Pertanika J. Sci. & Technol. 34 (4): 2149 - 2166 (2026)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Utilisation of Starch-Derivative Functionalised Biochar for Management of Industrial Effluent

Maria Adilah Basharuddin[1], Siti Fatimah Zaharah Mohamad Fuzi[1]*, Noor Mohd Syeqqal Ismail[2], Chia Kim Seng[3], and Nor Hasmaliana Abdul Manas[4,5]

[1]*Future Food Research and Innovation (FFRI), Faculty of Applied Sciences and Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Higher Education Hub, KM 1, Jalan Panchor, 84600 Muar, Johor, Malaysia*
[2]*Star Feedmills (M) Sdn. Bhd., Jalan Perindustrian Mahkota 2, Kawasan Perindustrian Mahkota Beranang, 43700 Beranang, Selangor, Malaysia*
[3]*Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia*
[4]*Faculty of Industrial Sciences and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), Lebuhraya Tun Razak, 26300 Gambang, Kuantan, Pahang, Malaysia*
[5]*Bioaromatic Research Centre, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Gambang, Pahang, Malaysia*

ABSTRACT

The increasing global demand for sustainable wastewater management in the food manufacturing industry underscores the need for efficient, environmentally friendly, and cost-effective treatment solutions. This study investigated the application of starch derivative-functionalised biochar (FBSD) as an adsorption-based polishing treatment for food manufacturing wastewater. FBSD was prepared from rice husk biochar and evaluated for its ability to reduce Chemical Oxygen Demand (COD) and colour in actual wastewater collected from the secondary clarifier of an industrial wastewater treatment facility. The adsorption performance of FBSD was assessed through COD reduction, colour removal, iodine adsorption number, and regeneration capability over three consecutive cycles. The functionalised biochar exhibited a high initial iodine adsorption number of 650.24 ± 0.03 mg/g, indicating substantial adsorption potential. Treatment with FBSD reduced COD from 160.00 ± 0.00 mg/L to 15.00 ± 0.00 mg/L, corresponding to a removal efficiency of 90.63%, while colour decreased from 315.00 ± 1.73 ADMI to 5.00 ± 0.00 ADMI, achieving 98.41% removal. The adsorbent maintained satisfactory performance during the first regeneration cycle but exhibited a gradual decline in adsorption efficiency with repeated regeneration due to the loss of active adsorption sites. A preliminary economic assessment indicated that although FBSD offers environmental benefits through the utilisation of

ARTICLE INFO

Article history:
Received: 04 September 2025
Accepted: 12 June 2026
Published: 20 August 2026

DOI: https://doi.org/10.47836/pjst.34.4.09

E-mail addresses:
mariaadilah19@gmail.com (Maria Adilah Basharuddin)
fatimahz@uthm.edu.my (Siti Fatimah Zaharah Mohamad Fuzi)
syeqqal@gmail.com (Noor Mohd Syeqqal Ismail)
kschia@uthm.edu.my (Chia Kim Seng)
hasmaliana@umpsa.edu.my (Nor Hasmaliana Abdul Manas)
* Corresponding author

e-ISSN: 2231-8526

agricultural biomass, further process optimisation and scale-up are required to improve its economic competitiveness with commercial activated carbon. Overall, the findings demonstrate the potential of FBSD as a sustainable polishing adsorbent for industrial wastewater treatment applications.

Keywords: Biochar, food effluent, starch derivatives, waste treatment, wastewater

INTRODUCTION

Food manufacturing effluent, generated as a byproduct during various food processing operations, contains a complex mixture of contaminants. These include organic matter, nutrients, fats and oils, industrial chemicals, and potentially pathogenic microorganisms, the composition of which varies depending on specific production activities (Qasem et al., 2021; Sathya et al., 2022). The treatment of such effluents is crucial to ensure compliance with environmental regulations and to support Malaysia's Sustainable Development Goal (SDG) 6, which advocates for clean water and sanitation for all (Kong et al., 2020). Although conventional treatment methods, such as sedimentation, filtration, and biological or chemical processes, are widely implemented, they often struggle to effectively address diverse and persistent pollutants found in industrial wastewater (Huang et al., 2015).

In recent years, biochar, a carbonaceous material produced via pyrolysis of biomass, has gained attention as an alternative adsorbent for wastewater remediation. Its high surface area, porous structure, and abundance of functional groups enable efficient adsorption of various pollutants, including organic compounds and heavy metals (Chataigner et al. 2023; Dutta et al., 2023). Enhancing biochar by functionalising it with starch derivatives (SD) may further improve its adsorption capabilities due to the unique cyclic structure and polarity of SD, offering a low-cost and eco-friendly substitute to conventional adsorbents such as activated carbon (Yusoff et al., 2019). This modification enhances the interaction between the biochar surface and target pollutants, rendering functionalised biochar (FBSD) a competitive and sustainable option for industrial-scale applications (Zhao et al., 2022).

Numerous studies have reported the favourable regeneration performance and cost-effectiveness of biochar compared to activated carbon, particularly when derived from abundant feedstocks like rice husks. This makes it especially attractive for industries aiming to meet the Environmental Quality Act 1974 and Industrial Effluent Regulations 2009 in Malaysia, while maintaining cost-efficiency (Carlini et al., 2023; Kuok et al., 2022; Wiśniewska et al., 2022). The challenge remains, however, in developing treatment solutions that consistently meet discharge standards and are resilient to multiple regeneration cycles.

Moreover, the increasing volume of wastewater being released underscores the growing imperative to employ an effective treatment with energy and resource efficiency. Some compelling insight was gathered during a recent interview with a food manufacturing company, which is that it became evident that FBSD could hold significant potential to fill a crucial gap and potentially replace existing solutions in the market. The industrial effluent treatment system (IETS) for that company is shown in Figure 1.

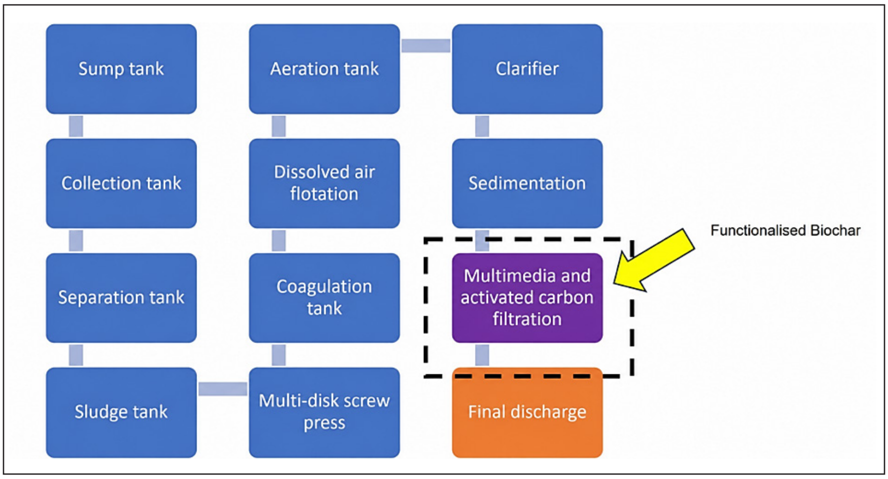

Figure 1. Industrial Effluent Treatment System (IETS) used by Company S and the potential role of functionalised biochar as an alternative treatment approach

In a previous study, Azman et al. (2024) characterised FBSD using SEM-EDX and FTIR analyses and demonstrated its effectiveness for carbazole removal from synthetic wastewater. While these findings established the adsorption capability of FBSD toward a model organic pollutant, adsorption behaviour in actual industrial wastewater cannot be directly inferred because real effluents contain complex mixtures of dissolved organic matter, colour-causing compounds, suspended particles, and competing contaminants. Therefore, the innovation of the present study is to investigate FBSD application as an adsorption-based treatment for food manufacturing wastewater. Specifically, the study evaluated the effectiveness of FBSD in reducing COD and colour through adsorption, examined its regeneration and recyclability performance, and assessed its potential as a polishing treatment in industrial wastewater management. In addition to assessing pollutant removal performance, this work investigates adsorbent regeneration, recyclability, and preliminary techno-economic feasibility, thereby providing practical insights for industrial wastewater treatment applications.

METHODOLOGY

Materials

The materials employed in this study include rice husk biochar, sourced from Tanegoodies Enterprise, and a high-purity starch derivative (HPLC grade, 98.0%, MW: 1134.98) from

Wako 1st Grade. Additional reagents comprised 85% phosphoric acid (Sigma-Aldrich), citric acid (MW: 192.12, Fisher Chemicals), and potassium dihydrogen phosphate (MW: 136.09, EMSURE® ISO grade). Sodium hydroxide pellets (MW: 40.00, EMSURE®), along with secondary-treated food industry effluents from Company S, were also used. Other chemicals included ethyl acetate (MW: 88.11, R&M Chemicals), potassium hydroxide (MW: 56.11), nitric acid (MW: 63.01), hydrochloric acid (5%, MW: 36.46), iodine (MW: 126.9), and sodium thiosulfate (MW: 158.11). All chemicals are used as received without additional purification. Deionised water is employed exclusively throughout research.

Preparation of Functionalised Biochar with Starch Derivative

The functionalised biochar (FB) was prepared through several sequential steps. An experimental framework for wastewater treatment using functionalised biochar is shown in Figure 2.

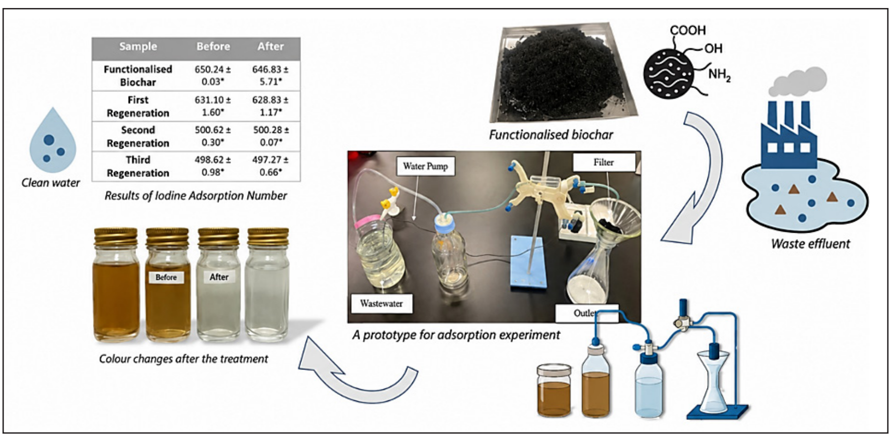

Figure 2. A conceptual framework for wastewater treatment using functionalised biochar

Initially, raw biochar was rinsed with deionised water, filtered, and dried at 60°C for 12 hours using a vacuum dryer (BINDER VD 53). This was followed by soaking in 50% phosphoric acid at a 1:10 (w/v) ratio for 12 hours at ambient temperature, with an initial agitation phase of 30 minutes at 250 rpm using a shaker incubator (Jiang et al., 2021). After acid treatment, the biochar was filtered and neutralised by washing with 0.1 M NaOH and deionised water until a pH of 7 was achieved, then vacuum-dried at 60°C and stored in a desiccator.

To prepare the starch derivative (SD)-based cross-linking agent, SD was blended with citric acid in a 1:1 ratio. This mixture was then combined with potassium dihydrogen phosphate at a 3:1 citric acid-to-phosphate ratio in deionised water. The mixture underwent heating at 140°C for 5 hours, was milled, thoroughly rinsed with deionised water, and dried at 60°C to yield a citric acid-crosslinked SD powder (Huang et al., 2015).

For biochar functionalisation, the SD powder was mixed with acid-treated biochar in a 2:1 ratio using deionised water. The suspension was subjected to ultrasonication at 37 kHz and 60°C, followed by filtration, rinsing to remove residual SD, and vacuum drying at 60°C until constant mass was achieved. The final functionalised biochar was stored in a desiccator until further use.

Preparation of Food Manufacturing Effluent

Effluent samples were collected from the secondary clarifier of a wastewater treatment facility operated by Company S, a manufacturer of aquatic feed for fish and shrimp. Sampling was conducted five times throughout the study to ensure data consistency.

Analysis of Performance

Iodine Adsorption Number

To evaluate the adsorptive surface characteristics of the biochar, the iodine number test was conducted as a rapid indicator of available surface area. This test involved treating the biochar with boiling 5% hydrochloric acid, cooling, and then reacting it with a standard 0.1N iodine solution. The mixture was shaken for 30 seconds, filtered, and the unreacted iodine in the filtrate was titrated against 0.1N sodium thiosulfate using starch as an endpoint indicator (Mariah et al., 2023) as calculated using Equation 1.

$$\%\ iodine\ number\ efficiency = \frac{titer\ value\ of\ sample - titer\ of\ blank}{titer\ of\ blank\ \times 100} \qquad [1]$$

Adsorption Experiment

The adsorption experiment was conducted following the procedure outlined in (Mondol & Jhung, 2022). A 200 mL aliquot of food manufacturing effluent solution with an initial concentration of 100 mg/L was used for each test. A 10 g portion of the adsorbent was introduced into individual conical flasks containing the effluent. These flasks were placed in an incubator shaker and agitated at 250 rpm under ambient temperature conditions for 2 hours to facilitate adsorption. The effluent samples were analysed before and after treatment to determine changes in pollutant concentration, using both colourimetric analysis and COD measurements as indicators of treatment efficiency, as depicted in Figure 3.

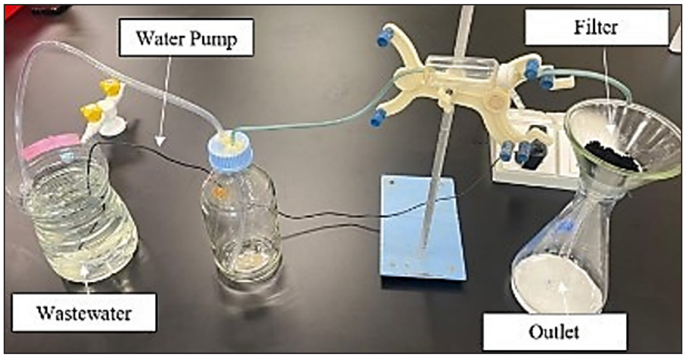

Figure 3. The setup of the prototype for the adsorption experiment

Characterisation of COD

The COD of the food manufacturing effluent was analysed both after the adsorption process and following each regeneration cycle. The analysis was performed using the Spectroquant® Thermoreactor TR320 in conjunction with the Macherey-Nagel Compact Photometer PF-12 Plus, as calculated using Equation 2. Both COD and colour removal were selected because they are key regulatory parameters under the Malaysian Environmental Quality (Industrial Effluent) Regulations 2009 and directly reflect treatment effectiveness for food manufacturing wastewater, as stated by Metcalf & Eddy, Inc., and AECOM (2014).

$$\% \, Removal \; efficiency = \frac{value \; of \; untreated \;\; sample - value \; of \; treated \;\; sample}{value \; of \; untreated \;\; sample \; \times 100} \qquad [2]$$

Colour

The colour intensity of both untreated and treated food manufacturing effluents, as shown in Figure 4, was assessed using a HACH DR6000 Benchtop Spectrophotometer, utilising Program 96 (Colour ADMI, 1-inch cell). The spectrophotometer was calibrated at a wavelength of 450 nm, in accordance with the method outlined by Puasa et al. (2021).

Figure 4. Colour changes after the treatment

Regeneration and Recyclability

To evaluate the reusability of the biochar, a regeneration process was applied to the spent adsorbent (Wu et al., 2024). The exhausted biochar was treated with potassium hydroxide (KOH) at a 1:4 mass ratio and subjected to thermal treatment in an SH-AC-60M Autoclave at 190°C for 24 hours. Following this, the material was rinsed with 35% nitric acid (HNO_3) to remove residual contaminants and then dried at 80°C for another 24 hours, as adapted from (Amdeha, 2023). This regeneration cycle was repeated three times to investigate the biochar's potential for repeated use. Before each adsorption cycle, the regenerated biochar was assessed for adsorption efficiency using the iodine number test. The effectiveness of the regeneration was further evaluated through COD measurements, while the overall durability of the biochar was assessed using a recyclability test over the three regeneration cycles. The results demonstrated the material's stability and its potential for sustainable, long-term application.

Statistical Analysis

Data collected from the experiments were statistically analysed using Minitab Statistical Software (version 2022). Experimental results are presented as mean ± standard deviation from triplicate measurements. One-way analysis of variance (ANOVA) was used to evaluate differences among treatment and regeneration conditions. A paired t-test was additionally conducted to compare iodine adsorption numbers before and after treatment to determine whether the adsorption process significantly affected the adsorbent surface characteristics. Statistical significance was established at $p < 0.05$ (Wahid et al., 2017).

Preliminary Techno-Economic Analysis

Although biochar has been reported as a lower-cost alternative to activated carbon, its true cost-effectiveness depends not only on initial material costs but also on long-term factors. These include production scalability, regeneration efficiency, and operational stability. Therefore, a preliminary techno-economic and risk assessment, factoring in both adsorption performance over multiple cycles, as well as operational and maintenance costs, is essential to validate its industrial potential (Towler & Sinnott, 2022). Such an analysis would provide a better understanding of its suitability for large-scale wastewater treatment applications. Equation 3 is as follows:

$$Cost\ per\ Cycle = \frac{material\ \ cost + energy\ \ cost + regeneration\ \ cost}{volume\ \ of\ wastewater\ \ treated\ \ per\ Cycle} \qquad [3]$$

RESULTS AND DISCUSSIONS

Iodine Adsorption Number Analysis

The iodine number was employed as an indirect indicator of microporous surface area and adsorption site availability rather than a direct measure of pollutant removal capacity. Although iodine adsorption provides useful information regarding adsorbent quality and regeneration performance, it does not fully describe pore structure or adsorption mechanisms. In this study, elevated iodine adsorption numbers correlated with enhanced adsorption capacity, indicative of the efficacy in pollutant removal by FBSD. According to (Mariah et al., 2023), high-carbon materials exhibit values ranging from 500 to 1200mg/g, which indicates the extent to which carbon is utilised. Figure 5 shows the iodine adsorption number for FBSD.

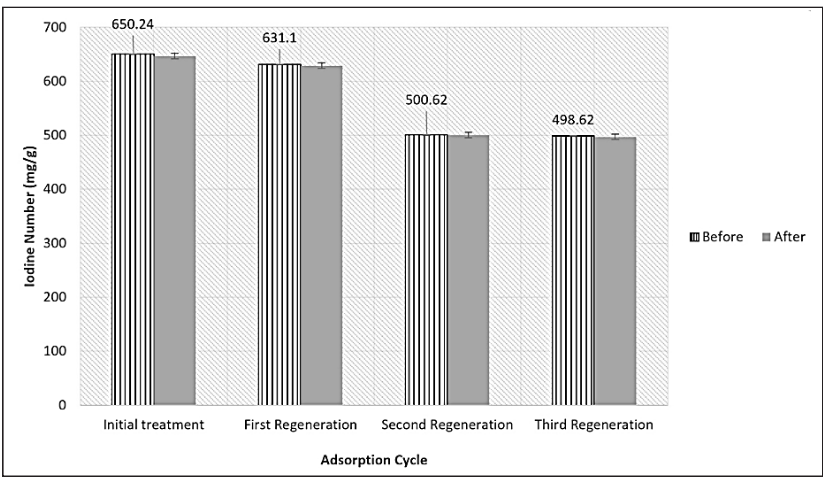

Figure 5. Results of iodine adsorption number vs regeneration cycle

The functionalised biochar exhibited a substantial initial iodine adsorption number of 650.24±0.03, suggesting a highly porous structure and extensive surface area conducive to adsorption processes. Following the adsorption process, a slight decrease in the iodine number to 646.83±5.71 was observed. However, this reduction was not statistically significant, with an efficiency retention of 99.48%. This marginal 0.52% decrease underscores the structural integrity and efficacy of biochar, affirming its potential as an effective adsorbent for iodine and other contaminants. These outcomes suggest that the functionalised surface of the biochar maintained its porosity and surface area, thereby highlighting its suitability for adsorption applications in water treatment systems.

Across the regeneration cycles, a gradual decrease in the iodine adsorption number was observed. During the first regeneration cycle, the number experienced a slight reduction to 631.10±1.60, which equates to a marginal 3.00% decrease, potentially resulting from minor blockage of adsorption sites. Progressing to the second cycle, the iodine number declined to 500.62 ± 0.30 and further diminished to 498.62±0.98 in the third cycle, culminating in a total reduction of 23.30% from the original value. This decline can be attributed to structural deterioration, fouling, and incomplete desorption during regeneration. Nevertheless, the biochar sustained a superior level of performance when compared to activated carbon, surpassing values such as 443.58 mg/g from coffee-based activated carbon (Yuliusman et al., 2020) and 420.47 mg/g (Mondol & Jhung, 2022). Table 1 shows the paired t-test that was conducted to evaluate the effect of the treatment on the iodine adsorption amount of biochar.

Table 1
Results of paired T-Test analysis

Sample	Before	After	Mean Diff.	95% Cl	t-value	p-value
FSD	570.1 ±74.0	568.3±73.0	1.844	(0.103, 3.585)	2.33	0.040

The results revealed that the iodine adsorption number decreased slightly from 570.1±74.0 before treatment to 568.3±73.0 after treatment. The mean paired difference of 1.844 was statistically significant ($t = 2.33$, $p = 0.040$), with a 95% confidence interval of (0.103,3.585). Although the statistical analysis suggests a significant difference, the small magnitude of the mean difference highlights that the practical impact on the biochar's performance is negligible. The minimal reduction in iodine adsorption number demonstrates that the structural integrity and adsorption capacity of the biochar were well preserved following the treatment. This is particularly important for applications that rely on biochar's adsorption capabilities, such as water purification or pollutant removal. The iodine adsorption number is a measure of the surface area and porosity of biochar, which are critical factors for effective adsorption. The slight decrease in adsorption performance could be attributed to minor structural changes during the treatment process, such as partial blockage or alteration of adsorption sites. However, the biochar retained over 99% of its adsorption efficiency, indicating excellent durability and resilience under the tested conditions.

These findings underscore the potential of biochar as a stable and effective adsorbent material, capable of maintaining its performance even after exposure to treatment processes. This resilience suggests that biochar could be a reliable material for multiple adsorption cycles, enhancing its sustainability and economic feasibility for industrial applications (Alsawy et al., 2022). In conclusion, overall findings indicate that the functionalised biochar is effective for one regeneration cycle while retaining most of its adsorption capacity. Future studies should incorporate Brunauer-Emmett-Teller (BET) surface area analysis and pore size distribution measurements to provide a more comprehensive evaluation of FBSD properties.

COD Analysis

It should be noted that the wastewater used in this study was collected from the secondary clarifier of an existing industrial wastewater treatment system that already complied with Standard B discharge requirements. Consequently, the untreated sample with a COD concentration of 160 mg/L was relatively low compared with raw industrial effluents. The purpose of this study was therefore not to replace primary or secondary treatment processes, but rather to evaluate FBSD as a polishing treatment capable of further reducing residual contaminants before discharge or potential water reuse. Under these conditions, FBSD successfully reduced COD from 160.00 ± 0.00 mg/L to 15.00 ± 0.00 mg/L, achieving a removal efficiency of 90.63% and producing an effluent quality approaching Standard A requirements. These values indicate the amount of oxygen needed to chemically oxidise both organic and inorganic substances present in the effluent, serving as a measure of the organic pollutant load (Figure 6). A decrease in COD values after treatment signifies effective removal of contaminants, while variations across regeneration cycles provide insight into the performance of the adsorbent and reusability over time.

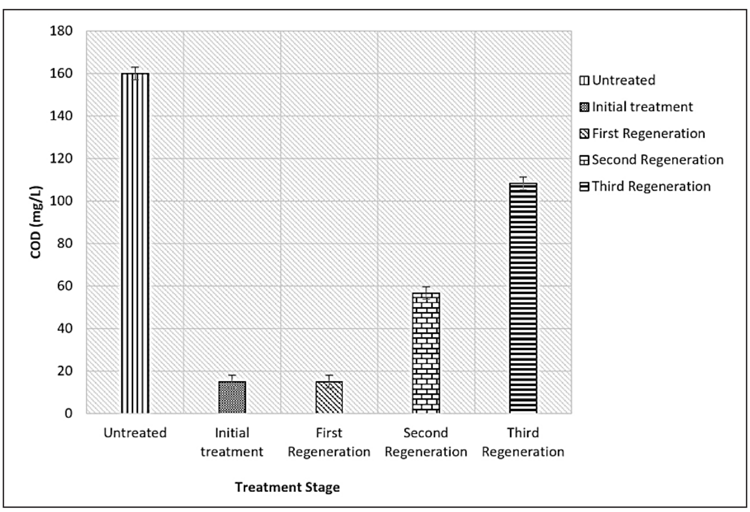

Figure 6. Results of COD Analysis vs regeneration cycle

The untreated sample exhibited a COD value of 160.00±0.00 mg/L, which served as the baseline for assessing organic pollutant concentrations. Following treatment, a significant reduction to 15.00±0.00 was observed in the COD, indicating a 90.63% decrease and highlighting the treatment's effectiveness in diminishing organic contaminants. The treated sample fulfilled the stipulated COD standard for direct discharge, as per regulatory guidelines (Sun et al, 2024). During the initial regeneration cycle, the COD value remained stable at 15.00±0.00, sustaining the original removal efficiency of 90.63%. This outcome substantiated the adsorbent's capacity to maintain its pollutant removal efficacy during the first cycle.

During the second regeneration cycle, the COD concentration increased to 56.67 ± 3.06 mg/L, leading to a reduction in removal efficiency to 64.58%. By the third cycle, COD levels rose further to 108.33 ± 1.16 mg/L, resulting in a significant drop in efficiency to 32.29%, which also exceeded the allowable discharge limit of 80 mg/L (Zhao et al, 2022). This progressive decline in removal efficiency was likely due to surface fouling, reduced availability of active adsorption sites, and partial structural degradation of the functionalised biochar. These factors contributed to a diminished ability of the material to maintain performance over successive cycles.

The findings indicate that the functionalised biochar was highly efficient in COD reduction during the initial treatment and retained this capacity in the first regeneration cycle. However, its effectiveness decreased noticeably beyond the second cycle. To improve the long-term viability of the material, future research should emphasise the enhancement of regeneration protocols and material modification strategies aimed at minimising fouling and preserving adsorption efficiency. Overall, this study underlines the critical importance of assessing the durability and sustainability of adsorbents for prolonged application in industrial wastewater treatment (Kuok et al., 2022).

Colour Analysis

Figure 7 presents the results of the colour analysis, illustrating variations in colour values across different stages: pre-treatment, post-treatment, and during regeneration cycles. These colour measurements serve as indicators of treatment effectiveness by reflecting the concentration of dissolved organic compounds and light-absorbing substances present in the samples.

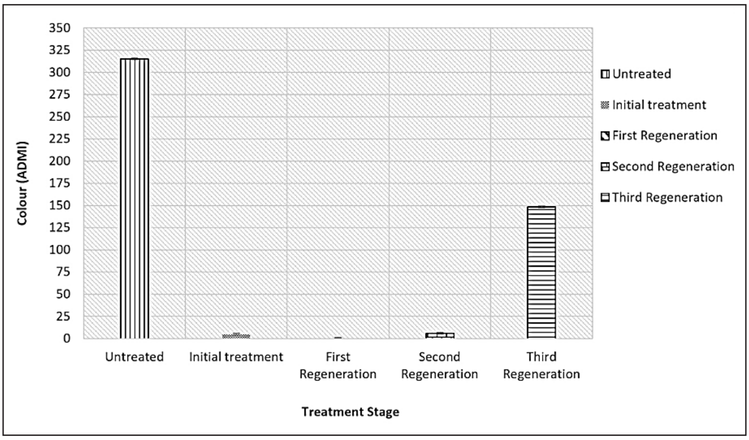

Figure 7. Results of colour analysis vs regeneration cycle

The untreated effluent sample exhibited a colour intensity of 315.00 ± 1.73 ADMI, indicating a high concentration of chromophoric compounds. Post-treatment, the colour value was significantly reduced to 5.00 ± 0.00 ADMI, achieving a removal efficiency of 98.41%. This result falls well within the Environmental Quality Act 2009 threshold of less than 100 ADMI (Yusoff et al, 2019), underscoring the adsorbent's high decolourisation capability. In the first regeneration cycle, the colour value remained low at 1.00 ± 0.00 ADMI, corresponding to a removal efficiency of 99.68%, showing no significant decline from the initial treatment and confirming the effectiveness during early reuse.

During the second regeneration, the colour intensity slightly increased to 6.00 ± 0.00 ADMI, resulting in a minor reduction in removal efficiency to 98.10%, which still met regulatory limits. However, by the third regeneration cycle, the colour value increased markedly to 148.33 ± 0.58 ADMI, reducing the removal efficiency to 52.91%. This sharp decline in performance is likely due to surface saturation, incomplete desorption during regeneration, or structural deterioration of the adsorbent matrix. Despite this, the functionalised biochar remained compliant with discharge standards for up to two regeneration cycles, after which its efficacy dropped below acceptable thresholds.

These trends were consistent with the findings from the COD analysis, both highlighting a high initial removal capacity that declines with repeated reuse. The adsorbent demonstrated satisfactory performance for up to two cycles, maintaining removal efficiencies above 98%, but showed significant deterioration by the third cycle. To extend the material's usability, further research should focus on optimising regeneration protocols and reinforcing the structural integrity of the biochar, ensuring sustained decolourisation performance over multiple cycles.

Regeneration and Recyclability Analysis

The functionalised biochar initially demonstrated strong adsorption performance, as reflected by a high iodine adsorption number of 650.24 ± 0.03 and significant reductions in both COD and colour intensity. COD levels decreased from 160.00 ± 0.00 mg/L to 15.00 ± 0.00 mg/L ($P < 0.05$), while colour values dropped from 315.00 ± 1.73 ADMI to 5.00 ± 0.00 ADMI ($P < 0.05$). These findings highlight the material's high adsorption capacity and effectiveness in removing organic and chromophoric pollutants during the initial treatment cycle.

Upon the first regeneration, the biochar largely retained its original efficiency. The iodine number exhibited a slight reduction to 631.10 ± 1.60 ($P < 0.05$), while COD (15.00 ± 0.00 mg/L) and colour (1.00 ± 0.00 ADMI) values remained statistically unchanged compared to the post-treatment results ($P > 0.05$). These observations suggest that the adsorbent remains effective after one regeneration cycle, with minimal loss in performance.

However, the second regeneration cycle showed a measurable decline in efficiency. The iodine number decreased to 500.62 ± 0.30 ($P < 0.05$), while COD and colour values increased to 56.67 ± 3.06 mg/L and 6.00 ± 0.00 ADMI, respectively, both statistically significant ($P < 0.05$). This deterioration may be attributed to partial saturation or blockage of adsorption sites and early signs of structural degradation in the biochar matrix.

By the third regeneration, the performance had substantially deteriorated. The iodine number further declined to 498.62 ± 0.98 ($P < 0.05$), accompanied by marked increases in COD (108.33 ± 1.16 mg/L) and colour (148.33 ± 0.58 ADMI), both exceeding acceptable discharge thresholds. The significant drop in adsorption capacity at this stage likely results from active site exhaustion, incomplete regeneration, and breakdown of the biochar structure, limiting its applicability beyond two regeneration cycles.

Although the KOH-HNO_3 regeneration protocol effectively restored adsorption performance during the first regeneration cycle, the process is relatively energy-intensive and chemically aggressive. The observed 23.3% reduction in iodine adsorption number after three regeneration cycles suggests partial structural deterioration of the biochar matrix. Consequently, the desorption process is pivotal in assessing FBSD reapplication potential, as it governs the efficacy of metal recovery for regeneration purposes (Rosales et al., 2015). Therefore, while the method is suitable for laboratory-scale evaluation, further optimisation is required before industrial implementation. Future work should investigate less intensive regeneration strategies, including lower chemical dosages, steam regeneration, thermal regeneration, and waste-heat-assisted processes to improve operational sustainability and reduce treatment costs.

Preliminary Techno-Economic Analysis and Risk Simulation

The economic assessment presented in this study should be regarded as a preliminary techno-economic evaluation rather than a definitive comparison with commercial activated carbon. The comparison was based primarily on estimated production and processing costs and did not account for adsorption capacity on an equivalent pollutant-removal basis.

The initial cost of deploying functionalised biochar systems plays a decisive role in determining their industrial viability, as shown in Table 2.

Meanwhile, Table 3 shows a comparison of total process costs of functionalised biochar and activated carbon projected by the Aspen Process Economic Analyser (APEA) v. 12. The simulation revealed that functionalised biochar involves a more complex synthesis route, including acid treatment, chemical functionalisation, and drying, which reflects in a higher cost.

An economic summary based on 1000 m^3/day treatment capacity is presented in Table 4. Despite a slightly higher initial processing cost, its low-cost feedstock and potential for regeneration result in a significantly lower cost per cubic meter of treated water. In contrast, activated carbon, despite its simplicity and commercial availability, incurs higher costs due to its purchase price and more energy-intensive regeneration processes.

Table 2
Estimated cost breakdown (per 1 kg of functionalised biochar)

Component	Usage	Approx. Price (RM/kg or L)	Subtotal
Biochar	0.5 kg	RM 0.50	RM 0.25
50% Phosphoric Acid	5.0 L	RM 4.00	RM 20.00
0.1M NaOH	2.0 L	RM 1.50	RM 3.00
Starch Derivative (SD)	0.25 kg	RM 8.00	RM 2.00
Citric Acid	0.25 kg	RM 6.00	RM 1.50
Potassium Dihydrogen Phosphate	0.083 kg	RM 10.00	RM 0.83
Deionised Water	5.0 L	RM 0.10	RM 0.50
Electricity (for heating/ drying/ operating)	~1.5 kWh	RM 0.50	RM 0.75
TOTAL			RM 28.83

Table 3
A comparative analysis of the total process costs of functionalised biochar and activated carbon projected by the Aspen Process Economic Analyser

Parameter	Functionalised Biochar	Activated Carbon (AC)
Plant Capacity	1,000 m^3/day	1,000 m^3/day
Equipment Sizing	Reactor, Dryer, Filter	Adsorber only
Labor & Maintenance	Standard or user-defined	Standard
Utility Costs	Heating (140°C), Water, Electricity	Less for AC
Raw Material	Acid, SD, biochar, etc.	AC from the supplier

Table 4
A summary of preliminary techno-economic analysis for functionalised biochar and activated carbon

Category	FBSD	Activated Carbon	Remarks
Raw Material Cost (RM/kg)	RM 28.83	RM 7.05	Lab-scale; Biochar includes chemicals & synthesis steps
Energy Cost per Cycle (RM)	RM 0.47	RM 1.18	Biochar may be less energy-intensive to regenerate
Regeneration Cost per Cycle (RM)	RM 0.24	RM 0.47	Chemical vs. thermal reactivation

Table 4 (*continued*)

Category	FBSD	Activated Carbon	Remarks
Total Cost per Cycle (RM)	RM 29.54	RM 8.70	From supplier estimation
Cost per m^3 Treated (RM/m^3)	RM 2.95	RM 0.87	Based on 10 m^3 per cycle volume
CAPEX (Plant & Equipment)	High (reactor, dryer, milling)	Moderate (mainly adsorbers)	Biochar setup includes more unit operations
OPEX (Operating Cost/year)	Higher (chemical input)	Lower (bulk purchase model)	Depends on the bulk supply chain
CO_2 Emissions per kg material	0.5 kg CO_2 eq	5.0 kg CO_2 eq	Biochar is environmentally friendlier
Scalability	Medium–High	High	Biochar is limited by the preprocessing capacity
Payback Period	Longer (5-7 years est.)	Shorter (2-4 years est.)	Due to the initial investment and material cost

A payback period of 5 to 7 years for using functionalised biochar in wastewater treatment suggests significant potential for cost reduction, particularly with process optimisation and broader industrial uptake. At laboratory scale, FBSD exhibited a higher production cost (RM 28.83/kg) than commercial activated carbon (RM 7.05/kg). This cost is expected to decrease with industrial-scale production, bulk procurement of inputs, and improved energy efficiency, especially if supported by environmental regulations and growing demand for sustainable materials (Tchobanoglous et al., 2014). Policy incentives, demonstration of local success stories, and demand for green technologies, such as continuous reactors for acid functionalisation and solar-assisted drying or waste heat recovery, will further drive adoption (Mongkollertlop & Sookkheo, 2024).

With effective optimisation and industrial integration, production costs could potentially decline by around 35%, while adoption rates may increase by over 30%, especially in regions prioritising sustainable water management and circular economy models. In addition to economic benefits, functionalised biochar offers notable environmental advantages, including CO_2 emission reductions of up to 700 kg per ton and the ability to treat up to 200 m^3 of wastewater per ton of material. Therefore, it cannot presently be considered more economical than activated carbon. Future economic evaluations should be based on functional units, such as cost per kilogram of COD removed, cost per kilogram of colour removed, and cost per cubic metre of wastewater treated, to facilitate more meaningful comparisons with conventional adsorbents. These findings suggest that, with further optimisation and validation, FBSD offers potential environmental advantages through the utilisation of agricultural waste feedstocks and reduced carbon emissions.

CONCLUSION

Functionalised biochar modified with starch derivative (FBSD) demonstrated strong potential as a polishing adsorbent for food manufacturing wastewater treatment. The material achieved substantial reductions in COD and colour, producing treated effluent that complied with regulatory discharge requirements. FBSD also maintained satisfactory performance for up to two regeneration cycles, indicating potential for reuse. However, the results also revealed a progressive decline in adsorption performance after repeated regeneration, highlighting the need for further optimisation of regeneration strategies. While FBSD offers environmental benefits through the utilisation of agricultural biomass resources, the current laboratory-scale production cost remains higher than commercial activated carbon. Therefore, although FBSD represents a promising sustainable adsorbent, additional studies on adsorption equilibrium, kinetics, and capacity using representative contaminants, process optimisation, scale-up production, and cost-per-treatment-performance evaluation are required before large-scale industrial implementation can be fully justified.

ACKNOWLEDGEMENT

The research was supported by Universiti Tun Hussein Onn Malaysia (UTHM), which provide Multidisciplinary Research (MDR) Grant (Project No. Q774).

REFERENCES

Alsawy, T., et al. (2022). A comprehensive review of the chemical regeneration of biochar adsorbent for sustainable wastewater treatment. *npj Clean Water, 5*(1), Article 35. https://doi.org/10.1038/s41545-022-00172-3

Amdeha, E. (2023). Biochar-based nanocomposites for industrial wastewater treatment via adsorption and photocatalytic degradation, and the parameters affecting these processes. *Biomass Conversion and Biorefinery*. Advance online publication. https://doi.org/10.1007/s13399-023-04512-2

Azman, N. A., et al. (2024). Improved heterocyclic aromatic hydrocarbon compound adsorption using functionalised rice husk biochar. *Bioresource Technology Reports, 25*, Article 101704. https://doi.org/10.1016/j.biteb.2023.101704

Carlini, C., et al. (2023). Benchmarking biochar with activated carbon for immobilising leachable PAH and heterocyclic PAH in contaminated soils. *Environmental Pollution, 325*, Article 121417. https://doi.org/10.1016/j.envpol.2023.121417

Chataigner, V., et al. (2023). Experimental and theoretical study of heat and mass transfer in a continuous, vertical and coaxial pyrolysis reactor for high-porosity biochar production. *Fuel, 351*, Article 128848. https://doi.org/10.1016/j.fuel.2023.128848

Dutta, A., Kumari, R., Rajbongshi, T., Sarma, J., & Rajkhowa, S. (2023). Biological methods for the treatment of industrial waste. In *Waste management and resource recycling in the developing world* (pp. 437-454). Elsevier. https://doi.org/10.1016/B978-0-323-90463-6.00022-1

Huang, X., Liu, Y., Liu, S., Tan, X., Ding, Y., Zeng, G., Zhou, Y., Zhang, M., Wang, S., & Zheng, B. (2016). Effective removal of Cr (VI) using β-cyclodextrin-chitosan modified biochars with adsorption/reduction bifunctional roles. *RSC Advances, 6*(1), 94-104. https://doi.org/10.1039/C5RA22886G

Jiang, L.-W., Zeng, F.-T., Zhang, Y., Xu, M.-Y., Xie, Z.-W., Wang, H.-Y., Wu, Y.-X., He, F.-A., & Zeng, F.-T. (2021). Preparation of a novel Fe_3O_4/graphite oxide nanosheet/citric acid-crosslinked β-cyclodextrin polymer composite to remove methylene blue from water. *Advanced Powder Technology, 32*(2), 492-503. https://doi.org/10.1016/j.apt.2020.12.026

Kong, Y.-L., Anis-Syakira, J., Fun, W. H., Balqis-Ali, N. Z., Shakirah, M. S., & Sararaks, S. (2020). Socio-economic factors related to drinking water source and sanitation in Malaysia. *International Journal of Environmental Research and Public Health, 17*(21), Article 7933. https://doi.org/10.3390/ijerph17217933

Kuok, K. K., Chiu, P. C., Rahman, M. R., Bakri, M. K. B., & Chin, M. Y. (2022). Effectiveness of centralised wastewater treatment plant in removing emerging contaminants: A case study at Kuching, Malaysia. *Journal of Water Resource and Protection, 14*(9), 650-663. https://doi.org/10.4236/jwarp.2022.149034

Mondol, M. M. H., & Jhung, S. H. (2022). Oxidative modification of metal–organic framework-derived carbon: An effective strategy for adsorptive elimination of carbazole and benzonitrile. *Fuel, 307*, Article 121764. https://doi.org/10.1016/j.fuel.2021.121764

Mongkollertlop, S., & Sookkheo, B. (2024). Specific investigation for the adsorption nature of iodine, reactive dye or wastewater model over low-priced biochar derived from biomass waste. *Research on Chemical Intermediates, 50*(2), 1013–1032. https://doi.org/10.1007/s11164-023-05198-x

Puasa, N. A., Hairom, N. H. H., Dzinun, H., Madon, R. H., Ahmad, N. S., Sidik, D. A. B., & Azmi, A. A. A. R. (2021). Photocatalytic degradation of palm oil mill secondary effluent in the presence of zinc oxide nanoparticles. *Environmental Nanotechnology, Monitoring & Management, 15*, Article 100413. https://doi.org/10.1016/j.enmm.2020.100413

Qasem, N. A. A., Mohammed, R. H., & Lawal, D. U. (2021). Removal of heavy metal ions from wastewater: A comprehensive and critical review. *npj Clean Water, 4*, Article 36. https://doi.org/10.1038/s41545-021-00127-0

Rosales, E., Ferreira, L., Sanromán, M. Á., Tavares, T., & Pazos, M. (2015). Enhanced selective metal adsorption on optimised agroforestry waste mixtures. *Bioresource Technology, 182*, 41-49. https://doi.org/10.1016/j.biortech.2015.01.094

Sathya, K., Nagarajan, K., Carlin Geor Malar, G., Rajalakshmi, S., & Raja Lakshmi, P. (2022). A comprehensive review on comparison among effluent treatment methods and modern methods of treatment of industrial wastewater effluent from different sources. *Applied Water Science, 12*(4), Article 70. https://doi.org/10.1007/s13201-022-01594-7

Sun, G., Chi, Y., Wang, Q., Huang, X., Zhang, Y., Yu, J., Tian, Z., & Yang, M. (2024). A combination of synchronised oxidation-adsorption with mesopore-rich powdered activated carbon in the deep removal of refractory COD from coking wastewater. *Journal of Water Process Engineering, 67*, Article 106128. https://doi.org/10.1016/j.jwpe.2024.106128

Metcalf & Eddy, Inc., & AECOM. (2014). *Wastewater engineering: Treatment and resource recovery* (5th ed.; G. Tchobanoglous, H. D. Stensel, R. Tsuchihashi, & F. Burton, Rev.). McGraw-Hill Education.

Towler, G., & Sinnott, R. (2022). *Chemical engineering design: Principles, practice and economics of plant and process design* (6th ed.). Elsevier.

Wahid, Z., Latiff, A. I., & Ahmad, K. (2017). Application of one-way ANOVA in completely randomised experiments. *Journal of Physics: Conference Series, 949*, Article 012017. https://doi.org/10.1088/1742-6596/949/1/012017

Wiśniewska, M., Rejer, K., Pietrzak, R., & Nowicki, P. (2022). Biochars and activated biocarbons prepared via conventional pyrolysis and chemical or physical activation of mugwort herb as potential adsorbents and renewable fuels. *Molecules, 27*(23), Article 8597. https://doi.org/10.3390/molecules27238597

Wu, Y., Wang, Z., Yan, Y., Zhou, Y., Huma, B., Tan, Z., & Zhou, T. (2024). Recovery and regeneration of water-hardened magnetic composite biochar sphere for the removal of multiple heavy metals in contaminated soils. *Journal of Cleaner Production, 450*, Article 141906. https://doi.org/10.1016/j.jclepro.2024.141906

Yuliusman, N., Afdhol, M. K., Sanal, A., Amiliana, R. A., & Hanafi, A. (2020). Synthesis and characterisation of coffee-based activated carbon with different activation methods. *IOP Conference Series: Materials Science and Engineering, 742*(1), Article 012036. https://doi.org/10.1088/1757-899X/742/1/012036

Yusoff, M. F. M., Sheikh Abdullah, S. R., Hasan, H. A., Janor, H., & Ahmad, H. (2019). Performance of continuous pilot subsurface constructed wetland using *Scirpus grossus* for removal of COD, colour and suspended solids in recycled pulp and paper effluent. *Environmental Technology & Innovation, 13*, 346-352. https://doi.org/10.1016/j.eti.2018.12.008

Zhao, B., Jiang, L., & Jia, Q. (2022). Advances in cyclodextrin polymers adsorbents for separation and enrichment: Classification, mechanism and applications. *Chinese Chemical Letters, 33*(1), 11-21. https://doi.org/10.1016/j.cclet.2021.06.031