Combination of Aeration-Adsorption Using Diffuser Aerator and Palmyra Palm Shell Activated Carbon For Groundwater Quality Improvement

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Abstract

This study examines the use of a combined aeration-adsorption process utilizing activated carbon derived from Borassus flabellifer (palmyra palm shell) to improve groundwater quality. The aeration process increases dissolved oxygen (DO) levels, facilitating the oxidation of metal contaminants such as iron (Fe) and manganese (Mn). Meanwhile, the activated carbon is used to adsorb any remaining contaminants that are not fully oxidized. The results show that with a 60-minute aeration time, the DO concentration increased to 6.6 mg/L, and Fe and Mn concentrations were reduced by 53.6% and 7.7%, respectively. In the adsorption phase, optimal conditions were achieved at a flow rate of 10 L/h and an adsorption media height of 45 cm, resulting in Fe removal of 63.19%, Mn removal of 99.25%, TDS reduction of 15.51%, and TOC reduction of 17.61%. These findings support the use of the combined aeration-adsorption process as a more environmentally friendly and efficient method for groundwater treatment.

Keywords: *aeration, adsorption, activated carbon, palmyra palm shell, groundwater quality*

Abstrak

Penelitian ini mengkaji penggunaan proses gabungan aerasi-adsorpsi dengan memanfaatkan karbon aktif yang berasal dari Borassus flabellifer (tempurung lontar) untuk meningkatkan kualitas air tanah. Proses aerasi meningkatkan kadar oksigen terlarut (DO), yang memfasilitasi oksidasi kontaminan logam seperti besi (Fe) dan mangan (Mn). Sementara itu, karbon aktif digunakan untuk mengadsorpsi sisa kontaminan yang belum sepenuhnya teroksidasi. Hasil penelitian menunjukkan bahwa dengan waktu aerasi selama 60 menit, konsentrasi DO meningkat menjadi 6,6 mg/L, dan konsentrasi Fe dan Mn berkurang masing- masing sebesar 53,6% dan 7,7%. Pada proses adsorpsi, kondisi optimal dicapai pada laju aliran 10 L/jam dan ketinggian media adsorpsi 45 cm, menghasilkan penghilangan Fe sebesar 63,19%, penghilangan Mn sebesar 99,25%, pengurangan TDS sebesar 15,51%, dan pengurangan TOC sebesar 17,61%. Temuan ini mendukung penggunaan proses gabungan aerasi-adsorpsi sebagai metode yang lebih ramah lingkungan dan efisien untuk pengolahan air tanah.

Kata Kunci: *aerasi, adsorpsi, karbon aktif, tempurung lontar, kualitas air tanah*

1. Introduction

Groundwater is one of the primary water sources used to meet domestic, agricultural, and industrial needs. However, groundwater quality often does not meet the required standards due to the presence of various contaminants, such as heavy metals and organic compounds. Iron (Fe) and manganese (Mn) are two types of dissolved metals commonly found in groundwater, especially in areas with specific geological characteristics. Excessive concentrations of iron and manganese can pose health risks to humans and damage piping infrastructure and water distribution systems [1].

Although various water treatment methods have been developed to address these issues, such as chemical oxidation, filtration, and precipitation, these methods generally have some drawbacks, such as excessive chemical usage, high operational costs, and limited efficiency in reducing contaminants at low concentrations [1], [2]. Therefore, this study proposes an alternative solution that is more environmentally friendly and efficient: a combination of aeration and adsorption processes using natural materials as adsorbent media.

The aeration process is used to increase the dissolved oxygen (DO) content in water. The increase in DO triggers oxidation reactions of contaminants such as Fe and Mn, which then form precipitates that are easier to remove in subsequent treatment stages. Meanwhile, the adsorption process using activated carbon derived from palmyra shell (Borassus flabellifer) aims to adsorb residual contaminants that are not fully oxidized during the aeration stage. Palmyra shell was selected as an adsorbent due to its well- developed pore structure and abundant availability, making it an effective and economical adsorbent [3].

This research focuses on developing a combination of aeration-adsorption processes to reduce iron (Fe), manganese (Mn), Total Dissolved Solids (TDS), and Total Organic Carbon (TOC) concentrations in groundwater. By utilizing activated carbon derived from palmyra shell as the adsorption medium, this study aims to determine the influence of aeration detention time, variations in adsorption media height, and flow rate on groundwater quality improvement. In addition, this research evaluates the most suitable adsorption isotherm model among the Freundlich, Langmuir, and BET isotherms to describe the adsorption process on the activated carbon used.

To date, research on the utilization of palmyra shell as a base material for activated carbon in groundwater treatment remains limited. Therefore, this research is expected to contribute scientifically to the development of more efficient and environmentally friendly water treatment methods. Moreover, the combination of aeration and adsorption processes is expected to serve as a more economical alternative for application on a larger scale, especially in areas facing groundwater quality issues.

This paper is structured as follows: Section 2 describes the research methodology, including the experimental design, variables used, and data processing and analysis techniques. Section 3 presents the research results and discusses the effects of varying aeration detention time and adsorption media height on groundwater quality. Section 4 concludes the main findings of this research and provides recommendations for future studies.

2. Material and Methods

Experimental Design

This study was conducted using a laboratory-scale experimental approach to evaluate the effectiveness of a combined aeration and adsorption process in improving groundwater quality. The experiment was designed to examine the influence of aeration detention time, variations in adsorption media height, and flow rate on the reduction of iron (Fe), manganese (Mn), Total Dissolved Solids (TDS), and Total Organic Carbon (TOC) concentrations. Groundwater samples were collected from local sources and treated under predetermined conditions.

Preparation of Activated Carbon

Activated carbon was produced from palmyra palm shells (Borassus flabellifer) through a carbonization process at a temperature of 400–500°C for 2 - 4 hours. After the carbonization process, the produced carbon was soaked in a 20% Na_2CO_3 solution for 48 hours to activate its surface area. The carbon was then rinsed using deionized water until reaching a neutral pH and dried at 105°C. *Experimental Setup and Procedure*

The experiment was conducted in two stages: aeration and adsorption. The experimental setup consists of several main components, as shown in **Figure 1**.

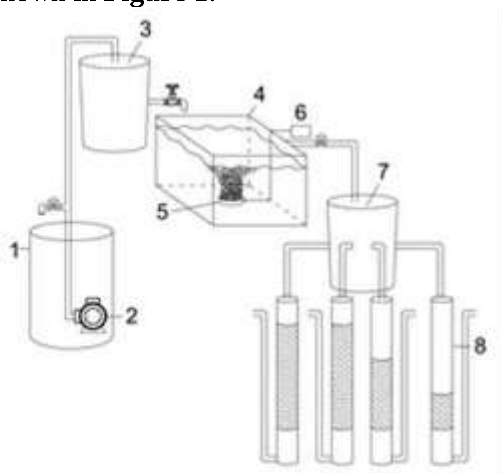

Figure 1. Reactor Configuration for Combined Aeration and Adsorption Processes

Description of the Setup:

- Overflow Tank (1): This tank serves as the initial water reservoir before being pumped to the aeration tank.
- Water Pump (2): Transfers the water from the overflow tank to the holding tank.
- Holding Tank (3): Stores water temporarily before it is introduced to the aeration tank.

- Aeration Tank (4): A 40-liter tank equipped with a diffuser aerator (5) for dispersing oxygen bubbles throughout the water.
- Diffuser Aerator (5): Produces small air bubbles to increase the dissolved oxygen content and oxidize Fe and Mn.
- Aerator Pump (6): Supplies air to the diffuser to maintain a consistent oxygen flow.
- Transition Tank (7): Holds the aerated water before it is passed through the adsorption columns.
- Adsorption Columns (8): Three adsorption columns containing different heights of activated carbon (15 cm, 30 cm, and 45 cm) to evaluate the effect of media height and flow rate on contaminant removal.

Water flows through the aeration tank, where it undergoes oxidation, and then moves into the adsorption columns, where it interacts with activated carbon media to reduce contaminant concentrations.

Measurement of Water Quality Parameter

Water quality parameters were measured before and after each treatment process. Dissolved Oxygen (DO) was measured using a DO meter, while Fe and Mn concentrations were determined using a spectrophotometer. TOC was analyzed using a TOC analyzer, and TDS was measured with a turbidimeter.

Data Analysis

Data obtained from the experiments were analyzed using statistical methods to determine the relationship between the independent variables (aeration detention time, adsorption media height, and flow rate) and the dependent variables (reduction of Fe, Mn, TDS, and TOC concentrations). The results were presented in tables and graphs to facilitate interpretation and discussion.

3. Results and Discussion

3.1 Aeration Process

Effect of Aeration Detention Time on Dissolved Oxygen (DO) Increase

The aeration process is used to increase the dissolved oxygen (DO) content in groundwater. Based on the measurement results, the initial DO concentration of groundwater was 0.8 mg/L. After aeration for 20 minutes, 40 minutes, and 60 minutes, the DO concentration increased to 4.3 mg/L, 5.1 mg/L, and 6.6 mg/L, respectively.

Table 1. The Effect of Aeration Detention Time on Dissolved Oxygen (DO) Concentration

Aeration Detention Time (minutes)	Initial DO (mg/L)	Final DO (mg/L)	Increase in DO (mg/L)
20	0.8	4.3	3.5
40	0.8	5.1	4.3
60	0.8	6.6	5.8

This increase in DO is due to the mass transfer of oxygen from the air to water triggered by the diffuser aerator, resulting in a significant rise in oxygen content within the water. The results show that a detention time of 60 minutes provided the highest DO increase, reaching 5.8 mg/L. However, at longer detention times, the rate of DO increase tends to decrease as the water reaches an oxygen saturation condition [4].

The significant increase in DO content plays an essential role in facilitating the oxidation reactions of Fe and Mn, which convert dissolved metals into precipitates that are easier to remove in subsequent treatment stages [5], [6].

The figure above illustrates the trend of DO increase at each aeration detention time. It can be observed that the DO concentration increases significantly with increasing detention time, with the highest value recorded at 60 minutes. However, the rate of increase tends to plateau as the water approaches oxygen saturation.

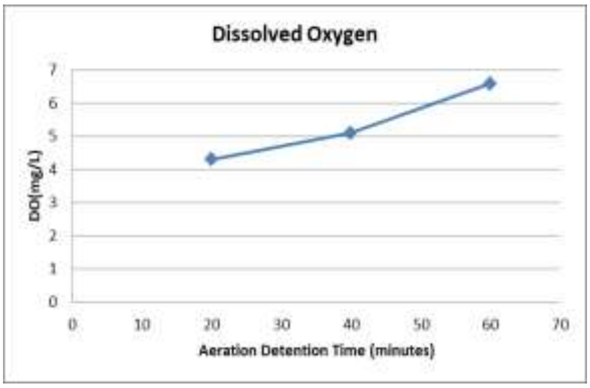

Figure 2. Effect of Aeration Detention Time on Dissolved Oxygen (DO) Increase

Reduction of Fe and Mn Concentration

The aeration process shows a decrease in the dissolved metal content, such as iron (Fe) and manganese (Mn), in groundwater at different aeration detention times. Based on **Table 2**, the reduction in Fe and Mn concentrations varies for each aeration detention time applied.

At a detention time of 20 minutes, the Fe concentration decreased from 0.743 mg/L to 0.684 mg/L, equivalent to a reduction of 0.059 mg/L or 7.9%. Meanwhile, at 40 minutes, the Fe concentration decreased by 13.7% to 0.641 mg/L. The greatest reduction occurred at a detention time of 60 minutes, where the final Fe concentration reached 0.345 mg/L, with a total reduction of 53.6%. This significant reduction indicates that a longer detention time allows for a more effective oxidation process of Fe^{2+} to Fe^{3+}, forming $Fe(OH)_3$ precipitates that are easier to remove during subsequent treatment stages [7], [8].

Table 3 shows the reduction in Mn concentration at the same aeration detention times. At a detention time of 20 minutes, the Mn concentration decreased from 2.09 mg/L to 2.02 mg/L, equivalent to a reduction of 0.07 mg/L or 3.3%. At a detention time of 40 minutes, the Mn reduction was greater, reaching 3.8%. The 60-minute detention time resulted in the most significant Mn reduction, where the final Mn concentration reached 1.93 mg/L, with a total reduction of 7.7%.

The smaller reduction in Mn concentration compared to Fe is due to the characteristics of Mn, which is more difficult to oxidize than Fe at low pH conditions. The oxidation of Mn requires a higher pH condition to form MnO_2 precipitates that are insoluble in water [9].

Table 2. Influence of Aeration Detention Time on Iron (Fe) Reduction

Aeration Detention Time (minutes)	Initial Fe (mg/L)	Final Fe (mg/L)	Fe Reduction (%)
20	0.743	0.684	7.9
40	0.743	0.641	13.7
60	0.743	0.345	53.6

Table 3. Influence of Aeration Detention Time on Manganese (Mn) Reduction

Aeration Detention Time (minutes)	Initial Mn (mg/L)	Final Mn (mg/L)	Mn Reduction (%)
20	2.09	2.02	3.3
40	2.09	2.01	3.8
60	2.09	1.93	7.7

The graph in **Figure 3** shows that the longer the aeration detention time, the greater the reduction in Fe and Mn concentrations. However, the reduction in Fe concentration is more significant than that of Mn at the same detention time. This is due to the optimal conditions required for Mn oxidation being higher than those for Fe. A longer detention time provides sufficient time for the oxidation reaction to occur, resulting in more stable precipitates [8].

The graph shows that the most significant reduction in Fe and Mn concentrations occurred at a detention time of 60 minutes, where the Fe reduction percentage reached 53.6% and Mn reached 7.7%. This indicates that a 60-minute aeration detention time is the optimal duration to reduce Fe and Mn metal content in groundwater.

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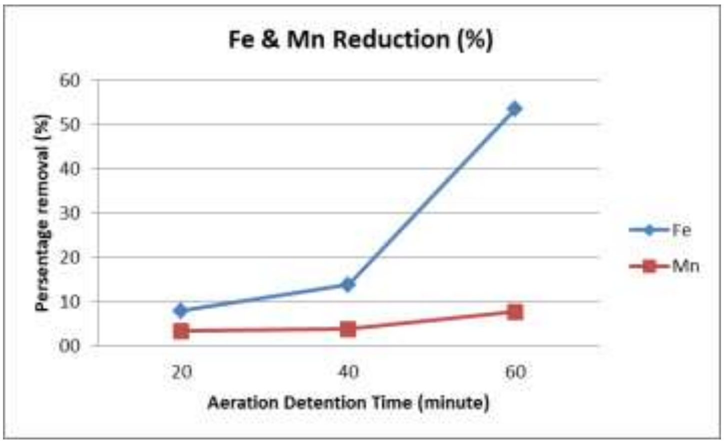


Figure 3. Influence of Aeration Detention Time on Fe and Mn Reduction

3.2 Adsorption Process

Reduction of Fe Concentration Based on Adsorption Media Height and Flow Rate

The adsorption process using activated carbon derived from palmyra palm shell showed a significant reduction in iron (Fe) concentration in groundwater. The Fe removal percentage is influenced by the variation in the height of the adsorption media and the flow rate applied.

Based on **Table 4**, it can be observed that a lower flow rate and a higher adsorption media height resulted in a greater Fe reduction. At a flow rate of 10 L/hour and a media height of 45 cm, the Fe removal percentage reached 63.19%, with the final Fe concentration being 0.127 mg/L, reduced from an initial concentration of 0.345 mg/L. This indicates that the longer contact time between water and the adsorption media at a lower flow rate allows the adsorption process to proceed more effectively [10].

Additionally, the effect of adsorption media height is also significant. At every flow rate, the higher the adsorption media (15 cm, 30 cm, 45 cm), the greater the Fe removal percentage. For instance, at a flow rate of 15 L/hour, the Fe removal increased from 29.33% at a media height of 15 cm to 60.37% at a media height of 45 cm. This phenomenon shows that as the adsorption media height increases, the larger the surface area available for interaction between water and activated carbon, allowing more Fe ions to be adsorbed by the activated carbon [11].

Table 4. Effect of Adsorption Media Height and Flow Rate on Iron (Fe) Reduction

Laju Alir	Tinggi Media Karbon Aktif	Kandungan Fe Awal	Kandungan Fe Akhir	Presentase Removal Fe (%)
30 L/jam	15 cm	0.684	0.540	21.05
30 L/jam	30 cm	0.684	0.504	26.35
30 L/jam	45 cm	0.684	0.504	26.32
15 L/jam	15 cm	0.641	0.453	29.33
15 L/jam	30 cm	0.641	0.381	40.54
15 L/jam	45 cm	0.641	0.254	60.37
10 L/jam	15 cm	0.345	0.240	30.43
10 L/jam	30 cm	0.345	0.179	48.20
10 L/jam	45 cm	0.345	0.127	63.19

Figure 4 illustrates the relationship between adsorption media height, flow rate, and Fe removal percentage. The figure shows that as the adsorption media height increases and the flow rate decreases, the Fe removal also increases. The combination of a 45 cm media height and a flow rate of 10 L/hour resulted in the highest Fe removal.

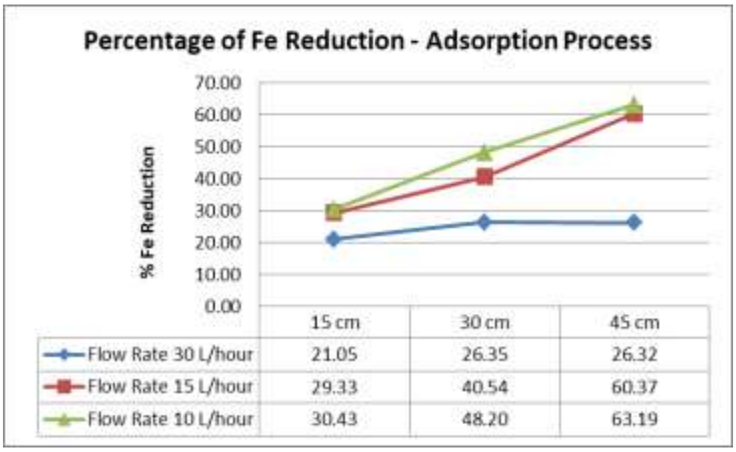


Figure 4. Effect of Adsorption Media Height and Flow Rate on Iron (Fe) Reduction

This figure confirms that the optimal condition for Fe removal is achieved at a slower flow rate, which allows for a longer contact time between water and the adsorption media, and the use of a higher adsorption media height, which increases the surface area for ion interaction [10].

Reduction of Mn Concentration Based on Adsorption Media Height and Flow Rate

The adsorption process using activated carbon derived from palmyra palm shell showed a significant reduction in manganese (Mn) concentration in groundwater. The Mn removal percentage is influenced by variations in the adsorption media height and flow rate applied.

From **Table 5**, it can be observed that a lower flow rate and a higher adsorption media height resulted in a greater Mn reduction. At a flow rate of 10 L/hour and a media height of 45 cm, the Mn removal percentage reached up to 99.25%, with the final Mn concentration being 0.015 mg/L from an initial concentration of 1.93 mg/L. This indicates that the lower flow rate allows for a longer contact time between water and the adsorption media, enhancing the efficiency of the adsorption process [12].

The effect of adsorption media height is also significant. At every flow rate, an increase in adsorption media height (15 cm, 30 cm, and 45 cm) led to a higher Mn removal percentage. For example, at a flow rate of 15 L/hour, the Mn removal increased from 9.45% at a media height of 15 cm to 52.74% at a media height of 45 cm. This trend suggests that as the adsorption media height increases, a larger surface area is available for the interaction between water and activated carbon, allowing more Mn ions to be adsorbed [13].

Table 5. Effect of Adsorption Media Height and Flow Rate on Manganese (Mn) Reduction

Flow Rate (L/hour)	Adsorption Media Height (cm)	Initial Mn (mg/L)	Final Mn (mg/L)	Mn Reduction (%)
30 L/jam	15 cm	2.02	1.93	4.46
30 L/jam	30 cm	2.02	1.82	9.90
30 L/jam	45 cm	2.02	1.60	20.79
15 L/jam	15 cm	2.01	1.82	9.45
15 L/jam	30 cm	2.01	1.57	21.89
15 L/jam	45 cm	2.01	0.95	52.74
10 L/jam	15 cm	1.93	0.14	92.95
10 L/jam	30 cm	1.93	0.01	99.25
10 L/jam	45 cm	1.93	0.015	99.25

The results presented in **Table 5** indicate that the optimal condition for Mn removal is achieved at a flow rate of 10 L/hour and a media height of 45 cm. Under these conditions, the adsorption process reached a removal efficiency of 99.25%, suggesting that the combination of low flow rate and high adsorption media height maximizes the contact time and surface area available for Mn ion adsorption.

This finding is further illustrated in **Figure 5**, where the Mn removal percentage is plotted against adsorption media height at different flow rates. The trend confirms that the Mn removal percentage increases as the adsorption media height increases and the flow rate decreases, highlighting the importance of optimizing both parameters to achieve maximum removal efficiency [12], [13].

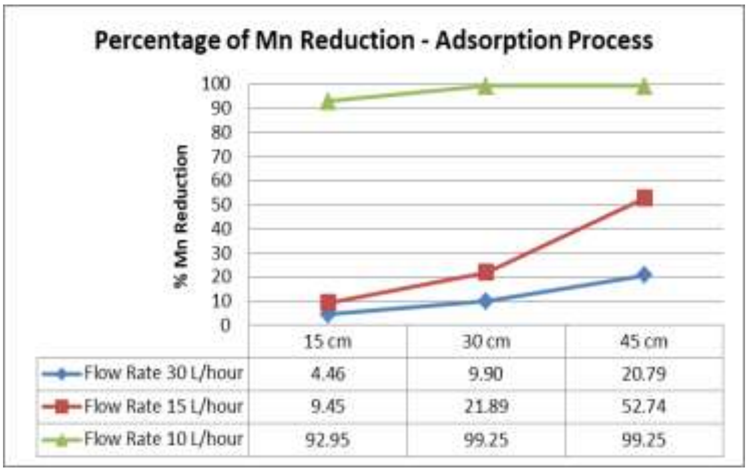


Figure 5. Effect of Adsorption Media Height and Flow Rate on Manganese (Mn) Reduction

The optimal condition for Mn reduction is thus achieved at a flow rate of 10 L/hour with media height of 30 and 45 cm, which allows for a longer contact time and a larger surface area, enhancing the adsorption capacity of the activated carbon derived from palmyra palm shell.

Reduction of Total Organic Carbon (TOC) Based on Adsorption Media Height and Flow Rate

The adsorption process using activated carbon derived from palmyra palm shell showed a reduction in Total Organic Carbon (TOC) content in groundwater. The TOC removal percentage is influenced by variations in adsorption media height and flow rate applied.

Based on Table 6, it can be observed that a lower flow rate and a higher adsorption media height result in a more significant TOC reduction. At a flow rate of 10 L/h and a media height of 30 cm, the TOC removal percentage reached 9.40%, with a final TOC concentration of 10.60 mg/L from an initial concentration of 11.70 mg/L. This indicates that a lower flow rate allows for longer contact time between water and the adsorption media, thereby enhancing the efficiency of organic compound adsorption by activated carbon [14].

In addition, the effect of adsorption media height also significantly contributes to TOC reduction. At each flow rate, an increase in adsorption media height (15 cm, 30 cm, and 45 cm) results in a greater TOC removal percentage. For example, at a flow rate of 30 L/h, the TOC reduction increased from 2.70% at a media height of 15 cm to 17.21% at a media height of 45 cm. This shows that as the adsorption media height increases, the surface area available for contact between water and activated carbon expands, allowing more organic compounds to be absorbed by the activated carbon [15].

However, at a flow rate of 15 L/h, increasing the adsorption media height from 30 cm to 45 cm actually decreased the TOC removal percentage from 21.81% to 16.23%. This phenomenon could be due to saturation occurring in the adsorption media, preventing the activated carbon from effectively adsorbing organic compounds. Thus, at a certain media height, the flow rate and media thickness should be considered to avoid adsorption saturation [16].

Table 6. Effect of Adsorption Media Height and Flow Rate on Total Organic Carbon (TOC) Reduction

Flow Rate (L/hour)	Adsorption Media Height (cm)	Initial TOC (mg/L)	Final TOC (mg/L)	TOC Reduction (%)
30 L/hour	15 cm	11.10	10.80	2.70
30 L/hour	30 cm	11.10	10.30	7.21
30 L/hour	45 cm	11.10	9.19	17.21
15 L/hour	15 cm	9.49	9.23	2.74
15 L/hour	30 cm	9.49	7.42	21.81
15 L/hour	45 cm	9.49	7.95	16.23
10 L/hour	15 cm	11.70	10.80	7.69
10 L/hour	30 cm	11.70	10.60	9.40
10 L/hour	45 cm	11.70	9.640	17.61

The results presented in **Table 6** show that the optimal condition for TOC reduction is achieved at a flow rate of 15 L/h and a media height of 30 cm, with a TOC reduction percentage of 21.81%. This indicates that a greater media height enables better adsorption of organic compounds at a lower flow rate [15].

These findings are illustrated in Figure 6, which shows the TOC removal percentage plotted against the adsorption media height at various flow rates. The trend confirms that TOC removal increases with increasing adsorption media height and decreasing flow rate, but attention should be given to potential saturation at certain media heights.

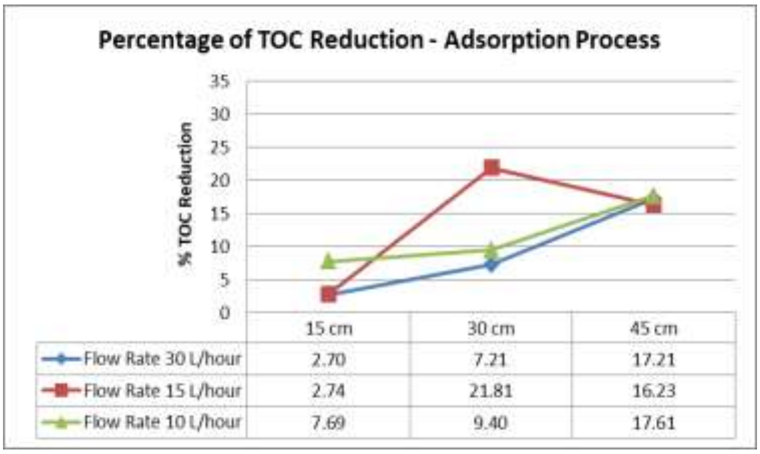


Figure 6. Effect of Adsorption Media Height and Flow Rate on Total Organic Carbon (TOC) Reduction

The optimal condition for TOC reduction is achieved at a flow rate of 15 L/h and a media height of 30 cm, which allows for a larger surface area and longer contact time between water and activated carbon derived from palmyra palm shell.

Reduction of Total Dissolved Solids (TDS) Based on Adsorption Media Height and Flow Rate

Total Dissolved Solids (TDS) refer to the sum of all dissolved substances in water, including inorganic salts and small amounts of organic matter. The reduction of TDS in groundwater using the adsorption process with activated carbon from palmyra palm shells is influenced by the height of the adsorption media and the flow rate. The data show that the efficiency of TDS reduction varies depending on these two parameters.

As seen in **Table 7**, the reduction in TDS is more pronounced at a flow rate of 10 L/h compared to higher flow rates. At a flow rate of 10 L/h and an adsorption media height of 45 cm, the TDS reduction percentage reached 15.51%, with the final TDS concentration at 376 mg/L, reduced from an initial concentration of 445 mg/L. This indicates that a lower flow rate allows for longer contact time between the water and the adsorption media, enhancing the efficiency of the adsorption process [17].

However, the increase in adsorption media height does not always result in a proportional improvement in TDS reduction. For instance, at a flow rate of 10 L/h, the TDS reduction increased significantly from 0.22% at a media height of 15 cm to 15.51% at a media height of 45 cm. This suggests that higher media heights allow for a larger surface area of contact, facilitating better adsorption of dissolved solids.

At higher flow rates, the TDS reduction percentages were notably lower. For example, at a flow rate of 30 L/h, the TDS reduction was 5.82% at a media height of 45 cm, compared to 15.51% at the same media height and a lower flow rate. This confirms that a slower flow rate leads to more effective adsorption, allowing for a more significant reduction in TDS [18].

Table 7. Effect of Adsorption Media Height and Flow Rate on Total Dissolved Solids (TDS) Reduction

Flow Rate (L/h)	Adsorption Media Height (cm)	Initial TDS (mg/L)	Final TDS (mg/L)	TDS Reduction (%)
30 L/jam	15 cm	378	365	3.44
30 L/jam	30 cm	378	365	3.44
30 L/jam	45 cm	378	356	5.82
15 L/jam	15 cm	424	397	6.37
15 L/jam	30 cm	424	394	7.08
15 L/jam	45 cm	424	378	10.85
10 L/jam	15 cm	445	444	0.22
10 L/jam	30 cm	445	400	10.11
10 L/jam	45 cm	445	376	15.51

The results indicate that the optimal condition for TDS reduction is achieved at a flow rate of 10 L/h and a media height of 15 cm. Under these conditions, the activated carbon can adsorb more dissolved ions in water, significantly reducing the TDS concentration in groundwater.

This finding is also illustrated in **Figure 7**, which shows that TDS reduction tends to decrease at higher media heights and faster flow rates. This trend indicates that optimizing the media height and flow rate is essential to enhance the efficiency of the TDS adsorption process.

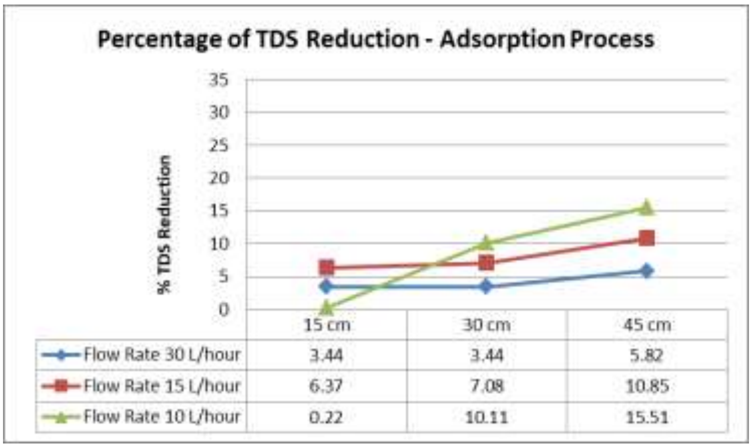


Figure 7. Effect of Adsorption Media Height and Flow Rate on Total Dissolved Solids (TDS) Reduction

3.3 Characterization of Palmyra Palm Shell Activated Carbon Using SEM-EDX

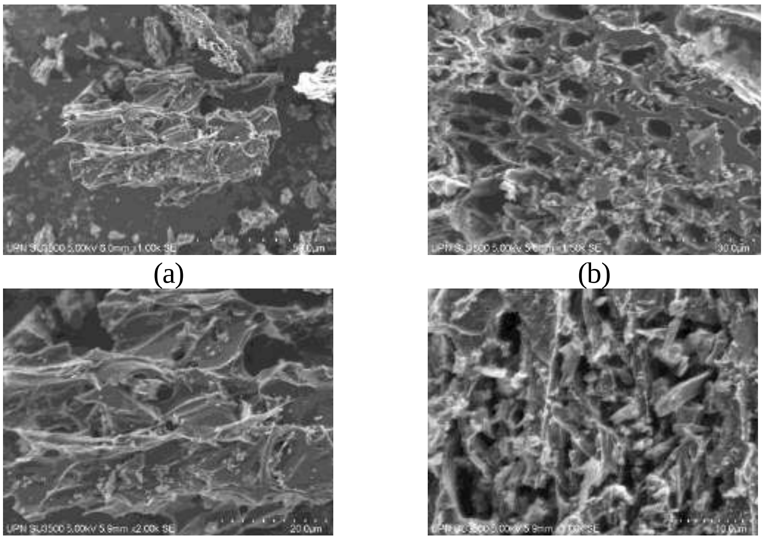
This section describes the morphological and elemental characterization of activated carbon derived from Borassus flabellifer (Palmyra palm shell) using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX). These tests aim to identify the pore structure of the activated carbon and the elemental composition that can affect its effectiveness as an adsorbent in groundwater treatment.

SEM Analysis

The SEM results (**Figure 8**) show the surface structure of the activated carbon with well-developed pore formations. The pore structure observed in the SEM images is crucial for understanding the adsorptive properties of this material, as the pores play a role in capturing contaminants such as iron (Fe) and manganese (Mn) ions during the adsorption process [19].

The SEM images reveal a distribution of pores of varying sizes. The macro and mesopores observed indicate that this activated carbon has good potential for adsorbing large organic molecules as well as dissolved metal ions. This structure also indicates a large surface area, which is a key characteristic of an effective adsorbent material.

Larger pores allow contaminated water to flow through the material more easily, while smaller pores provide more surface area for contact between the dissolved metal ions and the surface of the activated carbon, increasing the adsorption efficiency [20], [21].



(a) (b) (c) (d)

Figure 8. SEM Images of Palmyra Shell Activated Carbon at Magnifications of (a) 1000x, (b) 1500x, (c) 2000x, and (d) 3000x

EDX Analysis

The elemental composition of activated carbon was analyzed using Energy Dispersive X-ray Spectroscopy (EDX), and the results are summarized in **Table 8**. This analysis reveals the presence of carbon (C), oxygen (O), sodium (Na), and calcium (Ca) in the sample. The weight and atomic percentages can be seen in **Table 8**.

Table 8. Elemental composition of activated carbon based on EDX analysis.

Element	Weight (%)	Atomic (%)
C (Carbon)	58.07	71.19
O (Oxygen)	22.76	20.94
Na (Sodium)	3.02	1.93
Ca (Calsium)	16.15	5.93

The high carbon content (58.07% by weight) indicates that the carbonization process successfully produced a carbon-rich material, which is essential for adsorption. The presence of oxygen (22.76% by weight) suggests the formation of surface oxides that can enhance adsorption capacity through interaction with metal ions [22]. Additionally, the detection of calcium (16.15%) and sodium (3.02%) may originate from residual elements in the precursor material or from the activation process. These results confirm that the activated carbon is highly suitable for adsorption applications, with a high carbon content and the presence of other elements that can support the material's ability to adsorb contaminants.

In addition to the quantitative data, the EDX spectrum (**Figure 9**) provides a visual representation of the elemental composition. The peaks in this spectrum correspond to the detected elements, confirming the presence of carbon, oxygen, sodium, and calcium, as detailed in **Table 8**.

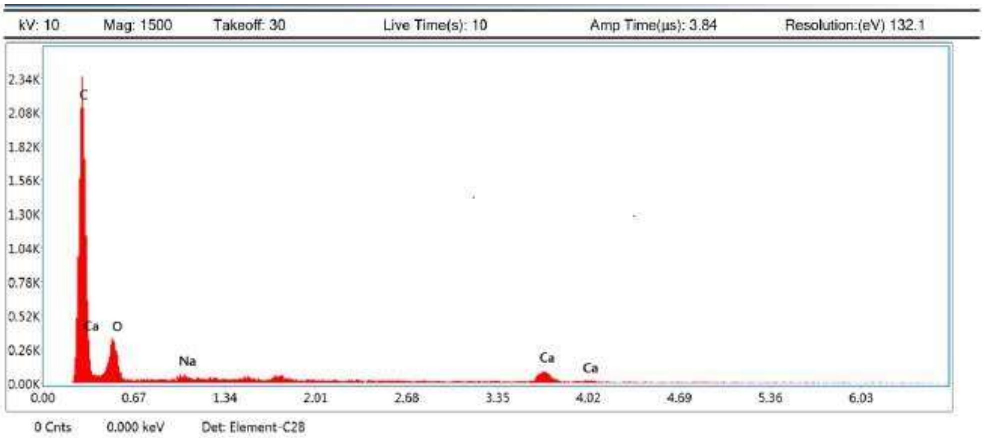


Figure 9. EDX spectrum of activated carbon derived from Borassus flabellifer at 1500x magnification

The peaks represent the presence of carbon (C), oxygen (O), sodium (Na), and calcium (Ca), confirming the elemental composition described in Table 8. This elemental composition highlights the material's potential as an adsorbent in groundwater treatment, particularly for removing metals and organic compounds. The high carbon content also suggests that the material offers good adsorption efficiency, as carbon-rich materials tend to have a larger surface area and higher adsorption capacity [23], [24].

4. Conclusion

This study successfully demonstrated that the combination of aeration and adsorption using activated carbon from Borassus flabellifer (palmyra palm shell) is effective in reducing concentrations of iron (Fe), manganese (Mn), Total Dissolved Solids (TDS), and Total Organic Carbon (TOC) in groundwater. The aeration process increased the dissolved oxygen (DO) level, which facilitated the oxidation of Fe and Mn. A 60-minute aeration time led to a 53.6% reduction in Fe and a 7.7% reduction in Mn. During the adsorption process, the optimal conditions for Fe and Mn removal were achieved with a flow rate of 10 L/h and an adsorption media height of 45 cm, resulting in Fe reduction by 63.19% and Mn reduction by 99.25%. Additionally, the process was effective in reducing TDS by 15.51% and TOC by 17.61%. These results suggest that the combination of aeration and adsorption is a viable and environmentally friendly solution for groundwater treatment, with significant potential for large-scale application.

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