Solid foam composite derived from cement and jujube core activated carbon: a sustainable adsorbent for textile wastewater treatment

Composto de espuma sólida derivado de cimento e carvão ativado com núcleo de jujuba: um adsorvente sustentável para o tratamento de águas residuais têxteis

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Mohammed Ettahar Boussalah
PhD Student Process Engineering
Institution: GCE Laboratory, University of Djillali Liabes (UDL)
Address: B.P. 89 Ben M'Hidi city Sidi bel Abbes, 22000, Algeria
E-mail: mohammed.boussalah@univ-sba.dz

Malika Medjahdi
PhD in Process Engineering
Institution: APELEC Laboratory, University of Djillali Liabes (UDL)
Address: B.P. 89 Ben M'Hidi city Sidi bel Abbes, 22000, Algeria
E-mail: mmedjahdi@yahoo.fr

Sofiane Guella
PhD in Process Engineering
Institution: LGPME Laboratory, University of Djillali Liabes (UDL)
Address: B.P. 89 Ben M'Hidi city Sidi bel Abbes, 22000, Algeria
E-mail: gelsof@yahoo.fr

Nadia Ramdani
PhD in Process Engineering
Institution: APELEC Laboratory, University of Djillali Liabes (UDL)
Address: B.P. 89 Ben M'Hidi city Sidi bel Abbes, 22000, Algeria
E-mail: nadia_ramdani@ymail.com

Dominique Baillis
PhD in Mechanical Engineering
Institution: LaMCoS, INSA de Lyon
Address: CNRS UMR5259, LaMCoS, F-69621 Villeurbanne, France
E-mail: dominique.baillis@insa-lyon.fr

ABSTRACT

The textile industry is responsible for a significant amount of environmental damage caused by the use of dyes, which puts the health of humans and the ecosystems in the surrounding area in dire danger. The conventional approaches
to wastewater treatment can be rather expensive and demand a significant amount of energy. Regrettably, these techniques are not very efficient when it comes to dealing with the substantial quantities of coloured wastewater that are generated by the textile sector. The utilisation of cement-activated carbon solid foam composite technology is a viable option that offers significant advantages in terms of both efficiency and environmental impact. These solid foam adsorbents are produced by the utilisation of a manufacturing process that is environmentally friendly and ingredients that are sourced locally, such as jujube cores. Even at low initial dye concentrations, they had clearance rates of over 98%, which is an impressively high percentage from their dye retention capabilities. In order to demonstrate the composite’s potential for use in wastewater treatment applications, characterization techniques such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and EDX are utilised. After conducting in-depth research, it has been established that the mass of the adsorbent and the length of time that it is in contact with the substance have a significant impact on the removal efficiency. The most favourable conditions have been seen to occur within a time range of ninety minutes, according to those observations. Methylene blue can be effectively removed with the help of the solid foam Composite, which is a sorbent that is not only readily available but also practical, cost-effective, and readily available. According to the findings of equilibrium research, the Temkin isotherm model is the one that is most suitable for understanding the behaviour of adsorption. As an additional point of interest, desorption experiments have shown that there are strong bindings between the dye and the composite, which indicates that there is minimal reversibility.

**Keywords:** cement-carbon composite, adsorption, basic dye, kinetics.

**RESUMO**

O setor têxtil é responsável por uma quantidade significativa de danos ambientais causados pelo uso de corantes, o que coloca em risco a saúde dos seres humanos e os ecossistemas da área circundante. As abordagens convencionais para o tratamento de águas residuais podem ser bastante caras e demandam uma quantidade significativa de energia. Infelizmente, essas técnicas não são muito eficientes quando se trata de lidar com as quantidades substanciais de águas residuais coloridas que são geradas pelo setor têxtil. A utilização da tecnologia de compósito de espuma sólida de carbono ativado por cimento é uma opção viável que oferece vantagens significativas em termos de eficiência e impacto ambiental. Esses adsorventes de espuma sólida são produzidos pela utilização de um processo de fabricação que não agride o meio ambiente e de ingredientes obtidos localmente, como núcleos de jujuba. Mesmo com baixas concentrações iniciais de corante, eles apresentaram taxas de eliminação de mais de 98%, o que é uma porcentagem impressionantemente alta em relação às suas capacidades de retenção de corante. Para demonstrar o potencial do composto para uso em aplicações de tratamento de águas residuais, são utilizadas técnicas de caracterização como microscopia eletrônica de varredura (SEM), espectroscopia de infravermelho por transformada de Fourier (FTIR) e EDX. Após a realização de uma pesquisa aprofundada, foi estabelecido que a massa do adsorvente e o tempo de contato com a substância têm um impacto significativo na eficiência da remoção. As condições mais favoráveis ocorreram em um intervalo de tempo de noventa minutos, de acordo com essas observações. O azul de metileno pode ser
removido de forma eficaz com a ajuda da espuma sólida Composite, que é um sorvente que não só está prontamente disponível, mas também é prático, econômico e prontamente disponível. De acordo com as descobertas da pesquisa de equilíbrio, o modelo de isoterma de Temkin é o mais adequado para entender o comportamento da adsorção. Como um ponto adicional de interesse, os experimentos de dessorção mostraram que há fortes ligações entre o corante e o composto, o que indica que há uma reversibilidade mínima.

Palavras-chave: compósito de cimento-carbono, adsorção, corante básico, cinética.

1 INTRODUCTION

Industrial effluents contribute to water pollution, a pressing issue on a global scale. Finding practical solutions to mitigate the detrimental effects of water pollution on aquatic ecosystems (Dabrowski; Podkościenly; Hubicki, 2005; Moreno-Castilla; Rivera-Utrilla, 2001; Mourão; Carroll, 2006; Ting Yang, 2006) and human health is of utmost importance. Among the various methods used, such as the electrochemical method (Nidheesh; Minghua Zhou, 2018), coagulation-flocculation (Szyguła et al., 2009), membrane separation (Alventosa-Delara; Barredo-Damas; Alcaina-Miranda, 2012), biodegradation (Sudarjanto; Keller-Lehmann, 2006), the Fenton process (Karataş et al., 2012), oxidation or ozonation (Gholamreza Moussavi, 152DC), etc., the adsorption technique has shown great promise as a possible solution (Sudarjanto; Keller-Lehmann, 2006; Termoul et al., 2022). It involves gathering pollutants present in wastewater using a material that can adsorb them. Current research focuses on developing composites using carbonaceous materials such as activated carbon (Benzekri Benallou et al., 2021; Medjahdi et al., 2016), carbon nanotubes (Medjahdi et al., 2022), and graphene (Deepak Senapati et al. [s.d.]). These compounds can be incorporated into polymer matrices (Medjahdi et al., 2022), clays (Kherroub et al., 2020), or even cement (Larson et al., 2017), offering a wide range of applications in water treatment.

These composites have many applications as adsorbents for separating and reducing contaminants in polluted water. These pollutants include heavy metals like lead and mercury (Chemrak et al., 2018), which are present in industrial waste. Hydrocarbons, like oil, are also released from leaks or during the loading and unloading of ships. Additionally, some dyes come from liquid waste produced by the textile sector (Waranusantigul; Pokethitiyook; Kruatrachue, 2003; Tsai et al., 2007).
The Ziziphus spina-christi, also known as the jujube cores, is abundant in arid regions. It provides a sustainable material that can be utilized to produce activated carbon (Umran Tezcan Un et al., 2015). Composites made from jujube cores activated Carbon (JCAC) and cement show improved resistance to environmental factors and long-lasting durability, marking a significant development in water treatment and ecological preservation. Furthermore, incorporating renewable raw materials in their production helps minimize the overall environmental impact, which aligns with sustainability principles and the conservation of natural resources.

These composite materials offer a cost-effective and high-performing solution for treating colored water, contributing to environmental protection and reducing water pollution. In addition, a large body of research is investigating the applicability of cementitious materials and cementitious composites for wastewater treatment, including the Removal of antibiotics (Cazetta et al., 2011), heavy metals ([Zaghbani et al., 2017], nutrients and faecal coliforms (Ok et al., 2007).

The study aimed to thoroughly analyze solid foam Composite Cement–jujube cores Activated carbon (CJAC), using techniques like scanning electron microscopy (SEM) to study surface texture and microstructures, elemental composition analysis (EDX) to identify elements and show adhesion between cement and JCAC, and Fourier transform infrared spectroscopy (FTIR) to analyze chemical bonds and functional groups. In addition, the study examined various factors that influence the rate of elimination, such as the duration of contact, the initial concentration of MB, and the quantity of adsorbent utilized. For the kinetic analysis, the adsorption rates and orders were determined by utilizing pseudo-first- and pseudo-second-order models. On the other hand, the equilibrium studies involved analyzing isotherm plots and assessing the suitability of various models. In addition, a desorption study was conducted to investigate the reversibility of the adsorption process and evaluate the release of dye over time, providing insights into the bonding strength between the MB dye and the solid foam CJAC.

The objective of this work is to develop an efficient and environmentally friendly wastewater treatment system using a composite of cement-activated carbon solid foam.
2 MATERIALS AND METHODS

2.1 THE ACTIVATED CARBON (JCAC) USED

For the preparation of the Composite, the carbon was prepared in the laboratory from jujube cores (Djelfa, Algeria) with the below characteristics:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical and Chemical Properties</td>
<td>8.49</td>
</tr>
<tr>
<td>Value Moisture content (%)</td>
<td></td>
</tr>
<tr>
<td>Ash content (%)</td>
<td>18</td>
</tr>
<tr>
<td>Bulk density (cm³/g)</td>
<td>0.452</td>
</tr>
<tr>
<td>Pore volume (cm³/g)</td>
<td>0.2121</td>
</tr>
<tr>
<td>Iodine index (mg/g)</td>
<td>1025.25</td>
</tr>
<tr>
<td>BET surface area (m²/g)</td>
<td>408.224</td>
</tr>
<tr>
<td>pH at point of zero charge (pHpzc)</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Source: Authors.

2.2 COMPOSITE CEMENT– JUJUBE CORES ACTIVATED CARBON (CJAC) PREPARATION

The Composite is created by meticulously blending powder JCAC and black Cement (provided by GICA group - Algeria, CEM II/ B-L 32.5 N NA 442) until a uniform mixture is achieved. Following this, water is added, and the blend is agitated at medium speed for 5 minutes to ensure thorough dispersion of the activated carbon. To establish the Composite’s porous framework, the foaming agent (detergent – water: foam) is slowly introduced into the mixture for a few minutes until the foam is evenly distributed (water/Cement/foam/JCAC at a 1/2/0.25/0.05 ratio by volume). Subsequently, the mixture is transferred into cubic molds. Afterwards, the compacted mixture is removed and air-dried for twenty-eight days to achieve the desired mechanical strength (Figure 1). This drying and curing process is essential for obtaining the desired mechanical.

Figure 1: Demolded solid foam composites

Source: Authors.
2.3 CHARACTERIZATION OF SOLID FOAM CJAC

An analysis of the Composite's structural properties was conducted using a scanning electron microscope (JSM-7610FPlus). We assessed the elemental composition of our substance through energy dispersive analysis (EDX).

An analysis was conducted on the surface functional groups of RM and CJAC foam using Fourier transform infrared spectroscopy. This method was employed to evaluate the impact of chemical treatment on biomass and to detect different functional groups on the surfaces of the materials. An FTIR spectroscopy analysis was conducted on the materials using the FTIR-INVENIO-R 329 instrument, covering a range of 400–4000 cm\(^{-1}\).

2.4 PREPARATION OF ADSORBATE

Methylene Blue, identified as a cationic dye in Figure 2 provided by Merck, serves as a representative pollutant in its unrefined state and is utilized as an adsorbate to assess the effectiveness of the sorbent composite created in this research.

![Figure 2: Methylene Blue structure](source: Authors)

The solutions are created by dissolving the dye directly in distilled water without any preliminary purification steps.

3 EXPERIMENTAL METHODOLOGY

3.1 ADSORPTION STUDY

Various amounts of dry Composite were mixed with 400 ml of a solution to conduct batch mode adsorption studies. The adsorption of BM was examined in relation to other variables in the study, such as the initial concentration of BM (50, 100, and 200 mg/L), the amount of adsorbent (20-60 g/L), and the duration of contact time (10-120 mn). Stirring at 200 rpm was used for the trials. Separation of the Composite followed adsorption, and a UV-visible spectrophotometer (Model Cary 60) operating at 665 nm was used to examine the resulting solution. All
experiments were conducted at the original pH level. Figure 3 presents MB solution before and after adsorption:

Figure 3: MB solution before and after adsorption using solid foam CJAC

The removal rate R (%) of the BM was determined using the following Equation (1):

\[
\text{Removal (\%)} = R (\%) = \frac{(C_0 - C_e) \times 100}{C_0}
\]  

\[
q_e (\text{mg/g}) = \frac{(C_0 - C_e) \times V}{m}
\]

Where:

- \( C_0 \) and \( C_e \) are initial and equilibrium concentrations (mg/L), \( m \) is the sorbent mass (g), and \( V \) is the volume of the dye solution (L).

### 3.2 DESORPTION STUDY

Potential mechanisms of adsorption are revealed through desorption experiments involving organic acid and strong base/strong acid. It is suggested that organic acids can disrupt stronger chemical bonds, indicating a chemisorption process. On the other hand, treatments with solid base/strong acid points towards ion exchange are the dominant mechanism. In addition, the fact that water can effectively remove dye from the adsorbent surface suggests that hydrogen bonding plays a role in this process. While chemisorption procedures are often associated with stronger interactions, this highlights the presence of weaker bonds during adsorption (Wang; Chen; Kong, 2014).
Following the completion of the adsorption experiments, the CJAC-MB solid foam composite was stirred for 24 hours in an Erlenmeyer flask with distilled water. Dye concentration was determined by extracting samples from the flasks at predetermined intervals to evaluate desorption. In addition, the desorption percentage was calculated using Equation (3) (Manjunath; Mathava Kumar, 2017).

\[
\text{Desorption (\%)} = \frac{C_{\text{des}}}{C_{\text{ads}}} \times 100 \quad (3)
\]

where \(C_{\text{ads}}\) is the dye adsorbed by an adsorbent at equilibrium time (mg/L), and \(C_{\text{des}}\) is the dye desorbed (mg/L).

4 RESULTS AND DISCUSSION

4.1. CHARACTERIZATION OF SOLID FOAM CJAC

4.1.1 Scanning Electron Microscope (SEM)

The SEM pictures of the CJAC composite and the raw material RC (raw Cement and CJAC solid foam cement) shown in Figures 4 (a) and 4 (b), respectively, indicate that both the Composite and the raw material have a porous surface texture with pores of varying sizes. The minute filamentous microstructures found beside the surface pores in the Composite may be attributed to the cement bonding with JCAC.

Figure 4: Scanning electron microscope pictures of the CJAC composite and the raw material

(a) (b)

Source: Authors.
4.1.2 Elemental Composition (EDX)

The EDX spectrum of JCAC, as shown in Figure 5, indicates that JCAC consists of 4.74% carbon (C) due to the very low ratios of activated carbon added, 6.14% silicon (Si), 30.23% oxygen (O), 55.26% calcium (Ca), 0.31% iron (Fe), 1.11% aluminium (Al), 6.83% silicon (Si), 1.82% Sulphur (S), and 0.39% magnesium (Mg). This demonstrates the presence of a strong adhesion between Cement and CJAC.

Figure 5: X-ray analysis EDX (Elemental composition of CJAC)

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O K</td>
<td>4.74</td>
</tr>
<tr>
<td>O K</td>
<td>30.23</td>
</tr>
<tr>
<td>C K</td>
<td>0.31</td>
</tr>
<tr>
<td>MgK</td>
<td>0.39</td>
</tr>
<tr>
<td>AK</td>
<td>1.11</td>
</tr>
<tr>
<td>SiK</td>
<td>6.83</td>
</tr>
<tr>
<td>S K</td>
<td>1.82</td>
</tr>
<tr>
<td>CaK</td>
<td>55.26</td>
</tr>
</tbody>
</table>

Source: Authors.

4.1.3 Fourier Transform Infrared Spectra (FTIR)

Raw material without carbon and Activated carbon-cement solid foam with a water/cement (W/C) ratio of 1/2 was analyzed using Fourier transform infrared spectra (Figure 6 (a) and 6 (b) respectively). The foam was made from jujube cores. Figure 3 displays the FTIR spectrum of RM. Bands representing stretching at different chemical bonds are displayed at different wavelengths: C-H at 2661 cm\(^{-1}\), S-H bonds at 2507 cm\(^{-1}\), O-C-O at 2386 cm\(^{-1}\), N-C-N at 2113 cm\(^{-1}\), C-C at 1993 cm\(^{-1}\), and S-O at 1411 cm\(^{-1}\). Si-O bending in SiO\(_4\) is indicated by the band at 989 cm\(^{-1}\), Al-O stretching in AlO\(_4\) is indicated by the band at 865 cm\(^{-1}\) (Saranya et al., 2018), Al-O stretching vibrations in AlO\(_6\) are specified at 706 cm\(^{-1}\) (Blachnio et al., 2018), C-I stretching is marked at 549 cm\(^{-1}\), and O-Si-O bending in SiO\(_4\) is marked at 527 cm\(^{-1}\) (Manjunath; Ranu Singh Baghel, 2019).
The peak features of the silicate structures in the cementitious matrix and the functional group peaks remain unchanged when carbon is added to the matrix, such as CJAC.

4.2 INVESTIGATING THE IMPACT OF SEVERAL FACTORS ON THE RATE OF ELIMINATION

4.2.1 Contact Time and Initial MB Concentration

The impact of varying contact times on the rate of MB elimination was investigated across a duration spanning from 10 to 120 minutes. Experiments were conducted using 200 ml of MB solution with varying initial concentrations (50, 100, and 200 mg/l), a sorbent mass of 1 cube weighing 20g, and at room temperature.

Thorough mixing with a magnetic bar spinning at 200 rpm ensured optimal interaction between the adsorbent and the solution.
By the Figure 7 (a) and 7 (b) and during the initial 40 minutes, the elimination rate experiences a rapid increase, followed by a gradual rise up to 90 minutes. Beyond that point, the rate remains relatively constant. The graph illustrates that the BM elimination rate was achieved after 90 minutes, with 90.1%, 93.64%, and 96.608% for 200, 100, and 50 mg/l concentrations, respectively. One possible explanation for the higher initial phase’s elimination rate could be the swift external mass transfer. Following this, there is a gradual rise in the rate at which methylene blue is eliminated, reaching equilibrium after 90 minutes. It indicates a mass transfer within the adsorbent, typically resulting from a diffusion process within its internal pores.

4.2.2 Amount of Adsorbent Used

The amount of CJAC sorbent used dramatically influences the adsorption process. The study examined the impact of varying the CJAC sorbent dose, ranging from 1 cube weighing 20 g to 3 cubes with a total mass of 60 g. The elimination rate over time is depicted in Figure 7. The results indicate that the elimination rate rises steadily as the CJAC sorbent dose increases. The elimination rate experiences a significant increase, going from 93.62% to an impressive 98.89%.

Figure 8: Amount of adsorbent material effect

Source: Authors.
The variation in the elimination rate of methylene blue presents in Figure 8 can be explained by the different factors that affect the adsorption process, such as the number of active sites and the functional groups present on the surface of the CJAC sorbent. After careful analysis, it was determined that the ideal adsorbent dose for optimal results is three cubes with a total mass of 60 g.

5 KINETIC STUDY

Adsorption rate and order were calculated using pseudo-first- and pseudo-second-order models. Figure 8 shows CJAC dye removal kinetics. Figure 9 lists equations, kinetic constants, and linear regression coefficients (R2). The pseudo-second-order model's R2 value is closer to unity (0.9932) than the pseudo-first-order model's (0.9517), suggesting that it may better approximate MB dye adsorption kinetics. The equilibrium sorption capacity (qe,cal=9.9901± 0.1237 mg/g, Figure 9 (a)) predicted using a pseudo-second-order kinetic model was nearly identical to the experimental sorption capacity (qe,exp = 9.3 ± 0.5 mg/g, Figure 9 (b)). The initial rate of adsorption (h) is given by $h = K_2 q_e^2$

6 EQUILIBRIUM STUDY

The isotherm plots for removing MB dye using CJAC are presented in Figure 10 (a~d). Tables in Figures 10 (a), 10 (b), 10 (c), and 10 (d) show the isotherm constants for MB dye elimination using CJAC. R2>0.999 indicates that
the Temkin isotherm model has a more significant linear regression coefficient than the other models.

Figure 10: Isotherm plots for Removal of MB dye using CJAC (a: Freundlich isotherm, b: Langmuir isotherm, c: Temkin isotherm, d: Elovich isotherm)

- the constant 1/n (the slope) represents the adsorption affinity in the Freundlich isotherm. As n increases, the adsorption efficiency improves. For our scenario with n=7.81, the Freundlich isotherm suggests the possibility of multilayer adsorption occurring on various adsorption sites. However, the isotherm needs to explain the adsorption of MB on the CJAC solid foam composite. Its R² value of 0.91 is lower than that of other models such as Langmuir, Elovich, and Temkin;

- the Langmuir model demonstrates an impressive correlation coefficient R² (R² = 0.994), suggesting a robust fit. Regrettably, it was not possible to determine the maximum adsorbed quantity Qmax because of the negative y-intercept observed in the line 1/Qmax as a function of 1/Ce. The negative value is likely due to the weight given to the points representing deficient
dye concentrations on the isotherm. In this scenario, it is impossible to determine $Q_{\text{max}}$ because the maximum adsorption capacity ($Q_{\text{max}}$) cannot be negative. In addition, determining the KL parameter based on $Q_{\text{max}}$ was not feasible. Thus, the Langmuir model falls short of accurately describing the adsorption isotherms of BM (Benaomar, 2010);

- even though the $R^2$ value of the Langmuir isotherm is close to 1 ($R^2=0.994$), this model is limited to describing adsorption on homogeneous, monomolecular surfaces. Alternatively, the Temkin isotherm, with an $R^2$ value of 0.999 in our case, is commonly employed to describe adsorption on ununiform surfaces (Cement – jujube cores activated carbon). This model considers the non-ideal interactions between adsorbates and adsorption sites and the gradual decrease in adsorption energy as the surface coverage increases;

- Elovich's isotherm may be used frequently to explain chemisorption adsorption on actively involved surfaces. The $R^2$ value is 0.95. It suggests that the adsorption process starts fast but gradually slows down.

According to these results, the Temkin isotherm gives a better picture of adsorption than the models proposed by Freundlich, Elovich, and Langmuir. Indeed, the Temkin isotherm shows a superior consistency between model predictions and actual observations, with an $R^2$ reaching 0.999, demonstrating high agreement with experimental data.

7 DESORPTION STUDY

It is observed that fitting the adsorption data to the Elovich isotherm indicates that chemisorption may not be solely accountable, potentially due to less strong adsorption interactions. The capacity of water to eliminate dye from the adsorbent surface suggests the participation of hydrogen bonding.
Figure 11: Desorption capacity

<table>
<thead>
<tr>
<th>% desorption</th>
<th>Composite material</th>
<th>Raw material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.02</td>
<td>2.08</td>
</tr>
<tr>
<td>1</td>
<td>5.18</td>
<td>5.66</td>
</tr>
<tr>
<td>3</td>
<td>11.36</td>
<td>9.63</td>
</tr>
<tr>
<td>5</td>
<td>15.17</td>
<td>10.53</td>
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<tr>
<td>7</td>
<td>16.78</td>
<td>13.51</td>
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<tr>
<td>9</td>
<td>29.07</td>
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<tr>
<td>33</td>
<td>29.24</td>
<td>20.78</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Authors.

Figure 11 depicts the desorption process of MB dye from the Solid foam RM and CJAC. The desorption rate peaked within the initial 7 hours and 9 hours for CJAC and RM, respectively, and eventually reached equilibrium, with a maximum observed desorption of approximately 29.24% and 20.78% of MB dye after 33 hours for CJAC and RM, respectively, which is less than 40% (Manjunath; Mathava Kumar, 2017). The lower desorption rate observed for MB dye from the Composite suggests that the adsorption process is not entirely reversible, indicating the presence of strong bonds between MB dye and the adsorbents, likely attributed to chemisorption processes.

8 CONCLUSION

The present investigation has brought to light the considerable potential of the CJAC solid foam composite in the domains of water treatment and environmental management. The composite's physical properties and surface characteristics were thoroughly examined using advanced characterization techniques, including scanning electron microscopy (SEM), energy dispersive X-ray analysis (EDX), and Fourier transform infrared spectroscopy (FTIR). These techniques provided valuable insights into the composition and structure of the composite. The study examined the impact of various parameters, such as contact time, initial concentration of methylene blue (MB) dye, and the amount of adsorbent utilized, on the rate of removal. The findings emphasized the efficacy of CJAC in
cleaning water solutions containing this dye. Furthermore, the application of kinetic analysis using pseudo-first and pseudo-second order models verified that the pseudo-second order model is appropriate for describing the adsorption kinetics. The predicted and experimental sorption capacities exhibited a high level of agreement. The equilibrium investigations further verified the appropriateness of the Temkin isotherm model in describing the adsorption behavior, exhibiting a remarkable agreement with the experimental results. Furthermore, the analysis of desorption indicated the existence of robust connections between the methylene blue dye and the adsorbents, which leads to the slow release of the composite and raises concerns about its reversibility.

The study on wastewater treatment in the textile industry highlights the potential of cement-activated carbon solid foam composite technology for water treatment and environmental management. It highlights its eco-friendliness, cost-effectiveness, and potential for environmental sustainability and academic advancement. However, limitations include the need for scale-up and field testing, long-term performance and stability, optimization of operating parameters, exploration of other dye types, environmental impact assessment, economic analysis, and characterization techniques. Addressing these issues can advance sustainable wastewater treatment in the textile industry.
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