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Adsorption Effectiveness of Coffee Grounds Activated Carbon in Reducing Iron (Fe) Control in Water

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High iron (Fe) content in water can be harmful to human health. A viable approach to diminish iron levels involves the utilization of an adsorbent, specifically activated carbon produced from coffee grounds. This study explores using activated carbon made from coffee grounds, treated with Nitric Acid (HNO_3), to reduce Fe levels in water. The experiment used a pretest-posttest controlled group design with 31 samples of 500 ml Fe solution. Adsorption was done using the batch method, with different adsorbent doses (0.5 and 1.5, g) and stirring times (30, 60, 120, 180, and 360 minutes) at 150 rpm and 80 mesh particle size. Data were analyzed using Two Way ANOVA. The study successfully produced activated carbon from coffee grounds, with water content at 1.46%, ash content at 8.58%, and iodine absorption of 1038 mg/g. The highest Fe reduction occurred at a 0.5 g dose and 120-minute contact time, resulting in 0.014 mg/l of Fe. Two Way ANOVA results showed a p-value above 0.05, indicating no significant difference. The adsorption followed the Freundlich isotherm model (R^2 = 0.9879), while the kinetics followed a zero-order model (R^2 = 0.2476). The findings suggest that coffee grounds are an effective adsorbent for reducing iron levels in water, though further research is needed to address water turbidity without compromising adsorption efficiency.

Keywords: Activated carbon; Adsorption; Coffee grounds; Iron (Fe); Isotherm model

INTRODUCTION

Water is an essential component that sustains life on our planet. The quality of clean water is crucial for preserving human health and ensuring environmental sustainability. Heavy metal contamination of water is a global issue that arises from the processes of bioaccumulation and biomagnification within the food web, coupled with the inherent toxicity of these metallic elements (Damayanty et al., 2020). The presence of metal contaminants in water sources can significantly endanger human health and adversely affect aquatic ecosystems (Sonone et al., 2021). Iron (Fe) is one such metal that can infiltrate groundwater supplies. This metal is frequently detected in both groundwater and surface water. Elevated levels of iron in water can lead to a range of health issues for humans, including serious conditions such as cancer, hyperkeratosis, melanosis, peripheral vascular disease, lung disease, and hypertension (Khalid et al., 2020).

Elevated concentrations of iron (Fe) can be affected by a range of factors, particularly groundwater contamination stemming from anthropogenic activities. Contributing elements include household waste, runoff from iron-rich sources, the buildup of industrial byproducts, the deterioration of iron water pipes, and inadequate handling of chemical effluents (Selviana et al., 2025). It is essential to implement strategies aimed at decreasing iron levels in well water to meet established quality standards. One method that can be used is adsorption.

Adsorption is considered effective due to its high efficiency, affordable cost, and ease of operation (Wołowiec, 2019). During the adsorption process, the constituents of a flowing fluid are either separated or purified by adhering to the surface of a solid material known as an adsorbent (Alkhaldi et al., 2024). Different adsorbent materials can enhance the process of adsorption, with activated carbon serving as a notable example. This material is characterized by the presence of metal ions and water molecules (Nurullita & Mifbakhuddin, 2016). Activated carbon can be derived from natural substances that contain lignocellulose (Lubis et al., 2020). Coffee grounds represent one such natural source of lignocellulose. According to research conducted by Baryatik et al. (Baryatik et al., 2019), the composition of coffee grounds comprises 47.8-58.9% carbon, 1.9-2.3% nitrogen, 6.7-13.6 g of protein per 100 g, 0.43-1.6% ash, and 8.6% cellulose.

Previous research has revealed that activated carbon from coffee grounds is effective in reducing aniline yellow levels in water (Pagalan et al., 2020). The use of coffee grounds activated carbon was able to reduce aniline yellow ranging from 75.01% to 95.52% with the best activator being the basic activator, KOH. The results of research by Baryatik et al.,(Baryatik et al., 2019) also showed that the use of activated carbon from coffee grounds can reduce the concentration of cadmium (Cd) in well water up to 55.75% with a mass of 10 gr/l coffee grounds adsorbent.

According to Indonesia's Central Bureau of Statistics (BPS) (Perkebunan, 2023), East Java Province was the foremost contributor to coffee production from Large Plantations (PB) in 2022, with a total output of 3.39 thousand tons, representing 85.15% of the overall PB production in Indonesia. The population's passion for coffee is fueled not only by its distinctive regional traits but also by the variety of flavors offered by different coffee types. As coffee consumption rises, the amount of waste generated from coffee grounds also increases. This study seeks to evaluate the efficacy of activated carbon produced from coffee grounds in lowering iron (Fe) concentrations in water.

METHODS

grounds consists of three phases: rendering, dehydration, and activation. First, the coffee grounds are placed in an Erlenmeyer tube, sealed, and autoclaved for 30 minutes at 121°C. Next, dehydration is done by heating the grounds to 120°C. Activation is completed by treating the carbon with a 0.3 M HNO_3 solution. Robusta coffee grounds used in this study. The quality of the activated carbon is tested for moisture content, ash content, and iodine absorbency, compared to the SNI 06-3730-1995 standard for technical activated charcoal. For powdered activated carbon to be considered high-quality, it should possess a moisture content not exceeding 15%, an ash content that does not surpass 10%, and an iodine adsorption capacity of at least 750 mg/g.

The adsorption process used varying masses of coffee grounds adsorbent (0.5 g and 1.5 g) in a 500 ml artificial iron solution. The pH of the solution was maintained at pH 6 as a controlled variable during the adsorption process, considering that pH is a critical factor influencing metal ion adsorption. pH 6 was selected to represent near-neutral conditions commonly found in water systems. Stirring was done at 150 rpm for 30, 60, 120, 180, and 360 minutes, after which the solution was filtered to separate the adsorbent. The resulting filtrate was tested for iron content using the SSA method. A Two-Way ANOVA was performed to examine the impact of adsorbent mass and stirring duration on the reduction of iron. Furthermore, the structure and pore dimensions of the activated carbon were analyzed through Scanning Electron Microscopy (SEM) at various magnifications (1000x, 3000x, 5000x, 10000x).

RESULTS AND DISCUSSION

Activated Carbon Characterization

The conversion of coffee grounds into activated carbon consists of multiple specific phases. Once the coffee grounds have been transformed into activated carbon, a characterization process is conducted to evaluate the quality of the activated carbon. This evaluation includes parameters such as ash content, moisture content, iodine adsorption capacity, and scanning electron microscopy (SEM). The assessment of ash content, moisture content, and iodine adsorption capacity is intended to verify whether the activated carbon derived from coffee grounds complies with the standards set forth in SNI 06-3730-1995 regarding Technical Activated Charcoal.

Table 1 demonstrates that the quality of activated carbon produced from coffee grounds is of high standard, as it complies with SNI 06-3730-1995 regulations concerning Technical Activated Charcoal. The analysis results indicate that the moisture content of the activated carbon from coffee grounds is 1.458%, the ash content is 8.575%, and its iodine absorption capacity is 1038 mg/g.

Table 1.
Water Content, Ash Content, and Iodine Number Analysis Result of Coffee Grounds Activated Carbon

Parameters	Standard	Results
Water content	Max 15%	1.458%
Ash content	Max 10%	8.575%
Iodine Number	Min 750 mg/g	1038 mg/g

Table 1 illustrates that the moisture content of activated carbon produced from coffee grounds using HNO_3 is 1.458%. Nitric acid (HNO_3) was selected as the inorganic acid activator for the activated carbon obtained from coffee grounds due to its enhanced capacity to augment the surface area of the adsorbent in comparison to organic acids like citric acid. This advantage is due to the greater strength of the H^+ ions present in nitric acid, which facilitates the formation of new ions on the adsorbent. Furthermore, the activation process utilizing nitric acid leads to a rise in the quantity of active sites present on the adsorbent. This study is consistent with earlier research indicating that the use of nitric acid not only improves adsorption capacity but also prolongs the durability of the adsorbent, thereby rendering it a more economical and effective option (Kasturi, 2019).

Ash content testing is conducted to measure the mineral residue present in activated carbon. A lower ash content in a material indicates a higher level of purity. According to research conducted by Adawi et al. (2021), high ash content can inhibit the ability of activated carbon to adsorb substances, as the pores of the activated carbon are blocked by minerals such as Ca, Mg, K, and Na that adhere to the surface of the activated carbon.

The iodine absorption test is designed to determine the iodine number. The iodine number is defined as the quantity of iodine (milligrams) that one gram of carbon can absorb under particular testing conditions (Du et al., 2021). The results of the iodine absorption capacity test on activated carbon from coffee grounds are shown in Table 1. The iodine absorption obtained from activated carbon from coffee grounds was 1038 mg/g, indicating that this product meets the established quality standards.

Figure 1 illustrates the morphological characteristics of activated carbon obtained from coffee grounds activated with 0.3 M HNO_3. Scanning Electron Microscopy (SEM) analysis was performed at magnifications of 1000x, 3000x, 5000x, and 10000x. The morphological evaluation of the surface of activated carbon derived from coffee grounds revealed a more uniform and consistent pore distribution, particularly in the mesopore range, alongside the presence of limited micropores.

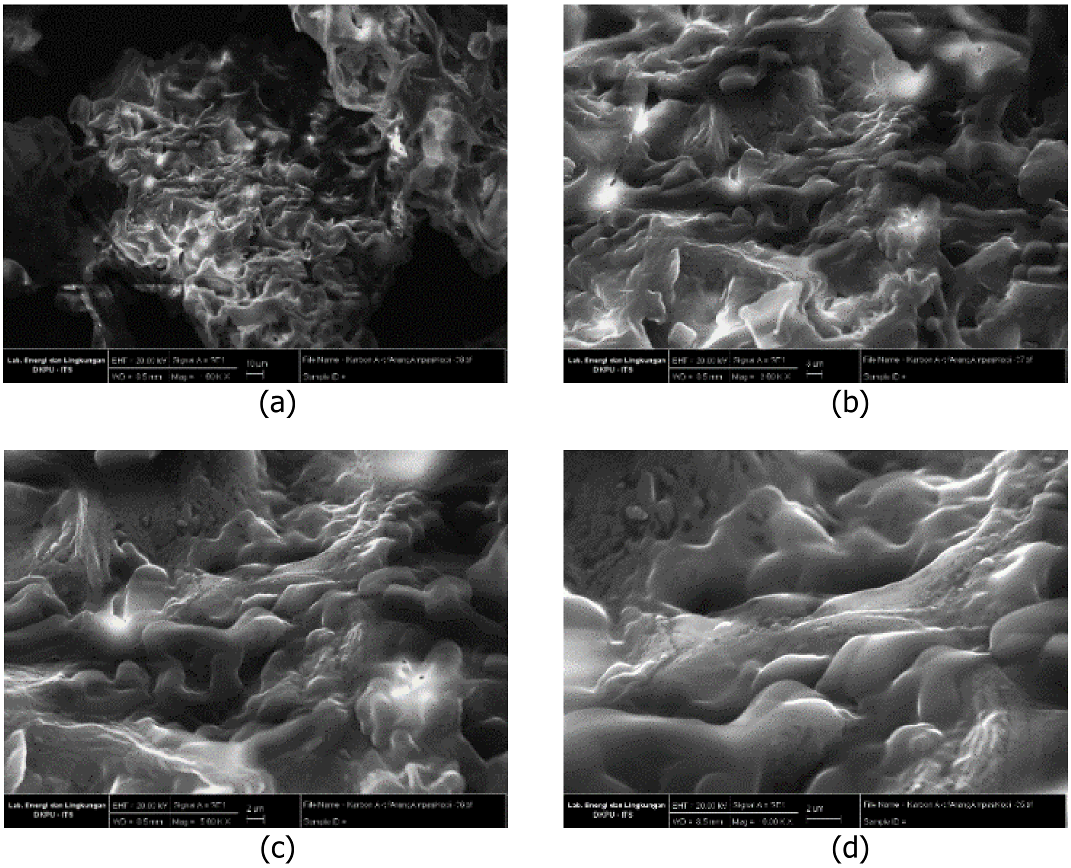


Figure 1.
The SEM Analysis Results of Coffee Grounds Activated Carbon with a (a) 1000x, (b) 3000x, (c) 5000x, and (d) 1000x magnification

The method of characterization employing Scanning Electron Microscopy (SEM) is intended to examine the morphological structure and pore sizes on the adsorbent's surface. As noted by Yunita et al. (2024), the fundamental principle behind SEM usage is that variations in cracks, indentations, and material structure will influence the emitted energy. This energy is subsequently converted into electronic signals, which are recorded and displayed as images on the SEM screen.

The results of SEM testing of activated carbon from coffee grounds conducted at magnifications of 1000, 3000, 5000, and 10000 times show a large pore morphological structure (Figure 1). Surface pore characteristics are one of the key factors influencing the adsorbent's ability in the adsorption process. The analysis of the surface morphology of activated carbon obtained from coffee grounds indicates a more uniform and consistent distribution of pores. The dominant pore sizes identified fall within the mesopore range, accompanied by the presence of limited micropores.

Iron Adsorption

The process of iron adsorption entails the preparation of artificial iron water with a concentration of 5 mg/L. The final concentration of iron in the sample is assessed through atomic absorption spectrometry (AAS). Results concerning the iron content are detailed in Table 2. The sample exhibiting the lowest average iron concentration was linked to an adsorbent dosage of 0.5 grams and a contact duration of 120 minutes, which resulted in a measurement of 0.014 mg/L. In contrast, the sample with the highest average iron concentration was recorded at the same adsorbent dosage of 0.5 grams but with a contact duration of 30 minutes, producing a value of 0.044 mg/L. The residual iron concentration complies with the established standards, as the allowable iron (Fe) level does not surpass 0.2 mg/L.

Table 2.
Iron Adsorption Data

Adsorbent Consentration (grams)	Contac Time (minutes)	The average of Iron removal (mg/L)
0.5	30	0.044
	60	0.018
	120	0.014
	180	0.019
	360	0.017
1.5	30	0.028
	60	0.021
	120	0.021
	180	0.020
	360	0.030

The results of iron content measurements after treatment with varying amounts of coffee grounds adsorbent (0.5 g and 1.5 g) and contact times of 30 minutes, 60 minutes, 120 minutes, 180 minutes, and 360 minutes produced the reduction values shown in Table 2. These findings indicate that the reduction in iron content varies and generally decreases with increasing mixing time. The variation in iron content after treatment with activated carbon can be attributed to the adsorbent mass-to-adsorbate solution volume ratio of 1:1000 (b/v), as illustrated in Table 2. The data presented in Table 2 further show that extended adsorption contact time correlates with an increase in the amount of Fe adsorbed. During the first minute of the adsorption process, the absorption of heavy metal Fe occurs rapidly. This rate decreases over time, eventually reaching equilibrium conditions. This phenomenon can be explained by the saturation of activated carbon derived from coffee grounds, which results in adsorption contact time becoming less effective.

This condition is also influenced by the high adsorbent-to-adsorbate ratio used in this study. The adsorbent doses of 0.5 g and 1.5 g in 500 mL solution are equivalent to 1 g/L and 3 g/L, respectively, while the initial Fe concentration was relatively low (5 mg/L). This disproportionate ratio may have led to rapid adsorption and early saturation of the adsorbent surface, resulting in a significant reduction of Fe concentration within a short contact time. Consequently, the removal efficiencies between the two adsorbent doses appear relatively similar. Therefore, this study has a limitation in terms of adsorbent-to-adsorbate ratio optimization, and future research is recommended to investigate a wider range of adsorbent dosages and higher initial Fe concentrations.

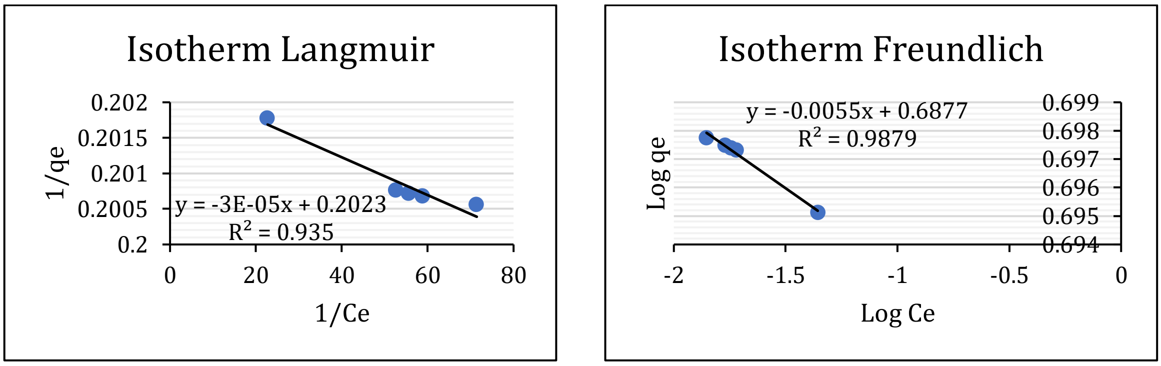
Table 3.
Test of Between-Subject Effect

Adsorbent	Variations	Sig.
Coffee Grounds	Stirring time	0.039
	Adsorbent concentration	0.691
	Stirring time* Adsorbent concentration	0.231

A two-way ANOVA was performed to assess the differences in the means of each variable (Angraini et al., 2023). The findings from the two-way ANOVA concerning the decrease in iron concentration achieved by utilizing activated carbon sourced from coffee grounds are displayed in Table 3 below. The results indicate that coffee grounds adsorbents exhibit differences in reducing iron levels in artificial water over mixing time (Sig value = 0.039 < 0.05). However, no differences were observed in adsorbent concentration, mixing time interaction, or adsorbent dosage.

Adsorption Capacity and Kinetics

The analysis presented in Figure 2 illustrates that the calculated adsorption capacities derived from both the Langmuir and Freundlich equations are represented as a linear equilibrium curve. The determination of the adsorption isotherm is based on identifying the coefficient of determination (R^2) that approaches unity, indicating a strong linearity. The regression coefficient (R^2) for the Freundlich isotherm model reveals a robust linear correlation, with a value of 0.9879. This R^2 value surpasses that of the Langmuir equation, suggesting that the adsorption capacity of activated carbon derived from coffee grounds for the reduction of iron concentrations in synthetic water aligns with the Freundlich isotherm model, exhibiting a maximum adsorption capacity of 4.986 mg/g.



(a) (b)

Figure 2.
Langmuir Isotherm Model and Freundlich Isotherm Model of Iron Adsorption by Coffee Grounds Activated Carbon

Adsorption kinetics can be assessed using various kinetic models. Isotherms commonly used in this research include the Langmuir and Freundlich isotherms (Rajabi et al., 2023). The Langmuir isotherm is primarily used to describe adsorption processes occurring through chemical interactions, while the Freundlich isotherm better represents adsorption phenomena related to physical characteristics (Amrutha et al., 2023).

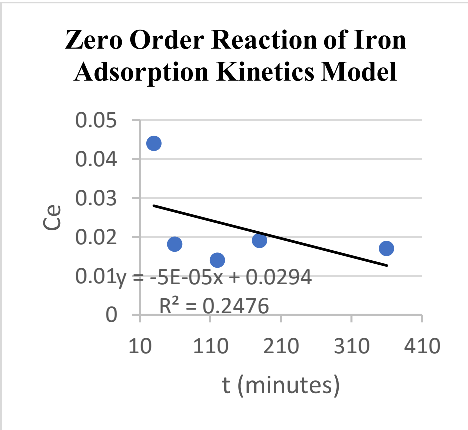
The linear equation for activated carbon from coffee grounds based on the Langmuir equation is y = -3E-05x + 0.2023 with an R^2 value of 0.935, while the Freundlich equation is y = -0.00055x + 0.6877 with an R^2 value of 0.9879 (Figure 2). The R^2 coefficient in the Freundlich equation exceeds that of the Langmuir equation, suggesting that the adsorption capacity of activated carbon for reducing iron concentrations in artificial water adheres to the Freundlich isotherm model, with a peak adsorption capacity of 4.986 mg/g. This Freundlich isotherm model signifies the existence of multiple surface layers (multilayer adsorption) and emphasizes the heterogeneous nature of the surface characteristics, leading to variations in binding energy across different surface areas.

This finding indicates that the adsorption process does not occur uniformly on a single surface, but rather on multiple active sites with varying energy levels. In the case of coffee grounds activated carbon, the heterogeneous surface is associated with the presence of diverse functional groups such as hydroxyl, carbonyl, and carboxyl groups, as well as irregular pore structures formed during the activation process. These characteristics allow Fe ions to bind at different sites and form multiple adsorption layers, thereby enhancing the overall adsorption capacity. This also suggests that the adsorption mechanism is more physical in nature and influenced by surface heterogeneity rather than a uniform chemical interaction. Therefore, the suitability of the Freundlich model supports the potential of coffee grounds activated carbon as an effective adsorbent for Fe removal in water.

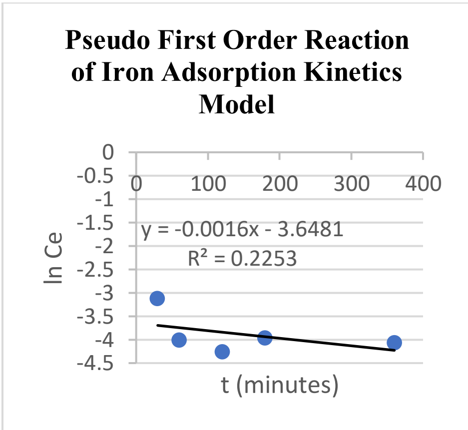
The linear equation for activated carbon from coffee grounds based on the Langmuir equation is y = -3E-05x + 0.2023 with an R^2 value of 0.935, while for the Freundlich equation it is y = -0.00055x + 0.6877 with an R^2 value of 0.9879 (Figure 2). The R^2 coefficient value in the Freundlich equation is greater than that in the Langmuir equation, indicating that the adsorption capacity of activated carbon in reducing iron levels in artificial water follows the Freundlich isotherm pattern with a maximum adsorption capacity of 4.986 mg/g. The Freundlich isotherm model indicates the presence of multiple surface layers (multilayer adsorption) and highlights the heterogeneous surface characteristics, which result in differences in binding energy on different surface sides.

Adsorption kinetics analysis requires data on adsorption capacity and contact duration. This study used several kinetic models, specifically the zero-order, first-order, and second-order models. The optimal mass for determining the kinetic model was set at 0.5 grams of activated carbon derived from coffee grounds, with stirring times varied at 30, 60, 120, 180, and 360 minutes.

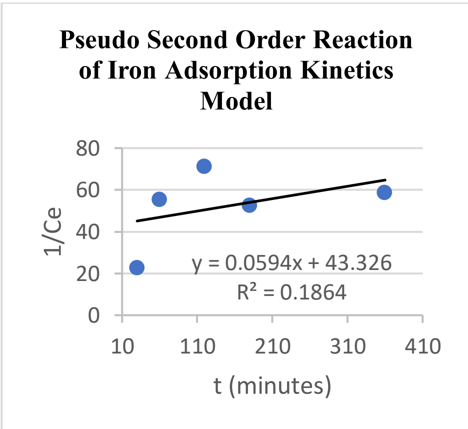
The adsorption kinetics curve analysis indicates that activated carbon produced from coffee grounds follows a zero-order kinetics model, as evidenced by the highest R^2 value of 0.2476 compared to alternative kinetics models (Figure 3). The process of adsorption utilizing activated carbon derived from coffee grounds to diminish iron concentration adheres to a zero-order kinetic model, exhibiting a measured rate constant (k) of $-5x10^{-5}$. The linear relationship described by the zero-order equation illustrates the correlation between stirring time and equilibrium concentration (Ce).



(a)



(b)



(c)

Figure 3.
(a) Zero Order, (b) Pesudo-First-Order, (c) Pseudo-Second-Order Kinetics Model of Iron Adsorption by Coffee Grounds Activated Carbon

The adsorption kinetics were evaluated by measuring the rate of decrease in iron concentration in both types of activated carbon (23,24). Coffee grounds activated carbon adsorbed iron according to the zero-order adsorption kinetics model (Figure 3). This determination was based on the highest regression value (R^2). The zero-order equation yields an R^2 value of 0.2476 with a reaction rate constant of $-5x10^{-5}$. The linear curve of the zero-order equation represents the relationship between stirring time and Ce. Tahad & Sanjaya (Tahad & Sanjaya, 2018) explain that a reaction is categorized as zero-order if the reaction rate remains constant despite changes in reactant concentration. Thus, an increase in reactant concentration will not affect the reaction rate.

The results of iron concentration reduction at doses of 0.5 and 1.5 grams are nearly identical, as the amount of adsorbent is greater than the amount of adsorbate. Excessive adsorbent causes the reduction data to be similar, and the adsorption capacity has regression values (R^2) that are not significantly different between Langmuir and Freundlich. This also affects the adsorption kinetics results, yielding R^2 values below 0.5. The concentration of adsorbent used must be adjusted to the amount of adsorbate to be removed.

CONCLUSIONS

The findings of this study demonstrate the effectiveness of used coffee grounds in removing total iron (Fe) ions. Activated carbon derived from coffee grounds has a moisture content of 1.458%, ash content of 8.575%, and iodine adsorption capacity of 1038 mg/g, thereby meeting the standards outlined in SNI 06-3730-1995. The most significant reduction in iron concentration occurred with 0.5 grams of activated carbon and a mixing time of 120 minutes, resulting in a decrease of 4.986 mg/l. The adsorption kinetics of iron on activated carbon from coffee grounds align with the Freundlich isotherm model, characterized by zero-order kinetics. It is recommended to consider various factors that may affect the stability of iron (Fe) levels, including measures to minimize potential contamination from the environment and the presence of impurities that may interfere with the adsorption process.

SUGGESTION

Communities in areas with high iron (Fe) content in water sources are encouraged to adopt this method as an affordable and accessible water treatment alternative using coffee grounds. Future research should consider factors influencing the consistency of Fe removal, including potential environmental contamination and the presence of interfering substanc es, while optimizing variables such as adsorbent dosage, stirring duration, and turbidity reduction methods to enhance adsorption efficiency without compromising water quality.

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