Pemanfaatan Limbah Ampas Kopi sebagai Adsorben untuk Pengolahan Air Limbah Industri Tahu: Analisis Adsorpsi Batch dan Parameter Isoterm

Coffee Grounds Waste as an Adsorbent for Tofu Industry Wastewater: Analysis of Batch Adsorption and Isotherm Parameters

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ABSTRAK

Ampas kopi dapat dimanfaatkan sebagai adsorben yang murah dan ramah lingkungan untuk mengolah air limbah dari industri tahu. Eksperimen adsorpsi pada penelitian ini dilakukan untuk mengevaluasi efektivitas ampas kopi dalam menghilangkan polutan dari air limbah tahu. Pengaruh variasi dosis adsorben (1 g, 2 g, dan 3 g dalam 200 mL) dievaluasi dengan mengukur *Total Dissolved Solids* (TDS), tingkat kekeruhan, konduktivitas, dan pH sebelum dan sesudah proses perlakuan. Data kesetimbangan adsorpsi dianalisis menggunakan tiga model isoterm, yaitu Langmuir, Freundlich, dan Temkin. Hasil terbaik diperoleh pada dosis 3 g, dengan penurunan TDS sebesar 47% dan pengurangan kekeruhan hingga 80%. Analisis isoterm menunjukkan bahwa model Langmuir paling sesuai dengan data (R^2 = 0,999), mengindikasikan bahwa proses adsorpsi berlangsung secara monolayer di permukaan homogen. Penelitian ini membuktikan bahwa limbah ampas kopi berpotensi menjadi alternatif adsorben berkelanjutan bagi industri tahu skala kecil dan menengah yang umumnya menghadapi keterbatasan teknologi dan finansial dalam pengolahan air limbahnya.

Kata kunci: Ampas kopi, adsorpsi batch, air limbah tahu, isotherm Langmuir, pengolahan limbah.

ABSTRACT

Coffee grounds waste can be utilized as a cost-effective and eco-friendly adsorbent for treating wastewater from the tofu industry. Batch adsorption experiments were conducted to evaluate the performance of coffee grounds as an adsorbent in removing pollutants from tofu wastewater. Different adsorbent doses (1 g, 2 g, and 3 g per 200 mL) were tested, and the quality of the wastewater was assessed based on changes in Total Dissolved Solids (TDS), turbidity, conductivity, and pH. The specific adsorption capacity (mg/g) and removal efficiency (%) decreased with increasing adsorbent dose. The overall removal of contaminants was most effective at a 3 g dose, resulting in a 47% reduction in TDS and an 80% decrease in turbidity. Adsorption equilibrium data were further analyzed using Langmuir, Freundlich, and Temkin isotherm models. The Langmuir model showed the best fit (R^2 = 0.999), indicating monolayer adsorption on a homogeneous surface. These results demonstrate that coffee grounds waste is a promising sustainable adsorbent, particularly for small and medium-scale tofu industries with limited resources for wastewater treatment.

***Keywords:** coffee grounds, batch adsorption, tofu wastewater, Langmuir isotherm, wastewater treatment.*

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INTRODUCTION

The tofu industry is an important sector in food processing in many Asian countries, especially in Indonesia, where tofu is the main source of protein for millions of people. According to a 2010 report by Indonesia's Ministry for Research and Technology, Indonesia had approximately 84,000 of these micro and small-scale tofu factories. (Sintawardani et al., 2022).

The processing of soybeans into tofu results in the release of high volumes of wastewater, characterized by elevated levels of organic matter, Total Suspended Solids (TSS), and other pollutants (Widyastuti & Suprayitno, 2020). The discharge of untreated tofu industry wastewater into water bodies causes serious environmental damage through lowered oxygen levels, damaged aquatic ecosystems, and potential health risks for humans (Murwanto et al., 2021). While wastewater treatment methods exist (chemical coagulation, anaerobic method, and activated sludge systems), these often require substantial investment, specialized knowledge, and ongoing maintenance that small and medium-sized tofu producers in developing regions simply cannot afford (Faisal, 2016). This economic reality highlights the urgent need to develop alternative, affordable treatment solutions using locally available materials that these producers can implement (Mustikaningrum et al., 2025).

Concurrent with these challenges is the growing volume of coffee grounds waste generated globally. Coffee grounds represent the largest waste stream in coffee production. The production of instant coffee creates even more waste, producing one kilogram of instant coffee, which results in approximately 2 kilograms of wet coffee grounds (Stylianou et al., 2018). Instead of filling landfills, these grounds containing lignin, cellulose, and various organic compounds can be transformed into valuable products. Research shows coffee grounds waste makes excellent adsorbent material, offering a sustainable solution for environmental remediation while creating economic value from what was previously discarded.

Numerous studies have investigated the efficiency of both raw and treated coffee grounds in removing pollutants from wastewater. For instance, research has demonstrated that activated carbon produced from waste coffee grounds effectively removes bisphenol-A from aqueous solutions, achieving a maximum adsorption capacity of 123.22 mg/g (Alves et al., 2019). Another study reviewed the utilization of spent coffee grounds for the removal of hazardous substances from water, highlighting their potential as low-cost adsorbents in wastewater treatment (Blinová & Sirotiak, 2019).

The potential of coffee waste in wastewater treatment has been explored, but its application to complex industrial effluents such as tofu wastewater is still limited. The study examines the effectiveness of modified coffee grounds in reducing these parameters through the adsorption process. Additionally, isotherm studies are conducted to better understand the adsorption mechanism and the interaction between the modified adsorbent and the specific pollutants present.

MATERIALS AND METHODS

Materials

The coffee grounds waste was obtained from a local coffee brand in Jambi City, while the tofu industry wastewater was collected from a Tofu Industry in Kuningan, Talang Banjar, Jambi Province. The initial quality of the wastewater is presented in Table 1.

Table 1. The Quality of The Tofu Industry Wastewater

Parameters	Value
Temperature	29,6 °C
Total Dissolved Solid	2140 ppm
Turbidity	501
Colors	Slightly Yellow
Odor	Smell
pH	4,01
Thermal Conductivity	2256 µS/cm

Preparation of coffee grounds waste as an adsorbent.

The preparation of the adsorbent from coffee grounds waste involved heating it in an oven at 250°C for 30 minutes. The heated coffee grounds waste was then repeatedly washed with distilled water to remove any adhering impurities and color. The cleaned coffee grounds waste was dried in an oven at 60°C for 30 minutes, yielding the coffee grounds waste adsorbent.

Adsorption Experiment

The adsorption experiment was utilized. Prepared coffee grounds waste as the adsorbent and tofu industry wastewater as the adsorbate. Glass flasks were used as reaction vessels, each containing 200 mL of tofu wastewater and coffee grounds adsorbent in three different quantities: 1 gram, 2 grams, and 3 grams. A magnetic stirrer was employed to agitate the mixtures at 150 rpm for 30 minutes, while the temperature was maintained at 30 ± 2°C. After the adsorption period, the mixtures were filtered to obtain the treated samples for analysis. In addition to the variation in adsorbent dosage, other parameters were kept constant, including the particle size and pore structure of the coffee grounds waste. Although particle size was not specifically controlled, the drying and manual filtering steps resulted in a relatively uniform size distribution.

According to previous studies, coffee grounds generally exhibit a porous morphology dominated by mesopores, with the presence of micro- and macropores formed through thermal treatment and washing (Azouaou et al., 2010; Anastopoulos et al., 2017). These structural features enhance adsorptive performance by increasing the available surface area and improving access to adsorption sites. The capacity and removal efficiency of the coffee grounds waste were evaluated to determine their effectiveness in reducing pollutants from tofu wastewater, with tTDS selected as the primary indicator parameter. The contact time of 30 minutes was adopted based on previous literature that reported sufficient adsorption within this duration. (Franca et al., 2009; Yen & Lin, 2016). However, as no kinetic analysis was performed, it remains uncertain whether equilibrium was fully reached during the experiments. Consequently, the adsorption isotherms derived from this study may reflect performance at a fixed operation time rather than true saturation capacity. Future research should investigate adsorption kinetics across various contact times to confirm equilibrium conditions and improve the accuracy of isotherm modeling. The adsorption capacity was determined using the following equation: 1.

$$q_e = \frac{(C_0 - C_e)\,V}{m} \quad (1)$$

Where, C_0 (mg/mL) and C_e (mg/mL) are the initial and final amount of measured parameters, respectively, V is the volume of tofu industry wastewater (mL), and m is the weight of the adsorbent used (g). The removal efficiency was calculated as follows Equation 2.

$$removal\ efficiency\ (\%) = \frac{C_0 - C_e}{C_0} \times 100\,\% \quad (2)$$

Analysis

The physicochemical parameters evaluated before and after treatment included temperature, total dissolved solids (TDS), turbidity, pH, and electrical conductivity. 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.

Adsorption Isotherm Modeling

The adsorption experiment data were evaluated using three different isotherm models, including Langmuir, Freundlich, and Temkin. The Langmuir adsorption isotherm theory rests on three fundamental assumptions: adsorption only occurs as a single molecular layer, all surface sites are equivalent to one another, and each site can hold exactly one molecule, with a molecule's adsorption at any site happening independently of whether nearby sites are occupied (Yen & Lin, 2016a).

$$q_e = q_m - \left(\frac{1}{KL}\right) \times \frac{q_e}{C_e} \quad (3)$$

Its linear form can be represented by Equation (4).

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

The Langmuir isotherm is defined by the Langmuir separation factor and is represented by Equation (5). The favorability of adsorption equilibrium is determined based on the RL value. Specifically, the value of RL, which was in the range of RL > 1, implying unfavorable adsorption; RL = 1, linear adsorption; 0 < RL < 1, favorable adsorption; RL = 0, irreversible adsorption (Dai et al., 2019).

$$RL = \frac{1}{(1 + KL \times Co)} \quad (5)$$

The Freundlich isotherm, presented in Equation (6), and its linearized form, given in Equation (7). This model applies to adsorption on heterogeneous surfaces, where interactions occur between adsorbed molecules. Furthermore, the Freundlich equation suggests that adsorption energy decreases exponentially as the adsorption sites on the adsorbent become fully occupied. (Yen & Lin, 2016a).

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

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

The Temkin isotherm equation assumes that the heat of adsorption of all molecules in the layer decreases linearly with coverage due to adsorbent-adsorbate interactions, and it also suggests that the adsorption process has a uniform distribution of binding energies, with a set maximum binding energy (Hadj, 2020). The Temkin isotherm, presented in Equation (8), and its linearized form, given in Equation (9).

$$q_e = \frac{RT}{B_T} \ln K_T C_e \quad (8)$$

$$q_e = \frac{RT}{B_T} \ln K_T + \frac{RT}{B_T} \ln C_e \quad (9)$$

The coefficient of determination (R^2) was used to compare linear and nonlinear regression methods to determine the best-fitting isotherm model for the experimental adsorption data.

$$R^2 = \frac{\sum_{i=1}^{n} (q_{e,exp} - \overline{q_{e,cal}})_i^2}{\sum_{i=1}^{n} (q_{e,exp} - \overline{q_{e,cal}})_i^2 + (q_{e,exp} - \overline{q_{e,cal}})^2} \quad (10)$$

The expressions for error functions are presented in Equation (10) where $q_{e,cal}$ and $q_{e,exp}$ represent the calculated and experimental adsorbate concentrations in the solid phase (mg/g), respectively, and n is the number of data points.

RESULTS AND DISCUSSION

The Effect of Adsorbent Dosage Variation on Wastewater Quality

This study aimed to evaluate the potential of coffee grounds waste as an environmentally friendly adsorbent in the treatment of tofu industrial wastewater. The applied adsorbent masses varied at 1 g, 2 g, and 3 g, while samples without any adsorbent addition (0 g) served as the control. The wastewater quality parameters analyzed included temperature, Total Dissolved Solids (TDS), turbidity, pH, and electrical conductivity, as presented in Table 2. Based on the literature review, adsorbent dosage and process temperature do not act independently but rather influence each other in determining adsorption effectiveness. At certain dosages, increasing the temperature was found to enhance adsorption capacity, leading to optimal efficiency. This finding is further supported by the research of Thachnatharen Nagarajan (2024), which demonstrated that the interaction between adsorbent dosage and temperature plays a significant role in determining adsorption performance. Therefore, an experimental design employing a factorial approach is recommended to achieve a more comprehensive understanding of the interaction between these two variables.

Table 2. Effect of Coffee Grounds Waste Adsorbent Dosage Variation on the Quality Parameters of Tofu Industry Wastewater

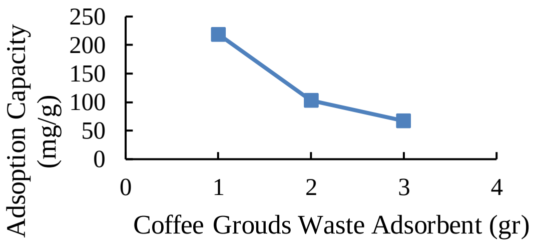
Parameter	Dosage of Adsorbent			
	Control	**1 g**	**2 g**	**3 g**
Temperature (°C)	29,6	30,4	31,4	30,2
TDS (mg/L)	2.140	1.045	1.106	1.133
Turbidity (NTU)	501	208	178	102
pH	4,01	4,69	4,69	4,48
Electrical Conductivity (µS/cm)	2.256	2.094	2.212	2.116

The TDS Parameter

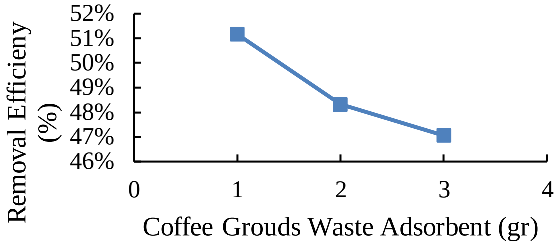
The TDS parameter reflects the total amount of dissolved substances in wastewater, consisting of inorganic salts and small amounts of organic substances (Pushpalatha et al., 2022). The initial TDS concentration of the tofu industrial wastewater was 2140 mg/L. As shown in Table 1, the addition of 1 g of coffee grounds waste adsorbent successfully reduced the TDS value to 1045 mg/L, corresponding to a removal efficiency of 51% and an adsorption capacity of 219 mg/g.

However, when the adsorbent dosage was increased to 2 g and 3 g, the TDS values unexpectedly rose to 1106 mg/L and 1133 mg/L, respectively. This resulted in a significant decrease in adsorption capacity from 219 mg/g (at 1 g dosage) to 103.4 mg/g (at 2 g dosage) and further down to 67.13 mg/g (at 3 g dosage). Simultaneously, the removal efficiency showed a modest reduction from 51% to 48% and 47% for the respective dosages, as shown in Fig. 1.

Comparative studies confirm that coffee ground waste, particularly when modified or combined with other materials, is a promising adsorbent for the treatment of tofu industry wastewater. Irmanto, (2009) demonstrated the effectiveness of activated carbon derived from coffee waste in removing nitrogen-based compounds from tofu wastewater, with removal efficiencies of 64.69% for ammonia, 52.35% for nitrite, and 86.40% for nitrate under optimal conditions of pH 7- and 30-minutes contact time. In addition, activated carbon derived from coffee husk was capable of significantly reducing biochemical oxygen demand (BOD_5) by 85.38%, COD by more than 650 mg/L, and nitrite by more than 20 mg/L(Sartika & Dani Supardan, 2019).



(a)



(b)

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

This counterintuitive phenomenon, where increasing the adsorbent amount leads to decreased performance, can be attributed to several factors. The influence of adsorbent dosage on the adsorption efficiency was further investigated based on the findings by Oliveira (2008), who reported that an increase in adsorbent mass enhances the overall surface area, thereby providing a greater number of active adsorption sites. However, the adsorption capacity per unit mass was observed to decrease at higher dosages. This phenomenon is attributed to the reduction in effective surface area, likely caused by particle aggregation or overlapping of active sites, which limits accessibility. Similar behavior regarding the influence of adsorbent concentration on adsorption capacity has been widely observed in the literature for methylene blue (MB) and other adsorbates (Oliveira et al., 2008).

Reduction of Turbidity

The porous structure of coffee grounds, characterized by interconnected pores, offers a suitable platform for adsorption processes (Azouaou et al., 2010). While increasing the adsorbent dosage can lead to greater total surface area due to the presence of more active sites, it may also result in particle aggregation or overlapping of adsorption sites, which reduces the effective surface area accessible for dissolved substances, as observed in the TDS results. However, for turbidity removal, which involves the capture of suspended particles rather than dissolved ions, the physical presence of more adsorbent particles enhances particle trapping through surface interactions and entrapment mechanisms. This structural advantage contributes to the significant reduction in turbidity with increasing adsorbent dosage (Getahun et al., 2024).

Turbidity is determined by the amount of light absorbed and scattered by materials present in wastewater (Novita et al., 2021). The initial high turbidity value of 501 NTU was substantially reduced to 208 NTU with the application of just 1 g of coffee grounds waste adsorbent. Increasing the dosage to 2 g further decreased turbidity to 178 NTU, while the optimal dosage of 3 g achieved a minimum turbidity value of 102 NTU, representing approximately 80% reduction from the initial measurement. This consistent and significant decrease in turbidity with increasing adsorbent dosage confirms that spent coffee grounds function effectively as a natural adsorbent.

While the adsorption behavior for turbidity is influenced by physical entrapment and surface interaction, a more detailed understanding of the adsorbent's pore structure is essential to explain variations in adsorption efficiency across parameters. Although pore size distribution was not directly measured in this study, literature reports indicate that thermally treated coffee grounds commonly possess a porous morphology dominated by mesopores, along with micro- and macropores, which contribute to their adsorption capability (Azouaou et al., 2010; Anastopoulos et al., 2017). Future studies are encouraged to include direct pore structure analysis to strengthen the correlation between physical properties and adsorption performance.

pH Changes

The initial pH value of the wastewater was 4.01, indicating acidic conditions. After treatment with the coffee grounds waste adsorbent, the pH showed a dose-dependent response pattern. At lower doses (1-2g), the pH increased from 4.01 to 4.69, indicating neutralization of acidic compounds through basic functional groups in coffee grounds waste. However, at a higher dose (3g), the pH decreased to 4.48, suggesting potential release of acidic compounds or saturation of buffering capacity.

This non-monotonic pH behavior observed in this study aligns with the amphoteric nature of coffee grounds waste documented in the literature. Boehm titration analysis reveals that coffee grounds contain both acidic functional groups (carboxylic: 0.60-0.97 mmol/g, phenolic: 0.12-2.24 mmol/g, lactonic: 0.07-1.05 mmol/g) and basic groups (0.49-0.93 mmol/g). The balance between these competing functional groups explains the dose-dependent pH response observed, where lower doses (1-2g) favor neutralization through basic groups, while higher doses (3g) may lead to predominance of acidic groups or release of organic acids. This amphoteric behavior indicates that coffee grounds waste exhibits complex surface chemistry containing both acidic and basic functional groups, consistent with its heterogeneous organic composition (Anastopoulos et al., 2017).

Electrical Conductivity

The initial electrical conductivity of 2.256 μS/cm decreased to 2.094 μS/cm at the 1 g adsorbent dose, indicating effective reduction in dissolved ionic species within the wastewater. This observation aligns with studies by (Franca et al., 2009) Who demonstrated that coffee grounds waste can effectively remove charged particles from aqueous solutions through electrostatic interactions. However, the conductivity subsequently increased to 2212 μS/cm and 2116 μS/cm for the 2 g and 3 g doses, respectively. The elevated conductivity at higher adsorbent concentrations results from the release of inherent ions such as potassium and organic acids from the coffee waste material (Kyzas, 2012), combined with saturation of active adsorption sites (Anastopoulos et al., 2017).

Adsorption isotherms

The models of Langmuir, Freundlich, and Temkin were used to study the experimental isotherm data of the adsorption of coffee grounds waste on tofu industrial wastewater. Previous studies have shown that these isotherm models can effectively describe the adsorption behavior of various contaminants (Azouaou et al., 2010),(Yen & Lin, 2016), (Cherdchoo et al., 2019). The adsorption isotherm parameters obtained are shown in Table 2. All models show a coefficient of determination (R^2) value greater than 0.9; therefore, these models can effectively describe the adsorption of dissolved substances on coffee grounds waste.

The Langmuir model assumes that adsorption occurs on a homogeneous surface with uniform adsorption energy, while the Freundlich model describes adsorption on a heterogeneous surface with non-uniform energy distribution. The Temkin model considers the effect of indirect interactions between adsorbate molecules (Serafin & Dziejarski, 2023).

Table 3. Isotherm Parameters for Tofu Industrial Wastewater Adsorption on Coffee Grounds Waste

Isotherm	Parameters	Constant	Equation
Langmuir			
	R^2	0,999	$q_e = \frac{(8{,}273)\ (0{,}00090)C_e}{1 + 0{,}00090C_e}$
	KL	0,00099	
	Qm	8,273	
Freundlich			
	R^2	0,994	$q_e = (418{,}509)Ce^{\frac{1}{0.0695}}$
	KF	418,509	
	n	0,0695	
Temkin			
	R^2	0,995	$q_e = 1.906{,}8 \ln 0{,}853C_e$
	KT	0,853	
	RT/BT	1.906,8	

Based on Table 3, the adsorption data were analyzed using multiple isotherm models. The conformity of the experimental data with the Langmuir isotherm model (R^2 = 0.999) reflected a strong linear relationship between the calculated and observed adsorption capacities. This pattern of adsorption was not limited to tofu wastewater, as comparable trends have been documented in multiple studies employing a variety of biomass-based adsorbents. For instance, biochar derived from rice husk and rice straw demonstrated a high degree of agreement with the Langmuir model in the removal of synthetic dyes and heavy metals. Sackey et al. (2021) reported R^2 values exceeding 0.98 for the adsorption of Congo red using rice straw-derived materials. Likewise, Hua et al. (2023) observed that orange peel biochar, after chemical modification, displayed a near-perfect fit to the Langmuir model (R^2 = 0.999) in similar dye removal applications. Such findings, along with supporting results from banana peel and coffee husk adsorbents, suggest that monolayer adsorption on a uniform surface is a prevailing mechanism governing the performance of a wide range of biomass-based adsorbents across diverse wastewater types. The Langmuir constant KL of 0,00099 represents the affinity between adsorbate and adsorbent, while the maximum adsorption capacity (Qm) is 8,273 mg/g, suggesting a moderate adsorption capacity of coffee ground waste.

Furthermore, the separation factor (RL) was calculated to be 0,00047, which lies between 0 and 1, confirming that the adsorption process is favorable according to the Langmuir model (Azouaou et al., 2010). This dimensionless parameter provides important information about the nature of the adsorption process and validates the applicability of the Langmuir isotherm for describing the adsorption of contaminants from tofu industrial wastewater onto coffee grounds waste. This finding aligns with results from related studies where the Langmuir isotherm also provided the best correlation for metal adsorption onto coffee grounds waste, confirming that the adsorption process is favorable (Azouaou et al., 2010).

The Freundlich model also demonstrates a strong correlation with an R^2 value of 0,994. The KF value of 418,509 indicates a high adsorption capacity, while the n value of 0,0695 (less than 1) suggests that the adsorption process is favorable but dominated by chemical processes rather than physical adsorption. The lower n value further indicates that the adsorption intensity increases with increasing surface density, which is characteristic of chemisorption processes. For the Temkin isotherm, the high R^2 value of 0,995 confirms its applicability. The binding energy parameter KT of 0,853 and RT/BT value of 1.906,8 suggest that the heat of adsorption decreases linearly with coverage due to adsorbent-adsorbate interactions.

The correlation coefficients across all models indicate that the adsorption of contaminants onto coffee ground waste involves complex mechanisms, including both physical and chemical interactions, heterogeneous surface binding, and varying energy distribution. The Langmuir model shows the best fit, suggesting that monolayer adsorption on homogeneous sites plays a predominant role in the removal of pollutants from tofu industrial wastewater by coffee ground waste adsorbent.

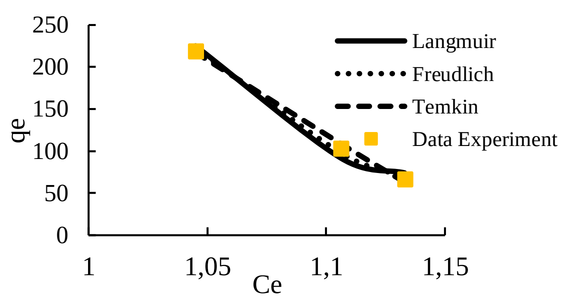


Figure 2. Comparison of Experimental Data with Isotherm Models for Tofu Industrial Wastewater Using Coffee Grounds Waste Adsorbent

Figure 2 presents the graphical comparison between the data experiment and the three isotherm models for the adsorption of pollutants from tofu industrial wastewater onto coffee ground waste. The graph plots the equilibrium adsorption capacity (qe) against the equilibrium concentration (Ce). As shown in the figure, all three models closely follow the experimental data points (represented by yellow squares), confirming the high R^2 values previously reported in Table 3. At lower equilibrium concentrations (Ce ≈ 1,04), all models predict similar adsorption capacities around 220 mg/g. However, as the equilibrium concentration increases, slight differences in the models become apparent.

The Langmuir model (solid line) shows the best fit with the experimental data across the entire concentration range, consistent with its highest R^2 value of 0,999. This supports the conclusion that monolayer adsorption is the dominant mechanism in this system.

The Freundlich model (dotted line) shows a minor deviation from experimental data at middle concentration ranges (Ce ≈ 1,10), which aligns with its slightly lower R^2 value of 0,994. The Temkin model (dashed line) shows a similar trend but deviates more at higher concentrations.

The convergence of all three models at Ce ≈ 1,13 indicates that at higher concentrations, the adsorption behavior becomes more uniform regardless of the underlying mechanism, possibly due to the approaching surface saturation of the coffee ground waste adsorbent. This graphical representation supports the numerical findings in Table 3 and provides visual confirmation that the Langmuir isotherm model best describes the adsorption process of pollutants from tofu industrial wastewater onto coffee grounds waste adsorbent.

CONCLUSION

This research demonstrates that coffee grounds waste has good potential as an adsorbent for wastewater treatment in the tofu industry. The use of a 1 g adsorbent dose in 200 mL of wastewater provided optimal results for the TDS parameter with a reduction from 2.140 mg/L to 1.045 mg/L (51.17% efficiency). Meanwhile, for the turbidity parameter, the 3 g adsorbent dose delivered the best results, with a reduction from 501 NTU to 102 NTU (79,64% efficiency). Considering the overall treatment objectives and practical applications, the 3 g dose is recommended as it provides the most comprehensive pollutant removal, achieving significant reductions in both parameters despite slightly lower TDS efficiency. Adsorption isotherm analysis showed that the Langmuir model provided the best fit (R^2 = 0,999), indicating that monolayer adsorption on a homogeneous surface is the dominant mechanism. This research proves that coffee grounds waste can be a sustainable alternative adsorbent for small and medium-scale tofu industries that typically have technological and financial limitations in their wastewater treatment. Further research is recommended to investigate the adsorption behavior at varying contact times to confirm equilibrium conditions and validate the maximum adsorption capacity of the adsorbent.

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