the ionization state of the pollutants in wastewater. Moksin *et al.* [11] investigated the effect of pH by varying the pH values within the range of 4–8 to determine the optimum conditions for adsorption performance.

2.5.2 Effect of Contact Time

In this study, adsorption experiments were conducted over varying contact times, up to a total duration of 3 h, following the method adapted by Moksin *et al.* [11]. A total of 1,000 mL of POME was mixed with 10 g of adsorbent in a reactor under controlled laboratory conditions. The contact time between the adsorbents and the POME was set at intervals of 60, 120, and 180 min to investigate the effect of contact time on the adsorption performance. The removal efficiencies of ammonia and COD at each interval were recorded to determine the optimum contact time for maximum pollutant removal.

2.6 Analysis after Treatment

The values of ammonia and COD of POME were rechecked after treatment using the SMART portable wastewater treatment system.

3. Results

3.1 Characterization of POME

To evaluate the treatment effectiveness of the SMART portable wastewater treatment system, it is essential to first characterize the raw POME. Palm oil mill effluent is an industrial wastewater with very high organic and nitrogenous content and a complex composition, making its treatment challenging. The characterization process involves determining key physicochemical parameters such as ammonia concentration and COD, as these are indicators of organic pollution and nutrient load in the selected effluent. This baseline study provides a critical reference point for evaluating subsequent treatments using adsorption with AC and a commercial adsorbent. Measurements taken before treatment offer a comprehensive understanding of pollutant levels, whereas post-treatment measurements enable comparison, allowing the extent of pollutant reduction achieved by the SMART system to be assessed.

3.1.1 Ammonia Analysis

The ammonia removal in POME was investigated using three approaches: untreated POME, AC, and the mixture of AC with a commercial absorbent material (AC-AR). The results, shown in Figure 2, illustrate the changes in ammonia concentration under optimal removal conditions of 120 min and pH 8.

The concentration of ammonia in the untreated POME sample was highest, at approximately 3.5 mg/L, indicating that a significant amount of nitrogenous waste is present in POME. This highlights the necessity of using ammonia-specific treatment methods prior to discharge. Treatment with AC alone reduced the ammonia level to approximately 2.8 mg/L. This outcome is expected, as AC is generally known to target organic compounds rather than nitrogen-based pollutants. Conversely, the combined treatment of AC-AR significantly decreased the ammonia concentration to approximately 1.2 mg/L. This demonstrates that the presence of a dedicated commercial material enhances the capacity to adsorb ammonia, whether through chemical binding or ion-exchange processes.

Based on this finding, the dual adsorbent origin explains the improved nitrogen removal, and therefore, may be a more effective approach for treating high-ammonia wastewater. This is in line with the findings by Dashti *et al.* [12], who underscored the synergistic benefits of using carbon-based and ammonia-specific materials to effectively remove pollutants from industrial wastewater.

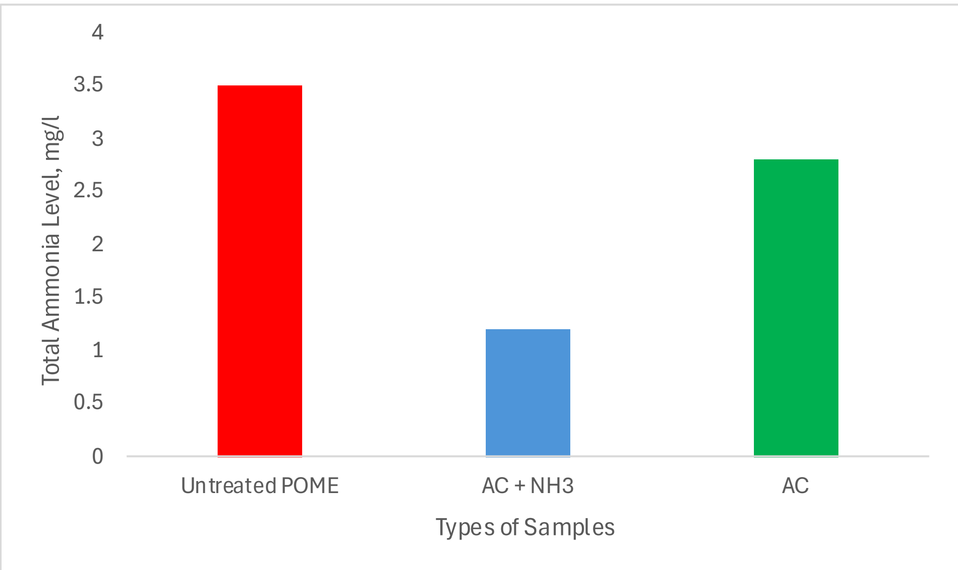

Fig. 2. Total Ammonia Level versus Sample Type

3.1.2 Chemical Oxygen Demand Analysis

Figure 3 presents a comparison of the COD levels in three samples: untreated POME, AC, and AC combined with an AR under optimized conditions of 120 min contact time and pH 8. These conditions were determined to be the most effective based on earlier parts of this work.

The raw POME sample contained 26,960 mg/L of COD, indicating a very high organic and biodegradable load characteristic of raw POME. This value shows that direct discharge of untreated POME poses a serious environmental threat and underlines the importance of effective treatment equipment. Subsequently, AC treatment achieved a higher removal efficiency of approximately 83.8%, as the COD level decreased significantly to 4,380 mg/L. This result indicates that AC possesses high adsorption capacity, attributed to its high porosity and large surface area.

The AC-AR mixture reduced the COD level to 5,060 mg/L, achieving a removal efficiency of around 81.2%. Although this combination performed slightly worse than AC alone, it still demonstrated good performance. The decrease in performance can be attributed to competitive adsorption on the surface, as the commercially available material is designed mainly to absorb ammonia and may be less effective in removing organic matter.

To summarize, the adsorbent treatment was highly effective in retaining COD under optimum conditions for both adsorbent methods. Although AC alone achieved slightly higher COD removal, the combined system offers the advantage of removing both ammonia and organic pollutants, rendering it a more versatile solution for treating complex industrial wastewater such as POME.

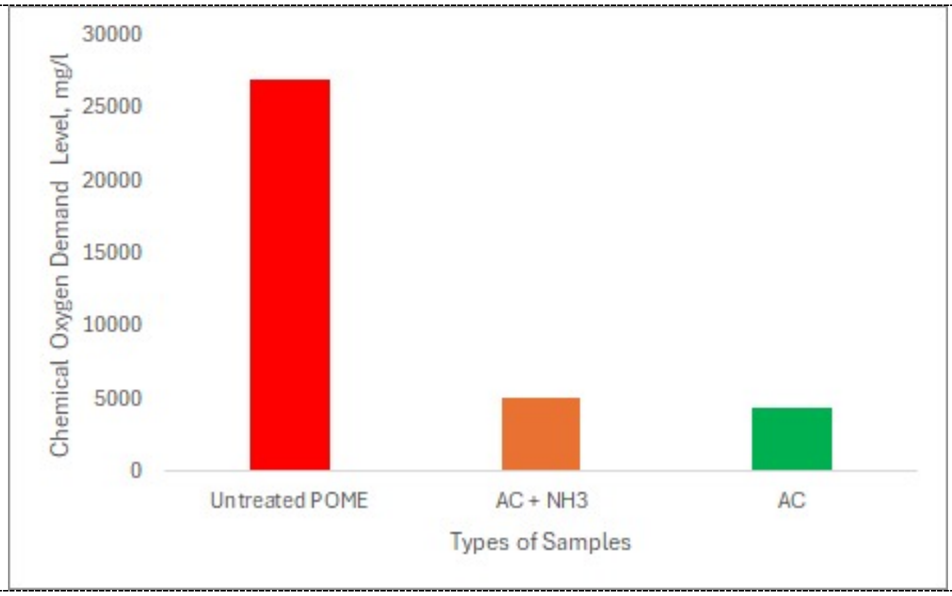

Fig. 3. Chemical Oxygen Demand Removal versus Sample Type

3.2. Adsorption Experiments using AC

Adsorption experiments were conducted to evaluate the efficiency of AC as an adsorbent for removing pollutants from POME. The study aimed to determine how two important parameters—contact time and pH—affect the adsorption capacity of AC in treating POME using the SMART portable wastewater treatment system.

3.2.1 Effect of Contact Time

The effect of contact time on the percentage removal of wastewater was studied by varying the contact time between the adsorbent and wastewater from 60 to 180 min using AC. Figure 3 shows the graph of the percentage removal of POME plotted against contact time.

As shown in Figure 4, the adsorption process achieved a removal efficiency of about 94.8% at 60 min, followed by a slight increase to 95% at 120 min. This high rate in the initial stages can be attributed to the abundance of available sites on the surface of the AC and the high concentration gradient between the POME solution and the adsorbent, resulting in a rapid adsorption rate. After 120 min, the adsorption efficiency slightly decreased to 94.85% at 180 min. This small decline may be due to the system reaching equilibrium, where the number of active sites becomes limited and desorption may occur as the adsorbent approaches saturation. Additionally, repulsive forces between adsorbed molecules and those remaining in the solution phase may prevent further adsorption.

In this study, the optimum contact time was found to be 120 min to achieve maximum removal efficiency. Beyond this point, no further improvement was observed; instead, a slight decline occurred, indicating that extending the duration past equilibrium is inefficient. This trend aligns with the results of Dashti et al. [12] and Hayawin et al. [13], who reported that in the range of 120–150 min, the efficiency of removal reached its maximum or began to slightly decline for most of the adsorption processes of POME and other industrial effluents.

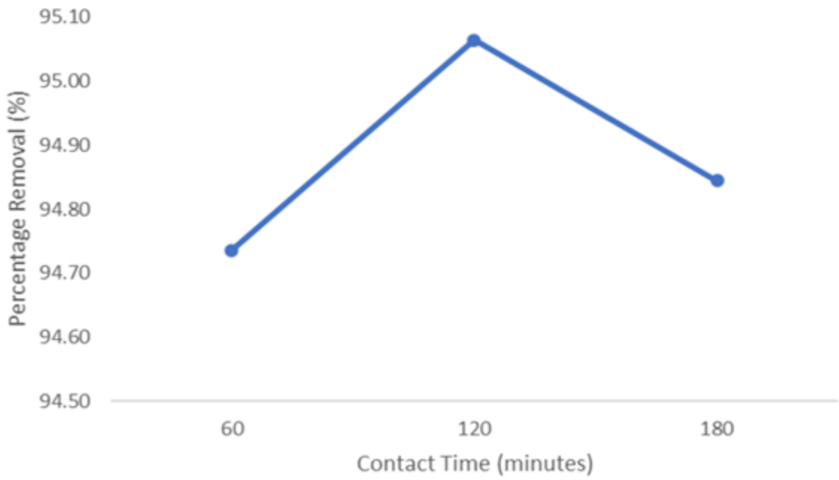

Fig. 4. Effect of Contact Time on the Percentage Removal of Colors in POME

3.2.2 Effect of pH

The effect of pH on the adsorption efficiency for POME treatment using AC was assessed by adjusting the pH of the wastewater samples to 4, 6, and 8. The results are presented in Figure 5. Removal efficiency moderately increased with pH values before the samples were placed in the incubator shaker. The percentage removal was 94% at pH 4, increasing to 96% at pH 6 and 96.5% at pH 8. The trend shows that as pH increases, the absorption of ammonia and organic pollutants onto AC is enhanced. This is likely because, at higher pH, fewer hydrogen ions compete with ammonia and organic pollutants for adsorption sites on the AC. Furthermore, the interaction between the negatively charged AC surface and the positively charged ammonium ions becomes more favorable.

The adsorption efficiencies improved further after 24 h of shaking, with all pH levels demonstrating that adequate mixing and contact time resulted in equilibrium. The percentage removal increased to 96.5% at pH 4, 97% at pH 6, and 98% at pH 8. The increased removal efficiency after shaking indicates that the additional contact time allowed greater diffusion of pollutants into the internal pores of the AC, as well as a reduction in resistance to mass transfer.

At pH 8, where removal efficiency reached 98%, the highest removal was observed after 24 h. This result suggests that alkaline conditions can slightly enhance the adsorption of ammonia and other pollutants from POME in this system. This effect may be explained by the ionization state of ammonia and the surface charge of AC, indicating that adsorption is more effective when the pH of the solution is near neutral or slightly alkaline. Although the increase in removal efficiency between pH 6 and pH 8 is noticeable, it is not significant. This implies that the adsorption process in this experiment is effective across a wide range of pH, with optimal adsorption occurring at pH levels above 6. Additionally, prolonged shaking can further enhance adsorption.

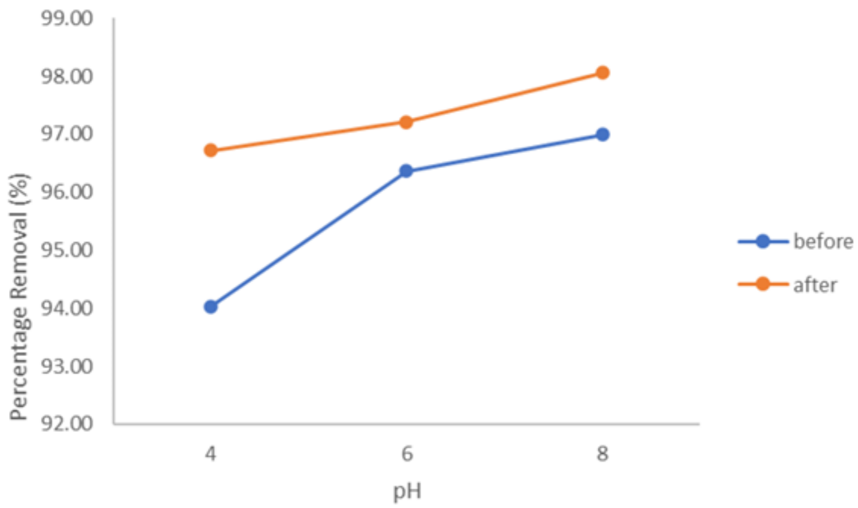

Fig. 5. Effect of pH on the Percentage Removal of Colors in POME

3.3. Adsorption Experiments using AC and a Commercial Material

The objective of this experiment was to test and compare the adsorption efficiency of a mixture of AC-AR in treating POME using the SMART portable wastewater treatment system. Additionally, these experiments were conducted by varying the contact time and pH to investigate their effects on adsorption efficiency. The combination of two or more adsorbents was examined in order to understand and evaluate the combined benefits of their collaboration in wastewater treatment. This was achieved by comparing the pollutant removal abilities of the individual materials and their combinations before and after exposure to UV-Vis spectrophotometry.

3.3.1 Effect of Contact Time

The influence of contact time on the removal efficiency of POME using a mixture of AC-AR was observed at 60, 120, and 180 min. The adsorption efficiency increased, reaching a maximum at 120 min, followed by a slight decrease at 180 min, as depicted in Figure 6.

At 60 min, the percentage removal was observed to be 96.5%, indicating a rapid adsorption phase due to the abundance of available active sites within the adsorbent mixture. When the contact time was increased to 120 min, the removal efficiency rose to 97.9%, representing the optimum contact time in which the surface area of the adsorbent was adequately exposed to the adsorbate, facilitating further uptake of pollutants. However, a slight decrease in removal efficiency to 97.6% was noted at 180 min. This small reduction may be attributed to the desorption of previously adsorbed molecules, saturation of adsorption sites, or disturbance of equilibrium caused by prolonged contact time. Additionally, competitive interactions among pollutants within the POME matrix could contribute to this effect.

The combination of AC-AR has demonstrated excellent adsorption performance, achieving a high removal efficiency within a relatively short contact time. This synergistic effect is likely due to the increased total surface area, the presence of different functional groups, and an improved pore structure provided by the combined adsorbents, which enhance pollutant capture efficiency.

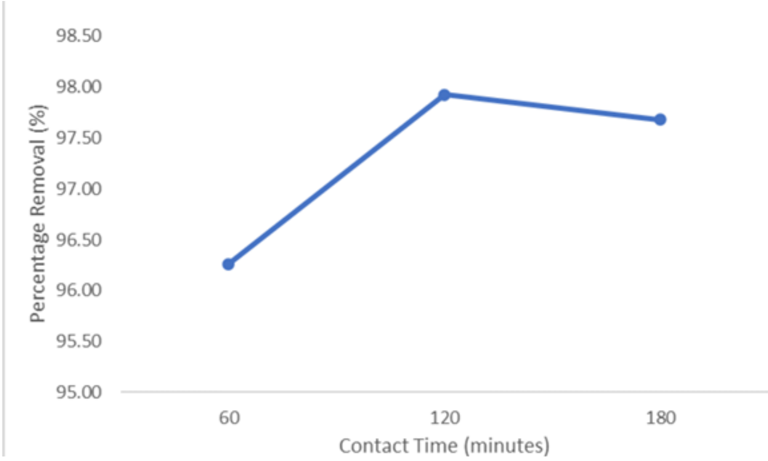

Fig. 6. Effect of Contact Time on the Percentage Removal of Colors in POME

3.3.2 Effect of pH

The parameter pH, which may influence the extent of adsorption of POME using the AC and AR mixture, was examined by varying the pH of the wastewater to 4, 6, and 8. Adsorption data were collected from the samples before and after mixing them in a shaker for 24 h to determine the effect of mixing time on pollutant removal, and the results are shown in Figure 7.

The removal efficiency gradually increased with increasing pH values prior to shaking. The removal percentage was 96.5%, which slightly increased to 96.7% at pH 6 and then progressively to 97.9% at pH 8. This trend indicates that the adsorption of pollutants in POME onto the combined adsorbent system is preferred at higher pH values. This is likely due to the reduced competition from hydrogen ions at higher pH, resulting in improved interactions between ammonia and organic pollutants with the available amorphous sites.

The removal efficiencies increased further after a 24-h shaking period at all pH values. The removal percentage at pH 4 rose slightly to 96.6%, while at pH 6, it increased more significantly to 97.7%. At pH 8, the removal efficiency was the highest, reaching 98.5%. The high level of removal performance observed even after prolonged shaking emphasizes the necessity of extended contact time and adequate mixing, which enhance the diffusion of pollutants into the adsorbent pores and minimize mass transfer resistance.

The high removal efficiency observed at pH 8 can be explained by the fact that, at a relatively neutral pH, the adsorption conditions are more favorable due to reduced competition from the unionized or less competitive form of ammonia, which interacts with the negatively charged functional groups. Moreover, the mixture of AC-AR offers a broader spectrum of adsorption sites and functionality groups, leading to increased adsorption capacity and enhanced pollutant removal.

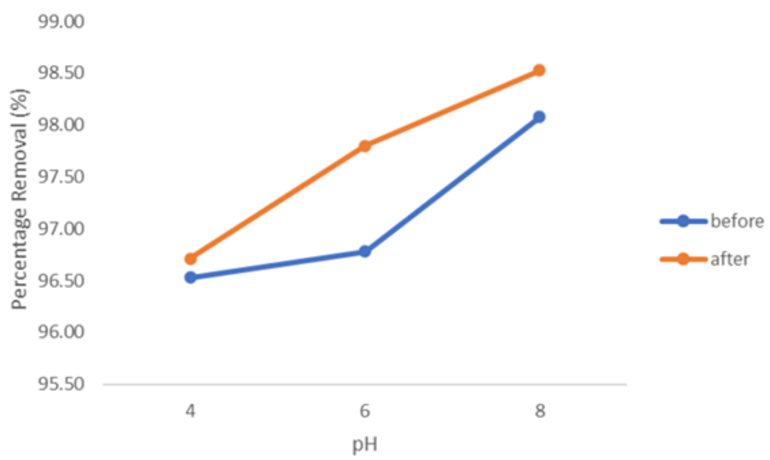

Fig. 7. Effect of pH on the Percentage Removal of Colors in POME

4. Conclusions

This research was conducted to evaluate the efficiency of the SMART portable wastewater treatment system in treating POME through adsorption processes, focusing on AC and its combination with a commercial material. The experiment began with the characterization of raw POME, measuring the initial concentrations of ammonia and COD to determine the initial point of the pollutant concentration before treatment. The initial ammonia level was recorded at 3.5 mg/L, whereas the COD concentration was 26,960 mg/L. These values are consistent with the high levels of organic and soluble nitrogenous compounds typically found in POME, as previously reported by Gamaralalage *et al.* [8] and Mahmod *et al*.[14-15].

In the adsorption experiment conducted using AC, the contact time factor indicated that removal efficiency increased sharply, reaching a peak of 95.1% at 120 min, and then slightly decreased to 94.85% after 180 min. This trend reflects that adsorption equilibrium was achieved within approximately 120 min, consistent with the findings of Dashti *et al*. [12], who reported that the adsorption capacity of organic pollutants in POME stabilizes between 120 and 150 min due to saturation of active sites.

The results of the pH and AC experiments showed that as the pH increased from 4 to 8, the removal efficiency also increased, reaching an optimum removal of 98% at pH 8 after 24 h of shaking. This increase in removal efficiency can be explained by a decrease in competition from hydrogen ions and enhanced positive electrostatic interactions between the adsorbent and ammonium ions, as previously demonstrated by Pan *et al*. [16].

In the adsorption experiment involving a combination of AC-AR, the removal efficiency improved significantly with contact time, reaching 97.9% after 120 min, compared to 96.5% at 60 min and a slight decrease to 97.6% in 180 min. The synergistic interaction between the two adsorbents was found to increase the surface area and provide a greater variety of functional groups, thereby enhancing pollutant adsorption. These findings are consistent with the results reported by Hayawin *et al*. [13] and Tan *et al*. [17].

A similar trend was observed when assessing the influence of pH on the combined absorbent system, demonstrating that removal efficiency improved with increasing pH. The removal efficiency rose to 97.9% at pH 8, compared to 96.5% at pH 4 prior to shaking, and further increased to 98.5% after 24 h of shaking. This finding proves that adsorption efficiency is enhanced in a slightly basic solution and with a longer mixing time, thus improving the mass transfer and reaching an equilibrium more effectively [12][16].

To summarize, this paper demonstrated that AC alone, as well as in combination with an AR, is an extremely effective choice of adsorbent for treating POME. The optimal performance parameters were identified as a pH of 8 and a contact time of 120 min. The SMART portable wastewater treatment system proved to be a viable, effective, and expandable decentralized solution for industrial wastewater treatment, with significant potential for future expansion across various industrial applications.

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