REKAYASA
Journal of Science and Technology
https://journal.trunojoyo.ac.id/rekayasa

Rekayasa, 2025; 18(3): 375-386
ISSN: 0216-9495 (Print)
ISSN: 2502-5325 (Online)

Sustainable River Water Treatment Using Coffee Grounds: A Case Study on the Batanghari River

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DOI: https://doi.org/10.21107/rekayasa.v18i3.31002
Submitted July 15th 2025, Accepted November 29th 2025, Published December 7th 2025

Abstrak

Sungai Batanghari semakin terkontaminasi oleh polutan organik dan anorganik akibat aktivitas manusia yang intensif, menimbulkan risiko signifikan bagi ekosistem dan kesehatan masyarakat. Penelitian ini mengevaluasi potensi ampas kopi bekas—limbah organik berbiaya rendah dan ramah lingkungan—sebagai biosorben untuk memurnikan air sungai, dengan fokus khusus pada penghilangan kontaminan terlarut yang diukur dengan Total Padatan Terlarut (TDS). Ampas kopi disiapkan melalui aktivasi termal (110 °C selama 30 menit) dan diuji secara sistematis dalam sistem adsorpsi batch menggunakan dosis 1, 2, dan 3 gram untuk menentukan dosis optimal peningkatan kualitas air. Perlakuan menunjukkan efikasi tinggi di berbagai parameter kualitas air. Adsorben mencapai efisiensi penghilangan kekeruhan sebesar 91,96% yang luar biasa, secara efektif menghilangkan partikel tersuspensi. Pengurangan optimal dalam TDS tercatat sebesar 4,9 mg/L menggunakan dosis 3 gram, mengkonfirmasi keberhasilan terhadap kontaminan terlarut. Seiring waktu, tingkat pH meningkat dari 6,65 menjadi 8,16 pada dosis 2 gram, mencerminkan netralitas air yang lebih baik, dan observasi fisik mengkonfirmasi air yang sebelumnya keruh dan berbau tidak sedap menjadi tampak lebih jernih dan tidak berbau. Analisis isoterm mengungkapkan bahwa proses adsorpsi diatur oleh model Langmuir, yang menegaskan mekanisme adsorpsi monomolekul yang menguntungkan. Hal ini dibuktikan dengan kapasitas adsorpsi maksimum (Q_{max}) sebesar 10,50 mg/g dan faktor pemisahan (R_L) sebesar 0,21. Hasil ini secara kuat menetapkan ampas kopi bekas sebagai solusi yang sangat mudah diakses dan berkelanjutan untuk remediasi lingkungan, menawarkan jalur yang layak untuk memulihkan kualitas air sungai sambil memanfaatkan limbah pertanian.

Kata Kunci: pengolahan air, adsorben ampas kopi, isoterm adsorpsi, kualitas air, model langmuir

Abstract

The Batanghari River is increasingly contaminated by organic and inorganic pollutants resulting from intensive human activities, posing significant risks to both ecosystems and public health. This study evaluates the potential of spent coffee grounds—a low-cost, eco-friendly organic waste—as a biosorbent to purify the river water, specifically focusing on the removal of soluble contaminants measured by Total Dissolved Solids (TDS). The coffee grounds were prepared via thermal activation (110 °C for 30 min) and systematically tested in a batch adsorption system using dosages of 1, 2, and 3 grams to determine the optimal dosage for water quality improvement. The treatment demonstrated high efficacy across multiple water quality parameters. The adsorbent achieved an outstanding turbidity removal efficiency of 91.96%, effectively eliminating suspended particles. The optimal reduction in TDS was recorded at 4.9 mg/L using the 3-gram dosage, confirming success against soluble contaminants. Concurrently, the pH level increased from 6.65 to 8.16 at the 2-gram dose, reflecting improved water neutrality, and physical observations confirmed the murky, foul-smelling water became visibly clearer and odorless. Isotherm analysis revealed that the adsorption process is governed by the Langmuir model, confirming a favorable monolayer adsorption mechanism. This is evidenced by a maximum adsorption capacity (Q_{max}) of 10.50 mg/g and a separation factor (R_L) of 0.21. These results robustly establish spent coffee grounds as a highly accessible and sustainable solution for environmental remediation, offering a viable pathway for restoring river water quality while utilizing agricultural waste.

Key words: *water treatment, coffee grounds adsorbent, adsorption isotherm, water quality, langmuir model*

INTRODUCTION

Water is an essential natural resource, but increasing anthropogenic pressures have led to a significant decline in its quality worldwide, posing threats to human health and ecosystem balance (du Plessis, 2022). Poor water quality diminishes the usability, productivity, and carrying capacity of water resources, a critical concern as global population growth and urbanization accelerate (Eko Wiriani, 2020).

Addressing water pollution, particularly in vital ecological areas, remains a pressing environmental and public health challenge globally.

The Batanghari River is one of Sumatra's longest and most important waterways. It currently faces dire pollution challenges exacerbated by a massive pollutant overage of 18.22 tons/hour driven by intense anthropogenic activities such as agriculture, industrial work, and urban marketplaces (Eko Wiriani, 2020). Previous studies confirm the severity of the crisis, noting that the river is heavily contaminated with toxic heavy metals, including lead (Pb), manganese (Mn), cadmium (Cd), and mercury (Hg), primarily due to industrial discharges (Yanova et al., 2022). The resultant bioaccumulation of these metals in local biota, such as mussels, demonstrates profound ecological impacts and public health concerns.

While many existing studies on the Batanghari River pollution focus on Total Suspended Solids (TSS), this research introduces a crucial focus on Total Dissolved Solids (TDS). TDS, a measure of soluble pollutants at the molecular or ionic level, offers a more effective measurement for chemical pollution, such as salinity and heavy metals, which are the specific toxins identified in the river (Adjovu et al., 2023). TDS directly influences electrical conductivity and treatment effectiveness, and its use as a primary metric provides a novel angle to assess the efficacy of advanced water purification techniques compared to previous TSS-centric approaches.

Conventional wastewater treatment methods, such as coagulation, flocculation, and advanced oxidation processes, are effective but suffer from major disadvantages, including high operational costs, high energy consumption, and the production of secondary chemical pollution (Hama Aziz & Mustafa, 2024). This context creates an urgent need for sustainable, low-cost, and emission-free alternatives. The development and use of natural biosorbents derived from agricultural and industrial waste offer a promising pathway to replace chemical processes, especially in developing regions with limited resources (Karić et al., 2022).

This research, therefore, focuses on evaluating spent coffee grounds as a low-cost, eco-friendly natural adsorbent. Prior work has established that coffee grounds are rich in hydrocarbons and contain biopolymers like cellulose and lignin that facilitate complexation and ion exchange—key mechanisms for binding heavy metals and organic substances (Lafi et al., 2014; McNutt & He, 2019). Specifically, this study aims: (1) to measure the effect of the coffee grounds adsorbent's mass on water quality parameters, focusing on TDS, turbidity, pH, and electrical conductivity; and (2) to determine the ideal adsorbent dosage that would effectively purify the highly polluted Batanghari River water. The ultimate goal is to provide accessible, appropriate treatment knowledge for ecologically restoring river water quality.

RESEARCH METHOD

This study examined how well coffee grounds can clean water from the Batanghari River using a quantitative experimental method. In October 2024, we collected water samples from the Batanghari River near Jambi City. Coffee grounds sourced from one of the Jelutung coffee shops in Jambi City serve as the main adsorbent material.

Preparation

Preparation and activation of coffee grounds adsorbent was carried out through several stages. First, the coffee grounds were washed with distilled water to remove impurities and residues still attached. After washing, the coffee grounds were physically activated by heating at 250°C for 3 hours in an oven to increase porosity and surface area. The heated sample was rewashed with distilled water at 30°C until it reached a neutral pH (pH = 7) to remove any remaining chemical compounds. The final preparation stage was drying the coffee grounds at 110°C for 30 minutes to remove the water content and ensure the adsorbent was perfectly dry before being used in adsorption.

Purification

The purification process of Batanghari River water using coffee grounds adsorbent was carried out with adsorbent mass variations of 1 g, 2 g, and 3 g for a constant water volume of 200 ml. Water samples and adsorbents were mixed in a glass beaker and stirred using a magnetic stirrer at 150 rpm for 30 minutes at room temperature to ensure optimal contact between adsorbents and contaminants in water. After

stirring, the mixture was filtered using filter paper to separate the adsorbent from the treated water. The filtered water was then taken to be analyzed for quality parameters.

Sample Preparation, Instrumentation, and Data Collection Procedures

This study was conducted through the preparation of water samples from the Batanghari River, preparation of coffee grounds, purification procedures, and the measurement of Batanghari River water quality after purification. Contaminated or turbid Batanghari River water was collected from its source. Since the coffee grounds used were only dried and extracted, frequent washing of the coffee grounds was not necessary when used as an adsorbent. Data measurement was carried out after the purification process, comparing the water quality of Batanghari River before and after treatment with coffee grounds adsorbent through data analysis.

Analytical Techniques and Data Processing

Data for this study were collected through testing the water quality of Batanghari River samples treated with coffee grounds adsorbent. The parameters analyzed included temperature, total dissolved solids (TDS), turbidity, color, odor, pH, thermal conductivity (inductivity), as well as calculations of adsorption capacity and removal efficiency for each parameter. TDS and conductivity were measured using a digital TDS & EC meter (range up to 9990 ppm/µS/cm) manufactured in China. Turbidity was analyzed using the Lutron TU-2016 turbidimeter from Taiwan, with a measurement capability up to 1000 NTU. pH was determined using a digital pH meter by APLUSTE, made in China. Temperature was measured with a digital thermometer. We used sensory observation to check for changes in color and odor of the water.

Adsorption capacity and removal efficiency were calculated by looking at the differences between the initial and final values of each tested parameter. All data were gathered in controlled laboratory conditions. The data were analyzed to assess how effective coffee grounds are as an adsorbent in purifying Batanghari River water.

The data obtained from measurement of Total Dissolved Solids (TDS), turbidity, color, pH, electrical conductivity, and removing capacity and removal efficiency have been analyzed thoroughly to understand the performance of coffee ground-based adsorbents in the purification of Batanghari River water. Each of the mentioned parameters was examined with the goal of knowing the capacity of the coffee ground adsorbents to lower contaminant levels in Batanghari River water, the main environmental problem.

High TDS concentrations, turbidity levels, and color in the Batanghari River show poor water quality, making it often unsuitable for use. We analyzed these parameters to assess how well the adsorbent can reduce these values. We also examined pH to see if the adsorbent could bring the water closer to neutral, in line with standard water quality requirements. We measured electrical conductivity to evaluate the water's physical characteristics after purification, indicating changes in solution properties due to interactions with the adsorbent.

Removal capacity and removal efficiency analyses were conducted to assess how well the coffee grounds adsorbent lowers the concentration of contaminants in Batanghari River water for each tested parameter. The adsorption capacity (qe) and removal efficiency (%) were calculated using the following equations:

$$q_e = \frac{(C_0 - C_e) \times V}{m} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

$$Removal\ efficiency = \frac{(C_0 - C_e) \times V}{C_0} \times 100\% \dots\dots\dots (2)$$

Where:

q_e = adsorption capacity (mg/g)

C_0 = initial concentration of contaminant (mg/L)

C_e = equilibrium or final concentration of contaminant (mg/L)

V = volume of solution (L)

m = mass of adsorbent (g)

Adsorption Isotherm Analysis

Adsorption isotherm analysis supports an understanding of the adsorption mechanism and the surface properties of coffee ground biosorbents in removing dissolved contaminants from Batanghari River water. The results of a two isotherm model were used Langmuir and Freundlich. The Langmuir isotherm is an empirical model based on kinetic theory where the rates of adsorption and desorption on the surface come into balance thereby achieving no net change at equilibrium. The Langmuir isotherm is developed based on several assumptions which are (a) the adsorption process take place in a single layer, (b) all the adsorption sites are saturated equally, (c) the energy of adsorption remains constant, and (d) there are no interactions between the molecules adsorbed in neighbouring sites (Kalam et al., 2021). Under these assumptions the Langmuir isotherm can be expressed:

$$qe = qm - \left(\frac{1}{KL}\right) \times \frac{qe}{Ce} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where C_e is the equilibrium concentration of the pollutant (mg/L), q_e is the adsorption capacity at equilibrium (mg/g), K_L is the Langmuir constant (L/mg), and Q_m is the maximum adsorption capacity (mg/g). Its linear form can be represented by Equation (4).

$$q_e = \frac{q_m K_L C_e}{1 + K_L C_e} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

A significant parameter associated with the Langmuir isotherm is the separation factor, or equilibrium parameter (R_L), which serves to determine whether the adsorption process is favorable or not. Mathematically, R_L is defined as:

$$R_L = \frac{1}{(1 + K_L \times C_0)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where K_L is the Langmuir constant and C_0 is the highest initial concentration of the adsorbate. Generally, an R_L value less than 1 (R_L<1) signifies favorable adsorption; an R_L value close to 0 (R_L=0) suggests the process is irreversible; R_L=1 implies a linear isotherm; and R_L>1 indicates unfavorable adsorption. The Freundlich isotherm, represented in Equation (6) along with its linear form in Equation (7), describes adsorption on heterogeneous surfaces, where interactions occur among adsorbed molecules. Additionally, the Freundlich equation indicates that the adsorption energy decreases exponentially as the adsorption sites on the adsorbent become increasingly occupied (Yen & Lin, 2016).

$$q_e = K_F C e^{\frac{1}{n}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$\ln q_e = \ln K_F + \left(\frac{1}{n}\right) \ln C_e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

RESULTS AND DISCUSSIONS

Characteristics of Batanghari River Water Before Treatment

The Batanghari River water prior to treatment exhibited signs of significant pollution, characterized by a high turbidity value of 99 NTU, acidic pH at 6.65, and substantial *Escherichia coli* (E. Coli) contamination measured at 70 µg/cm. The presence of organic matter and microbial contamination was further supported by organoleptic observations, which described the water as being extremely murky and having a fishy smell. These features are in line with findings from earlier research (Eko Wiriani, 2020), which pointed out that anthropogenic inputs from industry, agriculture, and household waste discharge frequently cause the Batanghari River's total suspended solids (TSS) to surpass environmental capacity thresholds. Table 1 shows the water quality of the Batanghari River.

Table 1. The water quality of the Batanghari River

Parameter	Value
Temperature	29.9 °C
Total Dissolved Solids	35 ppm
Turbidity	99 NTU
Color	Very Cloudy
Odor	Fishy
pH	6.65
Thermal conductivity	70 µg/cm
Volume	200 ml

The pre-treatment state demonstrates the pressing need for long-term, efficient water purification methods. Increased TDS and microbial activity indicate the presence of potentially dangerous organic pollutants in addition to inorganic ions. The environment and public health are at risk when chemical and biological contamination coexist. In order to develop affordable, locally applicable solutions for river pollution in rural and semi-urban areas, it is crucial to evaluate natural biosorbents like coffee grounds.

Effect of Varying Adsorbent Mass on Physical and Chemical Water Quality

The effectiveness of coffee grounds as a sustainable adsorbent in the treatment of Batanghari River water was evaluated in this study. The adsorbent mass variations applied were 1 g, 2 g, and 3 g, with untreated river water (0 g) serving as the control. Physical parameters observed included Total Dissolved Solids (TDS), turbidity, color, and odor. In addition, chemical parameters such as pH changes and E. coli concentrations were analyzed to assess the impact of the adsorbent on water acidity and microbial contamination. The analysis results are presented in Table 2.

Table 2. The Effect of Coffee Grounds Waste Adsorbent Variation on the Quality Parameters of Batanghari River Water

Parameter	Adsorben Mass			
	0 g	1 g	2 g	3 g
Temperature	29.9 °C	30.4 °C	30.5 °C	29.1 °C
TDS	127 ppm	53 ppm	90 ppm	53 ppm
Turbidity	99 NTU	8.63 NTU	8.20 NTU	7.95 NTU
Color	Very cloudy	Clear brownish	Clear brownish	Clear brownish
Odor	Fishy	Odorless	Odorless	Odorless
pH	6.65	7.36	8.16	7.46
Thermal conductivity	70 µg/cm	106 µg/cm	186 µg/cm	146 µg/cm
Volume	200 ml	130 ml	151 ml	155 ml

Total Dissolved Solids (TDS)

With different dosages of coffee ground adsorbents, the experimental data showed a non-linear trend in TDS removal. Although the TDS was significantly reduced from 127 ppm to 53 ppm (approximately 58.27% removal efficiency) by the 1 g and 3 g doses, the intermediate 2 g dose unexpectedly produced a smaller reduction, with the final TDS measured at 90 ppm. This irregularity emphasizes the complexity of adsorbent–adsorbate interactions in such systems and implies that the adsorption process does not show a straightforward linear relationship with adsorbent mass.

This behavior is consistent with the adsorption characteristics that have been reported in previous studies. Nandiyanto et al. (2020) pointed out that the adsorption equilibrium, when taking into consideration surface saturation, can change when using some dosages, leading to the agglomeration or clustering of adsorbent particles which will lower the effective surface area and the performance in terms of ion exchange and adsorption even though more mass is available.

Similarly, Mariana et al. (2021) investigated coffee-derived biosorbents found that the pore-blocking effect along with structural properties modified through chemical activation could increase or decrease adsorption performance depending on the particular chemical. In batch conditions, adsorbent

inconsistencies might also result from residual moisture, unstable particle dispersion, or poor internal diffusion.

Additionally, the study conducted by Hidayatulloh et al. (2024) mentioned that the performance of adsorption is very dependent on equilibrium time and consistency of adsorbent materials. The results of the methylene blue removal by coffee ground bioadsorbents indicated that inconsistent surface properties like those found in unoptimized or mixed adsorbent systems would cause different pollutant removal efficiencies under the exact same mass. These studies suggest that the inconsistencies observed at the 2 g dose in this study could be attributed to early saturation, heterogeneous dispersion, or a smaller mass transfer driving force if certain dosages were used. This emphasizes the importance of optimization in not only the amount of adsorbent, but also in physical preparation, particle size and agitation intensity if the consumer is to achieve consistent and replicable TDS removal in real life water treatments.

Besides the changes in concentration, the adsorption efficiency was determined based on the removal percentage and adsorption capacity. The maximum removal percentage of 58.27 was obtained for both 1 g and 3 g dosages, while the maximum adsorption capacity, qe, of 16.4 mg/g occurred at 2 g, which corresponds to the optimal concentration ratio of adsorbent to adsorbate maintained under batch conditions. This non-linear relationship, however, is a testament to saturation dynamic, in which higher adsorbent mass could induce agglomeration and/or limit surface accessibility, as expressly mentioned by Nandiyanto et al., (2020). Similar saturation behavior was reported by Mariana et al. (2021), who emphasized the role of surface deactivation and porosity loss at higher adsorbent loads. Moreover, Hidayatulloh et al. (2024) suggested that at certain dosages, leaching or desorption may occur due to competitive adsorption between soluble coffee components and existing solutes. These findings reinforce the need for dosage optimization in real-world applications, especially in low-cost biosorbent systems such as coffee grounds. These performance trends are further illustrated in Figure 1, which displays the inverse relationship between removal efficiency and adsorption capacity across the adsorbent mass variations

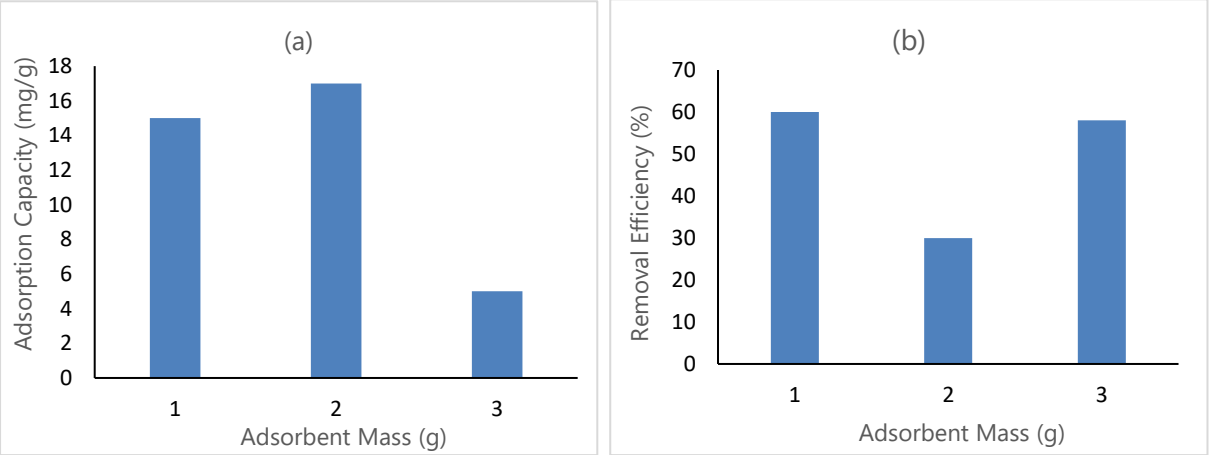


Figure 1. Effect of coffee grounds waste adsorbent mass on (a) adsorption capacity and (b) removal efficiency in tofu wastewater treatment

Reduction of Turbidity

In contrast to TDS, turbidity demonstrated a clear and consistent reduction as adsorbent dosage increased, emphasizing the effectiveness of coffee grounds in adsorbing suspended solids. The initial turbidity of 99 NTU was reduced dramatically to 8.63 NTU, 8.20 NTU, and 7.95 NTU at adsorbent dosages of 1, 2, and 3 grams respectively, each demonstrating removal efficiencies above 91%. These findings underline the robust capability of coffee grounds to serve as effective coagulants for suspended particulate matter, significantly improving water clarity. These experimental results strongly correlate with findings reported by Yustinah et al. (2022), who demonstrated that activated carbon derived from coffee grounds possesses excellent capability for capturing suspended solid particles, attributed primarily to the porous structure and the extensive surface area of the adsorbent. Shah et al., (2023) further backed these findings

by emphasizing how well natural biocoagulants created from organic trash including coffee grounds remove total suspended solids (TSS) via coagulation and flocculation processes. Taken together, these research validate coffee grounds as environmentally friendly adsorbents and natural coagulants.

Additional comparative analysis indicates that refining the particle size distribution and amount of the adsorbent may further improve the efficacy of turbidity removal. Widodo et al., (2020) indicate that the dimensions and consistency of adsorbent particles notably affect the efficiency of suspended solids removal, suggesting that precise management of these factors may enhance performance results. Therefore, subsequent research must focus on refining adsorbent preparation techniques and application parameters, enhancing the practical feasibility of coffee grounds as a cost-effective and eco-friendly option for decreasing turbidity in water treatment processes.

Color and Odor

The use of coffee grounds on Batanghari River water showed significant enhancements in color and odor properties. Before adsorption, the river water was clearly cloudy with a deep and unclear look, coupled with a strong fishy smell, suggesting considerable organic and potentially inorganic pollution. Following the application of coffee ground adsorbents, visual observations confirmed the transformation of the water from highly turbid to a clearer, transparent brownish color, coupled with a notable reduction in the previously detected unpleasant odor.

These improvements align with previous research on pollutant removal utilizing coffee-ground-based adsorbents. Chen et al., (2022) found that activated carbon made from coffee waste was similarly effective in eliminating volatile organic compounds that cause odors, crediting this efficacy to the adsorbent's high porosity and functional surface groups that can chemically and physically bind to contaminants. Additionally, the observed improvement in water clarity is consistent with findings by Badariah et al., (2023), who highlighted the prevalence of heavy metal contamination and sediment-associated pollutants in the Batanghari River. Their study emphasizes that substantial contamination by particulate-bound metals significantly influences both the turbidity and coloration of river waters in Jambi Province.

Further corroboration comes from recent investigations into the effectiveness of spent coffee grounds in removing colored substances from contaminated water. Woo et al., (2017) demonstrated that carbonized coffee waste effectively adsorbs color-causing pollutants and odor-producing aldehyde compounds due to the rich lignocellulosic composition and high porosity of coffee waste. Consequently, the coffee-ground adsorbent not only removes suspended solids but also captures dissolved organics, substantially improving aesthetic water quality. Considering these aligned findings, spent coffee grounds present a highly viable, sustainable, and economical option for remediation practices targeting both visual and odor pollutants in river water treatment systems.

pH Changes

The utilization of coffee grounds as an adsorbent exhibited significant capacity to alter the pH of Batanghari River water from its initial acidic state (pH 6.65) to neutral or slightly alkaline conditions. The most substantial increase in pH was observed at an adsorbent dose of 2 grams, elevating the pH to 8.16. Comparatively, moderate increases were noted with doses of 1 gram (pH 7.36) and 3 grams (pH 7.46). These variations indicate a non-linear correlation between adsorbent mass and pH adjustment efficiency, highlighting the necessity for dose optimization when considering practical, large-scale applications.

The noted rise in pH corresponds with the results from Kang et al., (2022) who indicated that coffee waste, abundant in cellulose and lignin polymers, naturally exhibits alkaline properties. These properties aid in the discharge of fundamental ions during adsorption, efficiently counteracting acidic elements present in the water. Additionally, Tran et al., (2022) noted that physically activated carbon from coffee grounds greatly improves the material's ability to neutralize, due to the higher porosity and active surface functional groups of the adsorbent that interact with and mitigate acidic components.

Modifying water pH to be more neutral enhances aesthetic quality, decreases corrosion risk, and improves the effectiveness of following treatment methods, like chemical disinfection, which usually works best under near-neutral conditions. As a result, coffee grounds can fulfill two functions, serving as both

efficient adsorbents and pH stabilizers. Additional studies concentrating on optimizing adsorbent conditions and their practical uses are suggested to maximize these neutralizing effects and successfully incorporate them into wider water treatment systems (Kang et al., 2022; Tran et al., 2022).

Electrical Conductivity (EC)

Electrical conductivity (EC) acts as an essential metric in evaluating water quality, as it indicates the level of dissolved ionic materials in the water. In this research, the EC levels of Batanghari River water indicated a rising trend following treatment with coffee ground adsorbents. The untreated sample exhibited an EC of 70 µg/cm, which rose to 106 µg/cm following the incorporation of 1 gram of adsorbent. The EC reached a maximum of 186 µg/cm with a 2-gram dosage and then slightly dropped to 146 µg/cm at 3 grams.

This pattern suggests that although the adsorbent could engage with dissolved solids, it might have simultaneously released soluble organic or ionic substances into the solution throughout the process. (Blinová & Sirotiak, 2019) noted that spent coffee grounds, even with their adsorption abilities, can release low-molecular-weight organic compounds and minerals into treated water, particularly during physical activation. In a similar manner. Similarly, Kim & Kim, (2020) observed that ionic exchange during adsorption might cause brief spikes in conductivity, particularly when metal ions or soluble substances from the adsorbent are released into the solution.

Volume Reduction

Besides enhancing water quality, the use of coffee ground adsorbents showed an effect on the physical volume of wastewater. After treatment, there was a decrease in the final volume of water, with losses between roughly 10 mL and 20 mL across different dosages. This reduction could be linked to various factors, such as water retention in the porous structure of the coffee grounds, moisture absorption by the organic components, and slight evaporation occurring during mixing and settling. The porous nature of spent coffee grounds is recognized for its significant ability to retain moisture, potentially resulting in the physical trapping of water within the adsorbent particles. (Alghamdi et al. (2024) showed that biochar from coffee waste greatly enhanced water retention in sandy soils because of its porous and water-attracting properties, which probably exhibit similar effects in water-based systems. Similarly, (Blinová & Sirotiak, 2019) observed that used coffee grounds can take up water and impurities during the treatment process, leading to a significant decrease in filtrate volume.

Adsorption Isotherm Data

The Langmuir model provided an R^2 value of 0.57, a maximum adsorption capacity (Qm) of 10.50 mg/g, and a Langmuir constant (KL) of 0.029 L/mg. Furthermore, the determined separation factor (RL) was roughly 0.21, suggesting advantageous adsorption. The RL value, which is below 1, indicates a strong affinity between the dissolved solids and the coffee ground biosorbent. This type of RL value is often observed in research where adsorbents show effective performance against specific pollutants, signifying that the adsorption process functions well within the tested concentration range.

Table 3. Adsorption Isotherm Model Results

Isotherm	Parameters	Constant
Langmuir		
	R^2	0.57
	K_L (L/mg)	0.029
	Q_m (mg/g)	10.50
Freundlich		
	R^2	0.44
	K_F	1.83
	n	2.12

The average Q_m value of 10.50 mg/g is consistent with the values documented in the literature for biosorbents derived from coffee or agricultural waste (Kyzas, 2012; Mariana et al., 2021). The Langmuir model posits that monolayer adsorption occurs on a uniform surface, indicating that the biosorbent surface

created from thermally processed coffee grounds offers a fairly consistent adsorption environment. Additionally, the K_L value of 0.029 L/mg indicates a moderate affinity between the dissolved solids and the adsorbent, which is advantageous for real-world uses. This moderate affinity is beneficial because it enables efficient adsorption while also allowing for regeneration or desorption as needed.

In contrast, the Freundlich model, which is often applied to heterogeneous surfaces and multilayer adsorption systems, resulted in an R^2 value of 0.44, a Freundlich constant (K_F) of 1.83, and an adsorption intensity (n) of 2.12. The n value being greater than 1 indicates that the adsorption process is favorable and, in this instance, appears to reflect a primarily physical adsorption process rather than a strongly chemisorptive one. However, the lower overall R^2 value compared to the Langmuir model suggests that the Freundlich model is less representative of the adsorption behavior for this system.

The higher coefficient of determination provided by the Langmuir model (R^2 = 0.57) compared to the Freundlich model (R^2 = 0.44) indicates that the adsorption of dissolved solids on coffee ground biosorbent is better described by a monolayer adsorption mechanism. This observation is in line with the inherent properties of the thermally treated coffee grounds, which, due to the pyrolysis process, tend to develop a relatively homogeneous surface. Similar findings were noted by Kyzas (2012) and Mariana et al. (2021) in studies using coffee-based adsorbents, where a Langmuir-type adsorption was reported.

The Freundlich model's lower R^2 value and its parameters (K_F = 1.83; n = 2.12) point out that, while the adsorption process is favorable, the heterogeneity and potential for multilayer adsorption are not the dominant processes in this system. The n value greater than 1 confirms favorable adsorption energetics but, in this context, supports the interpretation that adsorption occurs predominantly in a monolayer fashion, emphasizing physisorption rather than chemisorption. This is reinforced by the moderate binding strength indicated by the Langmuir constant.

Despite these findings, the moderate R^2 values obtained for both models suggest that there could be additional factors or complexities not fully captured by either isotherm. It is likely that optimizing the adsorbent preparation procedure, fine-tuning operational conditions, or even exploring hybrid adsorption models could provide a better fit. Such improvements have been recommended in similar studies (e.g., Lafi et al., 2014; Yustinah et al., 2022) to enhance performance and achieve adsorption efficiency closer to that of commercial activated carbons.

The findings indicate that the thermally processed coffee ground biosorbent displays a strong adsorption ability with properties that closely match the Langmuir model. The moderate K_L and advantageous R_L values suggest that the material provides a potential, cost-effective option for water purification. Future efforts may concentrate on refining process variables and integrating this biosorbent with additional treatment techniques to boost performance, thereby improving its practical use for wastewater cleanup. The findings of the adsorption isotherm modeling are presented in Table 5. The Langmuir model yielded an R^2 value of 0.57, a maximum adsorption capacity (Q_m) of 10.50 mg/g, and a Langmuir constant (K_L) of 0.029 L/mg. The Freundlich model produced an R^2 value of 0.44, with a constant (K_F) of 1.83 and an intensity of adsorption (n) of 2.12.

These findings suggest that the uptake of dissolved solids by coffee ground biosorbent fits the Langmuir model better than the Freundlich model, evidenced by the superior coefficient of determination (R^2). This indicates a mainly monolayer adsorption process on a fairly uniform surface, aligning with the physical and chemical properties of coffee grounds that have been thermally processed. The maximum adsorption capacity (Q_m) of 10.50 mg/g is similar to values found in earlier studies using coffee-derived or agro-waste biosorbents for water treatment (Kyzas, 2012; Mariana et al., 2021).

The Langmuir constant (K_L) signifies a moderate binding strength between the adsorbate and adsorbent, which is beneficial for practical uses as it facilitates effective adsorption without excessively strong or irreversible binding. The Freundlich adsorption intensity (n=2.12), which exceeds 1, further indicates that the adsorption process is favorable and primarily physical (physisorption) in nature (Gupta & Suhas, 2009).

These results align with Kyzas (2012), who indicated that spent coffee grounds and their activated forms generally display monolayer adsorption as a result of the relatively consistent surface characteristics formed via pyrolysis or thermal activation. Similarly, Mariana et al. (2021) discovered that biochar derived

from coffee endocarp exhibited Langmuir-like characteristics for lead extraction from water, validating the relevance of the Langmuir model for coffee-based adsorbents. The Q_m and K_L values found in this study fall within the range observed in other research, highlighting the efficacy of coffee grounds as a cost-effective, sustainable adsorbent.

Nevertheless, the reasonable R^2 values noted indicate that additional optimization, like improving adsorbent preparation, modifying operational parameters, or integrating with alternative treatment techniques, might improve effectiveness and model alignment. Such enhancements are frequently mentioned in the literature as essential measures to attain adsorption efficiencies nearer to those of commercial activated carbon (Lafi et al., 2014; Yustinah et al., 2022).

The calculated separation factor (R_L) in this study was around 0.21, suggesting favorable adsorption based on the Langmuir model. This value indicates a strong attraction between dissolved solids and the biosorbent made from coffee grounds, aligning with the notable adsorption capacity noted. Notably, comparable R_L values have been documented in research utilizing coffee ground-based adsorbents for different kinds of water, including synthetic solutions and industrial wastewater (Kyzas, 2012; Mariana et al., 2021). These results validate that the Langmuir isotherm is broadly relevant to coffee ground adsorption across various water matrices, not just in Batanghari River water. Consequently, the strong alignment of the Langmuir model further illustrates the adaptability and efficiency of coffee grounds as an eco-friendly biosorbent in various environmental conditions.

CONCLUSIONS

This research shows that thermally activated spent coffee grounds act as efficient, economical biosorbents for enhancing the quality of contaminated Batanghari River water. Notable improvements in water quality were accomplished, featuring turbidity reductions greater than 91%, TDS declines reaching 58.27%, pH restored to neutral or slightly alkaline ranges, and total odor removal. These findings validate the adsorbent's effectiveness in eliminating both physical and chemical contaminants effectively. Adsorption isotherm analysis revealed that the process is best described by the Langmuir model, suggesting monolayer adsorption on a relatively homogeneous surface. The moderate Langmuir constant (K_L = 0.029 L/mg) and favorable separation factor (R_L = 0.21) confirm the practicality and reliability of coffee grounds in adsorption applications. However, the nonlinear TDS response and moderate R^2 values in isotherm modeling indicate that adsorption dynamics are influenced by multiple variables, such as particle dispersion, saturation, and mass transfer effects. In conclusion, coffee grounds are a promising alternative for sustainable water treatment in resource-limited settings. For broader application, future research should focus on optimizing operational conditions, improving adsorbent activation methods, and integrating disinfection steps to ensure compliance with potable water standards. These developments would further enhance the scalability and effectiveness of coffee ground biosorbents in diverse environmental contexts.

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