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Continuous Fixed-Bed Treatment of Rice Industry Wastewater Using Carbonized Coconut Shell Powder as a Natural Adsorbent

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Abstract
Rice industry wastewater contains high concentrations of organic matter, suspended solids, and dissolved pollutants that require effective treatment before discharge. This study evaluated the performance of carbonized coconut shell powder as a natural adsorbent in a continuous fixed-bed column under varying bed heights and flow rates. The optimum operating conditions were a bed height of 4.5 cm and a flow rate of 5 mL min^{-1}. Under these conditions, maximum removal efficiencies of 90% for COD, 90% for turbidity, 87% for colour, and 74% for TDS were achieved. These findings demonstrate that carbonized coconut shell powder is an efficient, sustainable, and low-cost adsorbent for rice industry wastewater treatment.

Keywords: Rice industry wastewater, carbonized coconut shell powder, Natural adsorbent, Fixed-bed column, Bed height, Flow rate, COD removal, Turbidity removal, Wastewater treatment.

1. Introduction

Rice is one of the most important agricultural commodities worldwide, and its processing generates large volumes of wastewater containing high concentrations of organic matter, suspended solids, starch residues, bran particles, and dissolved impurities. The direct discharge of untreated rice industry wastewater into natural water bodies can cause serious environmental problems, including depletion of dissolved oxygen, deterioration of water quality, eutrophication, and adverse impacts on aquatic ecosystems. Therefore, effective treatment of rice industry wastewater is essential to ensure compliance with environmental discharge standards and to protect water resources [1], [2].

Among the various wastewater treatment technologies, adsorption has emerged as one of the most efficient and economical methods because of its simplicity, low operating cost, high pollutant removal efficiency, and ease of operation. Compared with conventional chemical and biological treatment methods, adsorption using natural adsorbents has attracted considerable attention owing to the abundance, renewability, and environmental compatibility of agricultural by-products. Carbon-based adsorbents are particularly effective because of their well-developed pore structure, large specific surface area, and abundance of surface functional groups that facilitate the adsorption of organic and inorganic pollutants from wastewater [3], [4].

Carbonized coconut shell powder is a promising natural adsorbent produced through the controlled carbonization of coconut shells, an abundant agricultural waste generated in tropical countries. The carbonization process enhances the porosity, surface area, and adsorption capacity of the material, making it suitable for removing dissolved organic matter, suspended solids, colour-causing compounds, and other contaminants from wastewater. Previous studies have reported that carbonized coconut shell-based adsorbents exhibit excellent adsorption performance because of their microporous structure and strong affinity for a wide range of pollutants [5], [7]. In addition to its high treatment efficiency, carbonized coconut shell powder is inexpensive, readily available, renewable, and environmentally sustainable, making it an attractive alternative to commercial activated carbon [5], [8].

Continuous fixed-bed adsorption systems are widely employed in wastewater treatment because they provide continuous operation, efficient contact between wastewater and adsorbent particles, and are easily scalable for industrial applications. The adsorption performance of fixed-bed columns is strongly influenced by operating parameters such as bed height and influent flow rate. Increasing the bed height generally enhances pollutant removal by increasing the quantity of adsorbent and extending the contact time between the wastewater and the adsorbent bed, whereas increasing the flow rate often results in earlier breakthrough because of reduced hydraulic retention time [7], [9], [10].

Although several studies have investigated coconut shell-derived adsorbents for the treatment of different industrial wastewaters, limited research has specifically examined the continuous fixed-bed treatment of rice industry wastewater using carbonized coconut shell powder under varying bed heights and flow rates. Furthermore, information regarding the breakthrough behaviour and optimization of operating conditions for this adsorbent remains limited. Addressing these knowledge gaps is important for developing efficient and sustainable treatment systems for agro-industrial wastewater.

Therefore, the present study aimed to evaluate the performance of carbonized coconut shell powder as a natural adsorbent for the continuous fixed-bed treatment of rice industry wastewater. Specifically, the study investigated the effects of bed height and influent flow rate on the removal of chemical oxygen demand (COD), turbidity, colour, and total dissolved solids (TDS), analysed breakthrough behaviour under continuous flow conditions, and identified the optimum operating conditions for efficient wastewater treatment. The findings of this study provide valuable information for the development of low-cost, sustainable, and environmentally friendly adsorption systems suitable for rice-processing industries.

2. Materials and Methodology

2.1 Collection of Rice Industry Wastewater

Rice industry wastewater was collected from the equalization tank of a local rice processing industry in Karnataka, India. The wastewater was transported to the Environmental Engineering Laboratory in clean polyethylene containers and stored at 4 °C prior to analysis to minimize biological degradation. Before each experiment, the wastewater was brought to room temperature and thoroughly mixed to ensure sample homogeneity. The initial physicochemical characteristics, including pH, chemical oxygen demand (COD), turbidity, colour, and total dissolved solids (TDS), were determined according to Standard Methods for the Examination of Water and Wastewater.

Table 1. Characteristics of Raw Rice Industry Wastewater Compared with Recommended Standards

Sl. No	**Water parameters**	**WHO quality standards**		**Initial characteristics of wastewater before treatment**
		Drinking purpose	**Irrigation purpose**	
1	pH	6.5-8.5	6-8.5	12.24
2	Turbidity	≤ 5 NTU	low turbidity preferred	79.7 NTU
3	TDS	≤ 500 mg L^{-1}	≤ 2000 mg L^{-1}	728 mg L^{-1}
4	BOD	≤ 5 mg L^{-1}	≤ 100 mg L^{-1}	120 mg L^{-1}
5	COD	≤ 10 mg L^{-1}	≤250 mg L^{-1}	240 mg L^{-1}
6	Colour	≤15 Pt-Co	low colour.	444 Pt-Co

2.2 Preparation of Carbonized Coconut Shell Powder

Raw coconut shells were collected locally and washed thoroughly with tap water followed by distilled water to remove adhering dirt and impurities. The cleaned shells were sun-dried and then carbonized in a muffle furnace at 500–600 °C for approximately 2 hours under limited oxygen conditions. The carbonized material was cooled to room temperature, ground into a fine powder using a laboratory grinder, and sieved to obtain a uniform particle size. The prepared carbonized coconut shell powder was stored in airtight containers until use.

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Figure 1 Carbonized coconut shell powder

2.3 Fixed-Bed Column Experimental Setup

Continuous adsorption experiments were carried out using a vertical borosilicate glass column with an internal diameter of 30 mm and a height of 450 mm. A layer of glass wool was placed at the bottom of the column, followed by glass beads and gravel to provide support for the adsorbent bed. Carbonized coconut shell powder was packed above the supporting layer to the required bed height. Rice industry wastewater was supplied to the column in a downward-flow mode using a peristaltic pump at controlled flow rates. Treated effluent samples were collected at 30-minute intervals over a total operating period of 240 minutes.

Table 2. Operating Conditions of the Fixed-Bed Column Experiment

Sl. No.	Experimental Factors	Values
1	Column size	Column Height: 45 cm Internal Diameter: 3 cm
2	Adsorbents used	Carbonized coconut shell powder
3	pH	7
4	Flow Rates Applied	5,10,15 mL min^{-1}
5	Initial concentration of Wastewater	240 mg L^{-1}
6	Bed height	1.5 cm, 3 cm, 4.5 cm

2.4 Experimental Procedure

The adsorption performance of carbonized coconut shell powder was evaluated by varying the bed height and influent flow rate. Bed heights of 1.5, 3.0, and 4.5 cm were investigated while maintaining a constant flow rate. Subsequently, flow rates of 5, 10, and 15 mL min^{-1} were studied using the optimum bed height. The experiments were conducted at pH 7 and room temperature. All experiments were performed in triplicate to ensure reproducibility.

Figure 2 Design of column experiment

2.5 Analytical Methods

The influent and treated wastewater samples were analysed according to APHA (2023) standard procedures. The pH was measured using a calibrated digital pH meter, turbidity using a nephelometric turbidity meter, TDS using a digital TDS meter, and colour using a UV–Visible spectrophotometer. COD was determined using the closed reflux colorimetric method. Instrument calibration was carried out before each analysis to ensure measurement accuracy.

2.6 Calculation of Removal Efficiency

The pollutant removal efficiency was calculated using Equation (1):
Removal efficiency (%) = Co-Ct/Co×100
where:

- Co= initial pollutant concentration
- Ct= pollutant concentration after treatment at time t

The calculated removal efficiencies were used to evaluate the adsorption performance of carbonized coconut shell powder under different operating conditions.

2.7 Statistical Analysis

All experiments were conducted in triplicate, and the results are presented as the mean values. Breakthrough profiles and removal efficiency graphs were prepared using Microsoft Excel 2021 to evaluate the influence of bed height and flow rate on the continuous fixed-bed adsorption process.

3. Results and Discussion

3.1 Effect of Bed Height on COD Removal

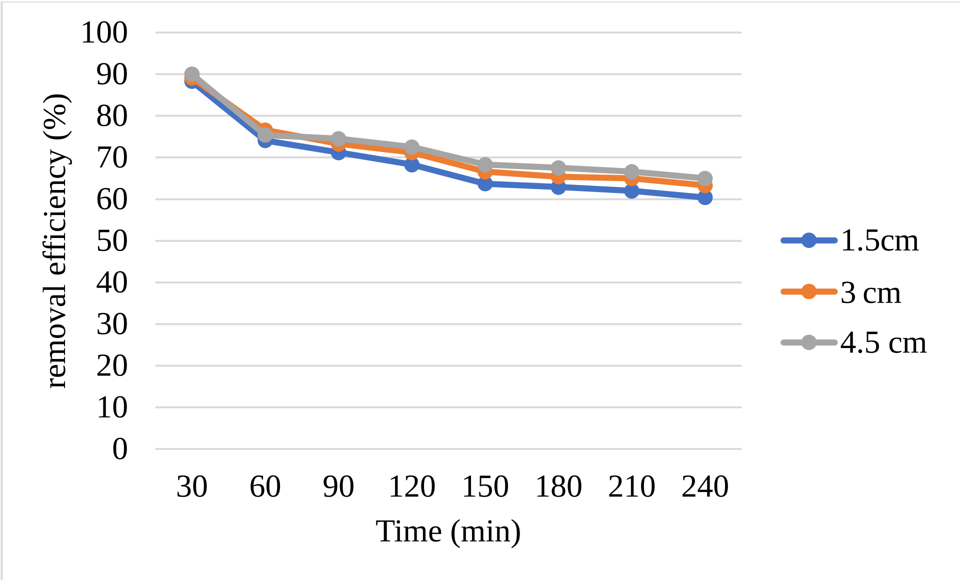

Figure 3 Breakthrough profile for COD removal using carbonized coconut shell powder at different Bed heights

Figure 3 illustrates that the removal efficiency gradually decreased with operating time because of the progressive saturation of the adsorption sites. High initial removal efficiencies 88–90% at 30 min indicate effective adsorption during the early treatment stage. The efficiency gradually decreased to 60–65% at 240 min, suggesting progressive saturation of adsorption sites. Among the investigated bed heights, the 4.5 cm bed consistently exhibited the highest COD removal efficiency, followed by the 3.0 cm and 1.5 cm beds. This improvement is attributed to the greater quantity of adsorbent, increased number of available adsorption sites, and longer contact time within the fixed-bed column.

3.2 Effect of Bed Height on Turbidity Removal

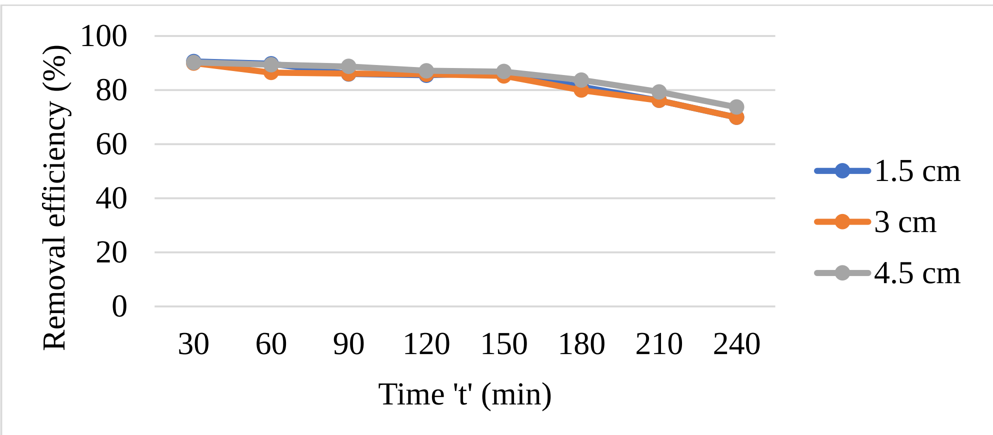

Figure 0 Breakthrough profile for Turbidity removal using carbonized coconut shell powder at different Bed heights

Figure 4 illustrates that the turbidity removal efficiency gradually decreased with increasing operating time because of the progressive saturation of the adsorption sites. Initial removal efficiencies ranged from 89% to 90% at 30 min, indicating effective adsorption during the early stage of treatment. The removal efficiency gradually declined to approximately 70–73% after 240 min because of the reduction in the available adsorption sites. Among the investigated bed heights, the 4.5 cm bed consistently exhibited the highest turbidity removal efficiency, followed by the 3 cm and 1.5 cm beds, owing to the increased adsorption capacity and longer contact time.

3.3 Effect of Bed Height on Colour Removal

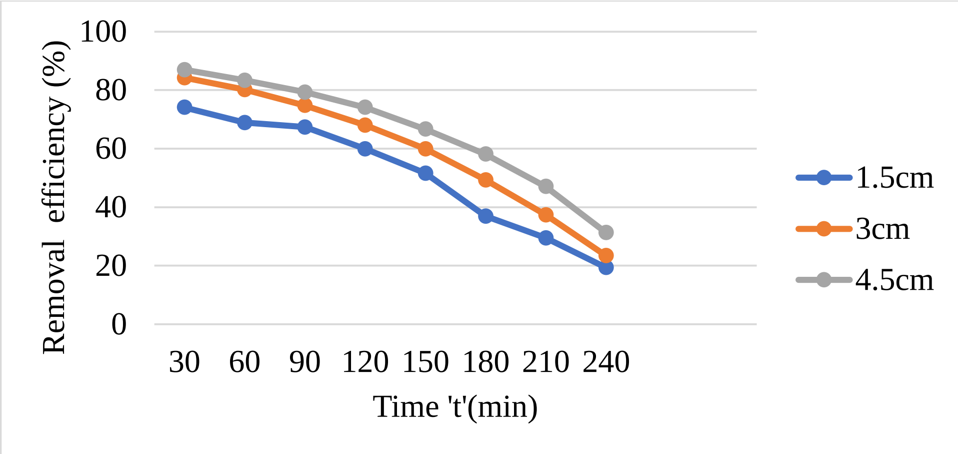

Figure 5 Breakthrough profile for colour removal using carbonized coconut shell powder at different Bed heights

Figure 5 illustrates that the colour removal efficiency gradually decreased with increasing operating time because of the progressive saturation of the adsorption sites. Initial removal efficiencies ranged from 74% to 87% at 30 min, indicating effective adsorption during the early stage of treatment. The removal efficiency gradually decreased with increasing operating time and reached approximately 19–31% after 240 min because of the progressive saturation of the adsorption sites. Among the tested media depths, the 4.5 cm bed consistently exhibited the highest removal efficiency, followed by the 3 cm and 1.5 cm beds throughout the experimental period.

3.4 Effect of Bed Height on TDS Removal

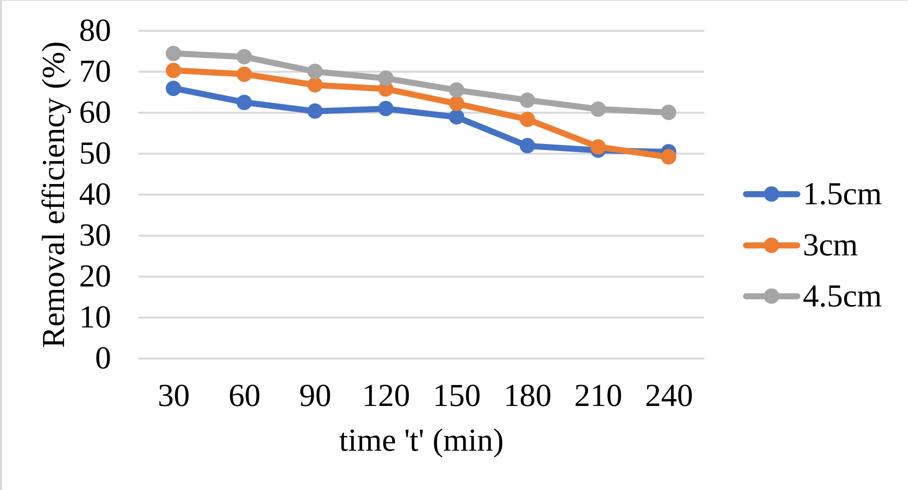

Figure 6 Breakthrough profile for TDS removal using carbonized coconut shell powder at different Bed heights

Figure 6 illustrates that the TDS removal efficiency gradually decreased with increasing operating time because of the progressive saturation of the adsorption sites. Initial removal efficiencies ranged from 66% to 74% at 30 min, indicating moderate adsorption performance during the early treatment stage. The removal efficiency gradually decreased with increasing operating time because of progressive saturation of the adsorption sites, decreasing to approximately 50–60% after 240 min because of progressive saturation of the adsorption sites. This decrease highlights that the filtering layer was losing its overall adsorption capacity because the available adsorption sites gradually became saturated with adsorbed pollutants, thereby reducing the adsorption capacity of the fixed-bed column. Among the tested media depths, the 4.5 cm bed consistently exhibited the highest removal efficiency, followed by the 3 cm and 1.5 cm beds throughout the experimental period.

3.5 Effect of Flow Rate on COD Removal

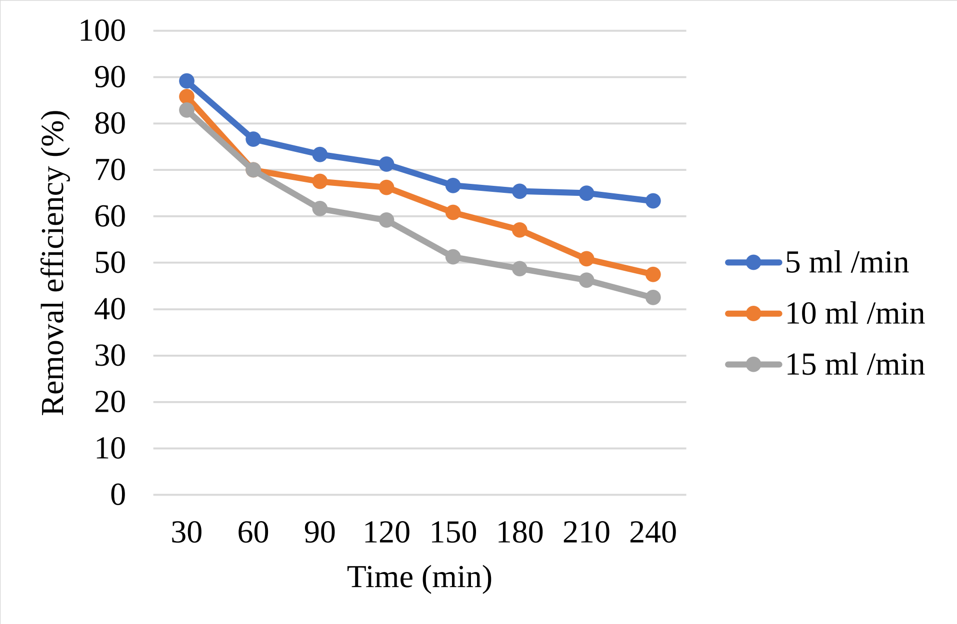

Figure 7 Breakthrough profile for COD removal using carbonized coconut shell powder at different flow rate.

Figure 7 illustrates that the COD removal efficiency gradually decreased with increasing operating time because of the progressive saturation of the adsorption sites. The high initial removal efficiencies of 83% to 89% at the 30-minute mark show that the material adsorbed pollutants effectively during the early phase of the test. However, this removal efficiency steadily decreased as time passed, dropping to a final level of 42% to 63% by the end of 240 minutes, which highlights that the adsorption sites were filling up and losing their overall adsorption capacity. Out of the different flow rates investigated, the slowest 5 mL min^{-1} rate consistently showed the best pollutant removal efficiencies, while the 10 mL min^{-1} and 15 mL min^{-1} speeds followed by 10 and 15 mL min^{-1}. These results demonstrate that lower flow rates improve adsorption performance by increasing the hydraulic retention time and enhancing contact between the wastewater and the adsorbent.

3.6 Effect of Flow Rate on Turbidity Removal

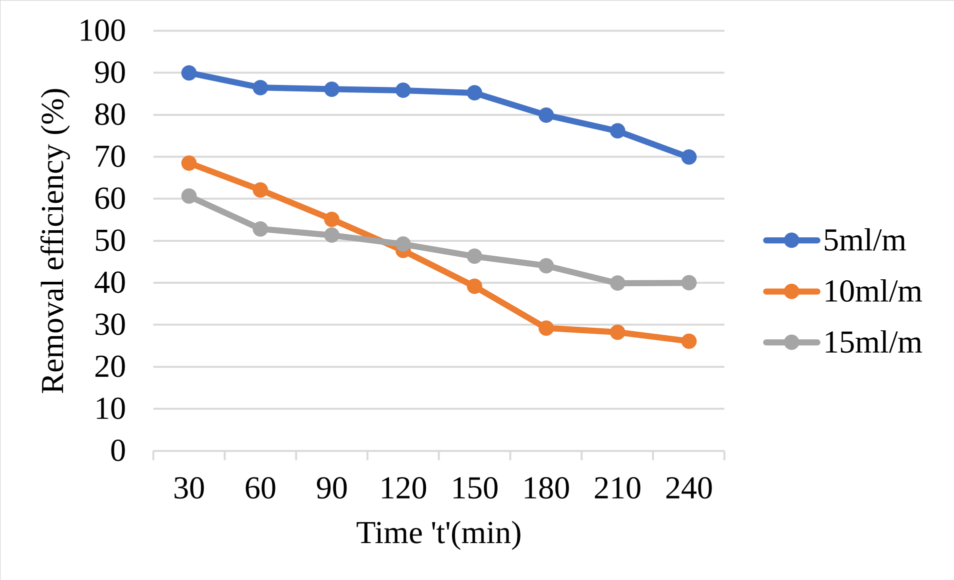

Figure 8 Breakthrough profile for turbidity removal using carbonized coconut shell powder at different flow rates.

The data trends in Figure 8 show the removal efficiency gradually decreased with operating time because of progressive saturation of adsorption sites. The high initial removal efficiencies of 60% to 90% at the 30-minute mark show that the adsorbent exhibited high initial adsorption performance during the early stage of treatment. However, this adsorption performance slowly decreased as time passed, dropping to a final level of 40% to 70% by the end of 240 minutes, which highlights that the adsorption sites were filling up and losing their overall adsorption capacity. Out of the different pumping speeds investigated, the slowest 5 mL min^{-1} rate consistently showed the best removal efficiencies, while the 10 mL min^{-1} and 15 mL min^{-1} speeds came in behind it. These results indicate that lower flow rates enhanced pollutant removal by providing longer contact time between the wastewater and the adsorbent.

3.7 Effect of Flow Rate on Colour Removal

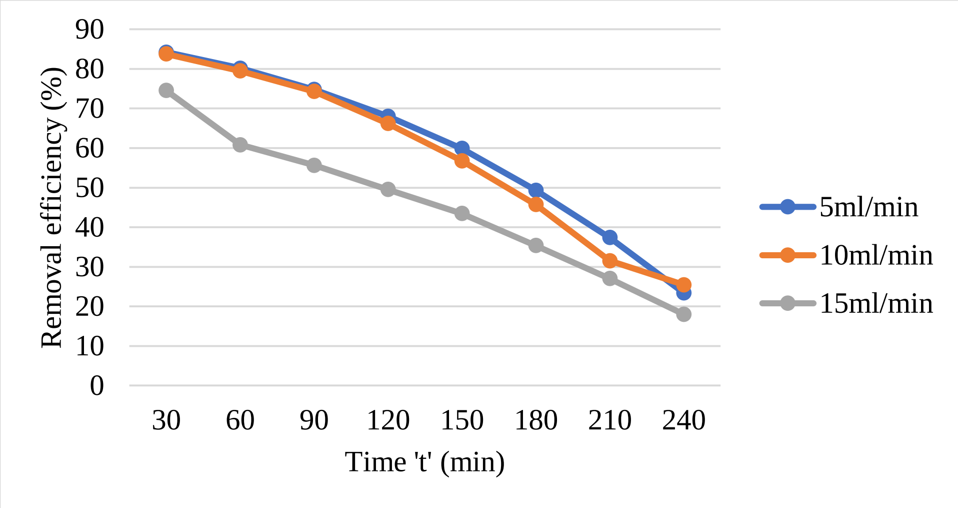

Figure 9 Breakthrough profile for colour removal using carbonized coconut shell powder at different flow rates.

Figure 9 shows that the colour removal efficiency gradually decreased as operating time increased due to the progressive saturation of the adsorption sites. At the 30-minute mark, the system showed high initial removal efficiencies of 74% to 84%, showing that the material traps pollution effectively early in the test. However, this performance steadily decreased over time, hitting a low of 18% to 23% by 240 minutes as the adsorption sites filled up and lost their overall adsorption capacity. Of all the runs, the 5 mL min^{-1} flow rate consistently exhibited the highest removal efficiency because the longer hydraulic retention time enhanced contact between the wastewater and the adsorbent.

3.8 Effect of Flow Rate on TDS Removal

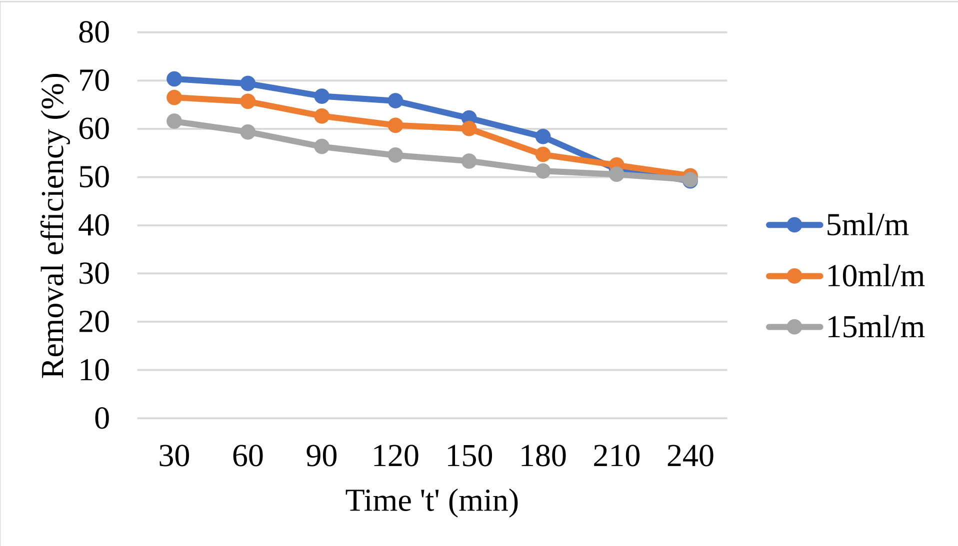

Figure 10 Breakthrough profile for TDS removal using carbonized coconut shell powder at different flow rates.

The breakthrough profiles presented in Figure 10 indicate that the TDS removal efficiency gradually decreased with increasing operating time because of the progressive saturation of the adsorption sites within the fixed-bed column. At the initial stage (30 min), the adsorption system achieved TDS removal efficiencies ranging from 61% to 70%, demonstrating effective pollutant removal. However, the removal efficiency gradually declined to approximately 49–50% after 240 min as the available adsorption sites became saturated. Among the investigated flow rates, 5 mL min^{-1} consistently achieved the highest TDS removal efficiency because the lower flow rate provided longer hydraulic retention time and enhanced contact between the wastewater and the adsorbent.

3.9 Optimum Operating Conditions

Table 3. Maximum Removal Efficiencies of Carbonized Coconut Shell Powder under Optimum Bed Height

Water quality parameter	Initial concentration	Optimum Bed Height (cm)	Maximum Removal efficiency (%)
COD (mg L^{-1})	240	4.5	90
Turbidity (NTU)	79.7	4.5	90
Colour (Pt-Co)	444	4.5	87
TDS (mg L^{-1})	728	4.5	74

Table 3 presents the maximum removal efficiencies of carbonized coconut shell powder under the optimum bed height of 4.5 cm. The highest removal efficiencies achieved were 90% for COD, 90% for turbidity, 87% for colour, and 74% for TDS. The increase in bed height improved pollutant removal by providing a greater quantity of adsorbent, increasing the number of available adsorption sites, and extending the contact time between the wastewater and the filtration medium. These findings indicate that a bed height of 4.5 cm is the optimum operating condition for enhancing the treatment performance of carbonized coconut shell powder in a continuous fixed-bed column.

Table 4. Maximum Removal Efficiencies of Carbonized Coconut Shell Powder under Optimum Flow Rate

Water quality parameter	Initial concentration	Optimum flow rate (mL min^{-1})	Maximum Removal efficiency (%)
COD (mg L^{-1})	240	5	89
Turbidity (NTU)	79.7	5	90
Colour (Pt-Co)	444	5	84
TDS (mg L^{-1})	728	5	70

Table 4 summarizes the maximum removal efficiencies of carbonized coconut shell powder under the optimum flow rate of 5 mL min^{-1}. The highest removal efficiencies obtained were 89% for COD, 90% for turbidity, 84% for colour, and 70% for TDS. The lower flow rate provided a longer hydraulic retention time, allowing better interaction between the wastewater and the carbonized coconut shell powder, thereby improving pollutant removal. These results demonstrate that a flow rate of 5 mL min^{-1} is the optimum condition for achieving efficient treatment of rice industry wastewater using carbonized coconut shell powder in a continuous fixed-bed adsorption system.

Conclusion

This study demonstrated that carbonized coconut shell powder is an effective natural adsorbent for the continuous fixed-bed treatment of rice industry wastewater. Increasing the bed height from 1.5 cm to 4.5 cm significantly enhanced pollutant removal by providing a larger adsorption surface area and longer hydraulic retention time within the fixed-bed column. Under the optimum bed height of 4.5 cm, maximum removal efficiencies of 90% for COD, 90% for turbidity, 87% for colour, and 74% for TDS were achieved. Similarly, a lower influent flow rate of 5 mL min^{-1} resulted in superior treatment performance by increasing the contact time between the wastewater and the adsorbent, yielding maximum removal efficiencies of 89% for COD, 90% for turbidity, 84% for colour, and 70% for TDS. Overall, the results demonstrate that carbonized coconut shell powder is a sustainable, economical, and environmentally friendly adsorbent with significant potential for the continuous treatment of rice industry wastewater.

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