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Effectiveness of Acid-Activated Oil Palm Fiber and Quartz Sand Adsorbents in Reducing Wastewater Pollutant Parameters

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Abstract: *Palm oil mill wastewater contains high concentrations of organic pollutants and suspended solids that may degrade environmental quality if discharged without proper treatment. This study evaluated the effectiveness of acid-activated oil palm fiber and quartz sand as column adsorbents for improving wastewater quality. The experiment employed a quantitative laboratory approach using a completely randomized design with three adsorbent ratios, namely 1:1, 1:2, and 1:3, each with three replications. The observed parameters included total suspended solids (TSS), total dissolved solids (TDS), color, biochemical oxygen demand (BOD), chemical oxygen demand (COD), and pH. The results showed that the adsorbent column was highly effective in reducing color and moderately effective in lowering BOD and COD, but it increased TSS and TDS. The best color removal was obtained at the 1:2 ratio with a final concentration of 22.00 TCU and an efficiency of 92.93%. The greatest BOD reduction occurred at the 1:3 ratio with a final concentration of 41.03 mg/L and an efficiency of 66.15%, while the best COD reduction was observed at the 1:1 ratio with a final concentration of 233.53 mg/L and an efficiency of 23.63%. The pH increased from 4.81 to 8.34-9.09 after treatment. ANOVA indicated that adsorbent ratio significantly affected BOD and COD, but did not significantly influence TSS, TDS, color, or pH. These findings suggest that acid-activated oil palm fiber and quartz sand have potential as alternative adsorbent media for palm oil mill wastewater treatment, particularly for color and biodegradable organic load removal.*

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INTRODUCTION

The palm oil industry plays an important role in the Indonesian economy, yet its processing activities generate considerable amounts of wastewater with high organic loads and unstable physicochemical characteristics. Palm oil mill wastewater generally contains elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, color, oil residues, and acidic compounds that may harm receiving water bodies when discharged without adequate treatment. The high pollutant load of palm oil mill effluent therefore remains an important environmental issue in palm oil-producing regions (Melisa & Apriyanto, 2020; Bancin, 2024)

Among the major challenges in palm oil mill wastewater treatment are the reduction of organic pollutants, color, and residual acidity in an efficient and affordable manner. Conventional treatment systems may require long retention times, extensive infrastructure, or high operating costs. Consequently, adsorption has attracted attention as an alternative or complementary method because it is relatively simple, effective, and adaptable for polishing wastewater quality. Adsorption

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performance depends on the characteristics of the adsorbent, the available active sites, contact time, flow pattern, and the physical arrangement of the adsorption media in the treatment column (Do, 1998; Reynolds & Richards, 1996).

Several studies have reported the use of adsorption media derived from oil palm residues or other agricultural wastes for wastewater polishing. Syukur et al. (2023) found that palm-based adsorbents were effective for color removal from palm oil mill wastewater, while Rusdianto et al. (2022) demonstrated that coconut shell charcoal adsorption could reduce BOD, COD, and TSS in detergent wastewater. Winardi and Prasetyo (2025) also reported that activated oil palm frond bioadsorbents improved the quality of palm oil mill wastewater. However, the combined use of acid-activated oil palm fiber and acid-activated quartz sand in an adsorption column, especially with different adsorbent ratios, has not been sufficiently discussed in previous studies. Most studies emphasize single adsorbents or focus only on a limited number of parameters. This creates a research gap regarding the comparative performance of mixed adsorbent ratios toward multiple wastewater quality parameters in one integrated column system.

This study was conducted to evaluate the effectiveness of acid-activated oil palm fiber and quartz sand adsorbents in improving palm oil mill wastewater quality based on TSS, TDS, color, BOD, COD, and pH. Specifically, this study aimed to determine the effect of three adsorbent ratios, namely 1:1, 1:2, and 1:3, on pollutant removal performance and to identify the most effective ratio for wastewater treatment. The findings are expected to contribute to the development of low-cost adsorbent media from plantation-based materials for palm oil mill wastewater treatment.

Previous studies have mainly focused on the use of single adsorbents or evaluated only a limited number of wastewater quality parameters. However, limited information is available regarding the combined application of acid-activated oil palm fiber and quartz sand in a column adsorption system with different adsorbent ratios. Therefore, this study introduces a combined adsorbent system and comprehensively evaluates its performance on TSS, TDS, color, BOD, COD, and pH. This approach provides new insights into the development of low-cost and environmentally friendly adsorbents for palm oil mill wastewater treatment.

RESEARCH METHOD

Research Design

This study used a quantitative experimental approach conducted at the Shafera Enviro Laboratory in 2025. The treatment process employed a column adsorption system using acid-activated oil palm fiber and quartz sand as adsorbent media. The experimental design applied was a Completely Randomized Design (CRD) with a single factor, namely the ratio of quartz sand to oil palm fiber adsorbent. Three treatment levels were used: P1 = 1:1, P2 = 1:2, and P3 = 1:3. Each treatment was replicated three times, resulting in nine experimental units.

Materials and Equipment

The materials used in this study consisted of wastewater sample, modified oil palm fiber adsorbent, quartz sand (SiO_2) activated with acid, hydrochloric acid (HCl), and distilled water. The main equipment included a pH meter, analytical balance, measuring cylinders, Erlenmeyer flasks, volumetric flasks, magnetic stirrer, oven, and TDS meter.

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Research Variables

The independent variable was the ratio of quartz sand and oil palm fiber adsorbent, consisting of:

- **P1 = 1:1**
- **P2 = 1:2**
- **P3 = 1:3**

The dependent variables were BOD, COD, pH, color, TSS, and TDS of the wastewater after treatment. Controlled variables included temperature (room temperature), solution volume, flow rate, and adsorbent bed height.

Adsorbent Preparation

Oil palm fiber was burned, cooled, and then modified using HCl solution to improve the availability of active functional groups. Quartz sand was washed, dried, and acid-activated to enhance surface cleanliness and reactivity. Both adsorbents were subsequently dried in an oven at 105°C for 24 hours. After drying, the materials were sieved using a 200-mesh sieve to obtain a more uniform adsorbent size. Oil palm fiber was immersed in 1 M hydrochloric acid (HCl) solution for 24 hours to remove impurities and enhance the availability of active adsorption sites. Similarly, quartz sand was activated by soaking in 1 M HCl solution for 24 hours. After activation, both materials were thoroughly rinsed with distilled water until neutral pH was achieved. The adsorbents were then oven-dried at 105°C for 24 hours and sieved through a 200-mesh sieve before being packed into the adsorption column according to the treatment ratios

Adsorption Procedure

A column adsorption unit was prepared using an acrylic pipe as the adsorption column. The adsorbent media were inserted into the column according to the treatment ratios of 1:1, 1:2, and 1:3. Wastewater was then passed through the adsorption column, and the treated effluent was collected for quality analysis. During the experiment, the flow rate through each treatment column was recorded to evaluate hydraulic performance.

Water Quality Analysis

The observed wastewater quality parameters were analyzed using the following methods:

- TSS: gravimetric method
- TDS: TDS meter
- Color: spectrophotometric analysis
- BOD: based on SNI 6989.72
- COD: based on SNI 6989.73
- pH: pH meter

Data Analysis

The efficiency of pollutant reduction was calculated using the following equation:

$$\text{Removal Efficiency (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

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where:

C_0 = initial concentration of the parameter

C_t = final concentration of the parameter after adsorption treatment

The experimental data were analyzed descriptively and statistically using one-way analysis of variance (ANOVA) at a significance level of 5% to determine the effect of adsorbent ratio on wastewater quality parameters. When the ANOVA result was significant, a Duncan Multiple Range Test (DMRT) was performed to identify differences among treatment means.

RESULTS AND DISCUSSION

Flow Rate During Column Adsorption

Flow rate is an important operational variable in column adsorption because it determines hydraulic retention time and affects the opportunity for pollutants to interact with adsorbent surfaces. The observed flow rates in this study are presented in Table 1.

Table 1. Flow rate of wastewater passing through the adsorption column

Treatment	Replicate 1	Replicate 2	Replicate 3	Average (mL/min)
P1 (1:1)	9.13	8.67	7.85	8.55
P2 (1:2)	8.71	8.12	7.47	8.10
P3 (1:3)	7.77	7.11	6.46	7.11

The flow rate was calculated using:

$$Q = \frac{V}{t}$$

where **Q** is flow rate (mL/min), **V** is volume (mL), and **t** is time (min).

The results show that the average flow rate decreased as the adsorbent ratio increased from 1:1 to 1:3. The highest flow rate was observed in P1 (8.55 mL/min), while the lowest occurred in P3 (7.11 mL/min). This decline suggests that increasing the amount of adsorbent media in the column raised hydraulic resistance and prolonged residence time. A longer contact time generally improves the probability of interaction between contaminants and active adsorption sites, thereby supporting pollutant removal performance. Similar observations regarding the role of contact time and adsorption behavior in palm-based adsorbent systems have been reported by Syukur et al. (2023). However, an excessive reduction in flow rate may also increase the risk of clogging or uneven flow distribution within the column, which can reduce treatment stability.

Total Suspended Solids (TSS)

The initial TSS concentration of the wastewater was **395 mg/L**. After adsorption treatment, TSS increased in all treatments, as presented in Table 2.

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Table 2. TSS of wastewater before and after adsorption treatment

Treatment	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)	Average (mg/L)
Initial sample	395	–	–	395
P1 (1:1)	874	980	1031	961.67
P2 (1:2)	1083	1083	965	1043.67
P3 (1:3)	1021	1096	1107	1074.67

The TSS values after treatment were considerably higher than the initial concentration, indicating that the adsorption column did not reduce suspended solids under the conditions tested. Instead, the average TSS reached 961.67 mg/L in P1, 1043.67 mg/L in P2, and 1074.67 mg/L in P3. This pattern indicates negative removal efficiency.

The increase in TSS was likely caused by the release of fine adsorbent particles from both oil palm fiber and quartz sand during column operation. Residual fine particles that remained after activation and washing may have been carried into the effluent, thereby increasing suspended solids. Chairunnisa and Fuadi (2023) similarly noted that adsorbent-based treatment systems can introduce suspended particles into treated water if adsorbent washing and stabilization are insufficient. In the present study, the results suggest that the media were more effective for removing certain dissolved or colored pollutants than for controlling suspended solids. Therefore, additional washing, stabilization, or post-filtration steps would be necessary if the adsorbent is to be applied for TSS-sensitive wastewater treatment. The one-way ANOVA result for TSS is shown in Table 3.

Table 3. One-way ANOVA for TSS

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	20,454.00	2	10,227.00	2.316	0.18
Within groups	26,497.33	6	4,416.22		
Total	46,951.33	8			

Because the significance value was 0.180 ($p > 0.05$), the adsorbent ratio had no significant effect on TSS. Although TSS increased numerically across treatments, the differences among the three adsorbent ratios were not statistically significant.

Total Dissolved Solids (TDS)

The initial TDS concentration was **1002 ppm**. Similar to TSS, TDS increased after treatment in all adsorption columns (**Table 4**).

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Table 4. TDS of wastewater before and after adsorption treatment

Treatment	Replicate 1 (ppm)	Replicate 2 (ppm)	Replicate 3 (ppm)	Average (ppm)
Initial sample	1002	–	–	1.002
P1 (1:1)	4087	3729	3474	3763.3
P2 (1:2)	6104	3239	2483	3942
P3 (1:3)	7218	4750	3922	5296.7

The average TDS increased to 3763.33 ppm in P1, 3942.00 ppm in P2, and 5296.67 ppm in P3. These results indicate that the adsorption treatment was ineffective for TDS removal and instead contributed additional dissolved material to the effluent.

A plausible explanation is the release of soluble ions from the acid-activated media during contact with wastewater. Acid treatment can alter mineral and lignocellulosic structures, and if the adsorbent is not thoroughly rinsed, residual soluble compounds may leach into the treated water. In addition, prolonged contact between wastewater and adsorbent may cause desorption or dissolution of certain components from the media. Husnawati et al. (2022) explained that dissolved solids in water can be strongly affected by the presence of mineral ions and other soluble substances, while Elsa Tenrilawa (2021) noted that TDS values may rise if dissolved contaminants or fine soluble residues are introduced during treatment. In the present study, the highest TDS was observed in P3, indicating that a greater adsorbent proportion may increase the risk of dissolved ion release. The ANOVA result for TDS is presented in Table 5.

Table 5. One-way ANOVA for TDS

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	4,218,154.667	2	2,109,077.333	0.947	0.439
Within groups	13,366,861.333	6	2,227,810.222		
Total	17,585,016.000	8			

The significance value of 0.439 ($p > 0.05$) indicates that the adsorbent ratio did not significantly affect TDS. Therefore, although TDS increased substantially after treatment, the differences among the three ratios were statistically insignificant. The increase in TSS and TDS after adsorption can be attributed to the release of fine particles and soluble mineral residues from the acid-activated adsorbents. During the adsorption process, some unstable particles detached from the oil palm fiber and quartz sand, increasing the suspended solids concentration. In addition, residual ions remaining after acid activation may have dissolved into the wastewater, contributing to the increase in TDS. Similar findings have been reported in previous studies, indicating that insufficient washing and stabilization of adsorbents may negatively affect TSS and TDS values. Therefore, additional washing or post-filtration is recommended before practical application.

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Color Removal

Color is one of the most visible indicators of wastewater pollution, especially in palm oil-related effluent, which often contains brownish compounds derived from organic matter, colloids, and lignin-based substances. The color removal results are shown in Table 6.

Table 6. Color of wastewater before and after adsorption treatment

Treatment	Replicate 1 (TCU)	Replicate 2 (TCU)	Replicate 3 (TCU)	Average (TCU)	Efficiency (%)
Initial sample	311	–	–	311.00	–
P1 (1:1)	28	29	43	33.33	89.28
P2 (1:2)	19	20	27	22.00	92.93
P3 (1:3)	28	29	31	29.33	90.57

Color removal efficiency was calculated using:

$$\text{Removal Efficiency (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

The initial color concentration of 311 TCU decreased sharply in all treatments. The final average color values were 33.33 TCU in P1, 22.00 TCU in P2, and 29.33 TCU in P3. Removal efficiency ranged from 89.28% to 92.93%, indicating that the adsorption system was highly effective in removing color. The best performance was achieved by P2 (1:2) with 92.93% efficiency.

The strong reduction in color suggests that acid-activated oil palm fiber and quartz sand provided favorable adsorption conditions for chromophoric compounds in the wastewater. Color in industrial wastewater commonly originates from dissolved organic compounds, pigments, lignin derivatives, tannins, and colloidal particles. Acid activation may clean the adsorbent surface, enlarge accessible pores, and increase active adsorption sites, thereby improving the removal of color-causing compounds.

Susmanto et al. (2020) showed that activated adsorbent media in column systems can effectively remove dye-related compounds from wastewater, while Syukur et al. (2023) reported that palm-derived adsorbents were highly effective in removing color from palm oil mill wastewater. In the present study, the combination of oil palm fiber as an adsorptive medium and quartz sand as a supporting filtration medium likely enhanced both adsorption and physical retention of color-forming substances. Although P2 showed the best descriptive performance, statistical testing was required to determine whether the differences among ratios were significant. The ANOVA result is presented in Table 7.

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Table 7. One-way ANOVA for color

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	198.222	2	99.111	3.244	0.111
Within groups	183.333	6	30.556		
Total	381.556	8			

The significance value of 0.111 ($p > 0.05$) indicates that the adsorbent ratio did not significantly affect color removal. Thus, although P2 numerically produced the lowest color value, the differences among P1, P2, and P3 were not statistically significant.

Biochemical Oxygen Demand (BOD)

BOD reflects the biodegradable organic load in wastewater and is a key indicator of treatment performance. The BOD results before and after adsorption treatment are shown in Table 8.

Table 8. BOD of wastewater before and after adsorption treatment

Treatment	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)	Average (mg/L)	Efficiency (%)
Initial sample	121.2	–	–	121.20	–
P1 (1:1)	60.6	53.4	57.9	57.30	52.72
P2 (1:2)	54.3	49.8	42.7	48.93	59.63
P3 (1:3)	44.4	40.8	37.9	41.03	66.15

The initial BOD concentration of 121.20 mg/L decreased in all treatments. The final average BOD values were 57.30 mg/L in P1, 48.93 mg/L in P2, and 41.03 mg/L in P3. The removal efficiency ranged from 52.72% to 66.15%, indicating that the adsorbent system was able to reduce biodegradable organic matter in the wastewater. The best result was obtained in P3 (1:3), which produced the lowest final BOD and the highest removal efficiency.

The decline in BOD indicates that part of the biodegradable organic fraction was retained by the adsorbent media during column operation. A lower BOD means less oxygen is required by microorganisms to decompose organic matter, which reflects improved wastewater quality. The effectiveness of BOD reduction in this study may be attributed to the active surface and porous structure of acid-activated oil palm fiber, which allowed adsorption of dissolved organic compounds. Quartz sand also contributed by stabilizing flow and supporting filtration within the column. Similar improvements in BOD through adsorption-based systems have been reported by Rusdianto et al. (2022), who found that agricultural adsorbents can reduce BOD in domestic wastewater, and by Winardi and Prasetyo (2025), who highlighted the potential of oil-palm-based bioadsorbents for improving palm oil mill wastewater quality.

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Descriptively, BOD removal improved as the adsorbent ratio increased, with the best result obtained at 1:3. This suggests that a larger adsorbent proportion provided more contact area and more active sites for the retention of biodegradable organic compounds. To verify whether these differences were statistically meaningful, ANOVA was performed and the result is shown in Table 9.

Table 9. One-way ANOVA for BOD

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	397.016	2	198.508	10.261	0.012
Within groups	116.073	6	19.346		
Total	513.089	8			

The significance value of 0.012 ($p < 0.05$) indicates that the adsorbent ratio had a significant effect on BOD reduction. Therefore, the composition of quartz sand and oil palm fiber significantly influenced the system's ability to remove biodegradable organic pollutants. Because the ANOVA result was significant, a Duncan Multiple Range Test (DMRT) was conducted to determine the differences among treatments (Table 10).

Table 10. Duncan Multiple Range Test for BOD

Treatment	N	Average BOD (mg/L)	Group
P3 (1:3)	3	41.03	a
P2 (1:2)	3	48.93	b
P1 (1:1)	3	57.30	c

The DMRT result shows that all treatments belonged to different groups, indicating significant differences among all three ratios. P3 (1:3) produced the lowest BOD and was statistically superior to P2 and P1, confirming that the highest proportion of adsorbent in this study provided the best performance for BOD removal.

Chemical Oxygen Demand (COD)

COD represents the total oxygen demand required to oxidize organic and certain inorganic substances chemically. The COD data are presented in Table 11.

Table 11. COD of wastewater before and after adsorption treatment

Treatment	Replicate 1 (mg/L)	Replicate 2 (mg/L)	Replicate 3 (mg/L)	Average (mg/L)	Efficiency (%)
Initial sample	305.8	–	–	305.80	–
P1 (1:1)	219.5	239.7	241.4	233.53	23.63

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P2 (1:2)	293.9	289.4	276.8	286.70	6.25
P3 (1:3)	254.6	243.7	233.8	244.03	20.20

The initial COD concentration was 305.80 mg/L, and all treatments reduced COD to some extent. The lowest final COD concentration was obtained in P1 (233.53 mg/L), followed by P3 (244.03 mg/L) and P2 (286.70 mg/L). COD removal efficiency ranged from 6.25% to 23.63%, which was noticeably lower than the efficiency obtained for color and BOD.

The relatively modest COD reduction indicates that not all oxidizable compounds in the wastewater were effectively adsorbed by the fiber-sand media. COD includes a broader range of compounds than BOD, including non-biodegradable organics and chemically oxidizable substances that may not be easily retained by a simple adsorption system. Faisal et al. (2023) similarly reported that COD removal from palm oil mill wastewater depends strongly on adsorbent characteristics and process conditions. Winardi and Prasetyo (2025) also emphasized that palm-based adsorbents may improve wastewater quality but often require optimization to achieve substantial COD reduction. In this study, the superior performance of P1 suggests that the best COD removal did not necessarily occur at the highest adsorbent proportion. This may be related to the internal arrangement of the media, flow distribution, contact behavior, or localized hydraulic resistance in the column. Syukur et al. (2023) noted that adsorption performance in column systems can be affected not only by adsorbent amount but also by flow dynamics and contact uniformity.

Despite the reduction achieved, none of the treatments lowered COD to the wastewater quality standard of 150 mg/L. This indicates that adsorption using acid-activated oil palm fiber and quartz sand alone was not sufficient to fully treat the chemical pollutant load under the tested conditions. Additional optimization or integration with other treatment methods may therefore be necessary. The ANOVA result for COD is shown in Table 12.

Table 12. One-way ANOVA for COD

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	4757.389	2	2378.694	21.287	0.002
Within groups	670.473	6	111.746		
Total	5427.862	8			

The significance value of 0.002 ($p < 0.05$) indicates that the adsorbent ratio had a significant effect on COD reduction. A DMRT was therefore performed to identify the treatment differences (Table 13).

Table 13. Duncan Multiple Range Test for COD

Treatment	N	Average COD (mg/L)	Group
P1 (1:1)	3	233.53	a
P3 (1:3)	3	244.03	a

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P2 (1:2)	3	286.70	b

The DMRT result shows that P1 and P3 belonged to the same group, meaning they were not significantly different from each other in reducing COD. In contrast, P2 was significantly different and showed the poorest COD removal performance. Therefore, P1 and P3 can be considered the more effective treatments for COD reduction in this study.

pH Change

The pH of wastewater is an important quality parameter because highly acidic or alkaline effluents can be harmful to receiving waters and biological treatment systems. The pH results before and after treatment are shown in Table 14.

Table 14. pH of wastewater before and after adsorption treatment

Treatment	Replicate 1	Replicate 2	Replicate 3	Average pH
Initial sample	4.81	–	–	4.81
P1 (1:1)	9.22	9.12	8.52	8.95
P2 (1:2)	9.18	9.05	6.80	8.34
P3 (1:3)	9.19	9.07	9.01	9.09

The initial wastewater was acidic, with a pH of 4.81. After adsorption treatment, pH increased substantially in all treatments, reaching 8.95 in P1, 8.34 in P2, and 9.09 in P3. This indicates that the adsorption process improved the acidity condition of the wastewater and shifted it toward neutral to slightly alkaline conditions.

The increase in pH suggests that the treatment reduced acidic components or altered the ionic balance of the wastewater during contact with the adsorbent media. Acid-activated oil palm fiber may adsorb part of the dissolved organic compounds contributing to acidity, while quartz sand acts as a supporting filtration medium that stabilizes the treatment process. Anggraini et al. (2022) explained that adsorption processes can influence wastewater pH through the removal of dissolved compounds and changes in hydrogen ion concentration. In this study, the pH improvement is environmentally beneficial because the untreated wastewater was clearly acidic.

When compared with the palm oil mill wastewater quality standard in the Indonesian environmental regulation, the pH values in P1 and P2 remained within or very close to the acceptable range, while P3 slightly exceeded the upper boundary with an average pH of 9.09. Even so, all treatments markedly improved the initial acidic condition of the wastewater.

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The ANOVA result for pH is presented in Table 15.

Table 15. One-way ANOVA for pH

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	0.948	2	0.474	0.732	0.519
Within groups	3.885	6	0.647		
Total	4.833	8			

The significance value of 0.519 ($p > 0.05$) indicates that the adsorbent ratio did not significantly affect pH change. Therefore, although all treatments improved pH substantially, the differences among P1, P2, and P3 were not statistically significant.

Overall Evaluation of Adsorbent Performance

The present study shows that the acid-activated oil palm fiber and quartz sand adsorption system had mixed performance depending on the wastewater parameter evaluated. The media were highly effective for color removal, effective for BOD reduction, and moderately effective for COD reduction, but ineffective for TSS and TDS reduction under the tested conditions. In fact, TSS and TDS increased after treatment, indicating that the adsorbent preparation and column operation still require refinement.

From a performance perspective, P2 (1:2) was the best treatment for color removal, P3 (1:3) was the best for BOD reduction, and P1 (1:1) produced the lowest COD concentration. Statistical analysis further confirmed that adsorbent ratio significantly influenced BOD and COD, but not TSS, TDS, color, or pH. These findings imply that the ratio of oil palm fiber and quartz sand can affect the removal of biodegradable and chemically oxidizable organic pollutants, yet its effect on solids-related parameters is less clear.

The increase in TSS and TDS is a critical limitation of the present adsorption system. This suggests that acid activation and post-activation washing of the adsorbent were not yet fully optimized. Fine particles from the fiber and quartz sand, as well as residual soluble compounds, may have leached into the effluent. Therefore, future improvements should focus on adsorbent stabilization, more intensive washing, optimized particle size selection, and the possible addition of a polishing filtration step after adsorption. Despite these limitations, the results demonstrate that oil-palm-based adsorbent media have promising potential for low-cost wastewater treatment, especially for reducing color and biodegradable organic matter.

CONCLUSION

Acid-activated oil palm fiber and quartz sand adsorbents showed promising potential for wastewater treatment in a column adsorption system, particularly for reducing color and biodegradable organic pollutants. The treatment effectively reduced color, BOD, and COD, while also improving wastewater pH from acidic to near-neutral or alkaline conditions. The best color removal was obtained at the 1:2 adsorbent ratio with a final concentration of 22.00 TCU and 92.93% efficiency, whereas the best BOD removal was achieved at the 1:3 ratio with a final concentration of 41.03 mg/L and 66.15% efficiency. The lowest COD concentration was obtained at the 1:1 ratio, reaching 233.53

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mg/L. Statistical analysis showed that adsorbent ratio significantly affected BOD and COD, but had no significant effect on TSS, TDS, color, or pH. However, the increase in TSS and TDS after treatment indicates that the adsorbent preparation and column operation still require optimization. Overall, acid-activated oil palm fiber and quartz sand can be considered a potential alternative adsorbent medium for wastewater treatment, but further improvement is necessary to minimize solids release and enhance overall treatment efficiency. Based on the Indonesian wastewater quality standards for palm oil mill effluent, the treated wastewater showed satisfactory improvement in pH and BOD. However, the final COD concentration remained above the permissible limit of 150 mg/L. Likewise, TSS and TDS increased after treatment, indicating that the adsorption system still requires further optimization before large-scale application. Nevertheless, the remarkable color removal efficiency demonstrates that the combined adsorbent has strong potential as a polishing treatment for palm oil mill wastewater.

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