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Optimizing Methylene Blue Removal from Textile Effluents: Comparative Study of Adsorption Efficiency Using Raw and Activated Carbon Derived from *Gmelina* Wood Wastes

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Abstract

This research investigates the efficacy of activated *Gmelina* Wood Sawdust (GWS) as an adsorbent for the removal of methylene blue (MB) dye from aqueous solutions, in comparison with raw GWS. The study employs laboratory experiments to assess the percentage of dye removal across various temperature and pH conditions. The adsorption process is scrutinized under different parameters, encompassing contact time, initial dye concentration, adsorbent dosage, temperature, and pH. Results demonstrate that activated GWS surpasses its raw counterpart, showcasing superior MB dye removal percentages. Extended contact times increased initial dye concentrations, and higher adsorbent dosages contribute positively to removal efficiency, while temperature exhibits an inverse relationship with dye removal. Optimal adsorption occurs at a pH of 7.0, aligning with the adsorbent's zero-point charge (pHzpc), underscoring the role of surface charge in the adsorption process. This study underscores the potential of activated GWS as an economical and promising adsorbent material for addressing pollutants. Furthermore, the utilization of activated carbon derived from abundant agricultural waste underscores an environmentally conscious approach to adsorption applications. The ability to tailor the size and properties of activated carbon particles opens avenues for optimizing adsorption capabilities, thereby presenting opportunities for enhanced water treatment solutions.

Keywords

Gmelina Wood, *Gmelina* Wood Sawdust, Activated Carbon, Adsorption, Methylene Blue (MB), pH (hydrogen Ion Index), SEM Examination

1. Introduction

Water pollution is one of the most unsuitable environmental problems in the world which requires adequate attention and solutions.

Textile industries produce a lot of effluents, which include a number of contaminants that are harmful to human beings as well aquatic life and micro-organisms. Dyes, which impart colour to the effluents, constitute the major pollutants in textile wastewater. The effluents, when discharged into a water body, adversely affect the penetration of light and photosynthesis, thereby jeopardizing aquatic life. Many of these dyes are said to be carcinogenic, mutagenic and toxic. Hence their removal from aquatic wastewater becomes necessary and important, so as to have an environment that is free of toxic materials [1].

Large quantities of dangerous dyes, pigments and metals are discharged into river as textile effluents. These make the treatment of wastewater contamination more difficult, because the colour tends to persist even after the conventional removal processes [2]. Some of the conventional methods used to treat coloured effluents are the physical, chemical and biological treatment.

Due to wide application of dye compound and their numerous hazards and toxic derivatives, the cleaning of wastewater from colour dyestuff becomes environmentally important [3]. The first Synthetic dyes Mauve, developed in (1856) was a coal tar product and contained the chemical aniline, but the term aniline has been used to include other chemical type dyes. Today aniline has been used to differentiate natural dyes from the synthetic dyes. Synthetic dyes have been increasing in textile industries for dyeing natural and synthetic fibres, although they are even biologically non-degradable and their treatments by other effective conventional procedure are impossible as a result of their high solubility and low biodegradability. There are many types of dyes used in textile industries which include reactive, direct, acid and basic dyes. Basic dyes are synthetic dyes also known as cationic dyes. Basic dyes act as bases but when made soluble in aqueous solution, their molecules form a coloured cationic salt, which can react with the anionic sites on the surface of the substrate. Basic dyes are used for dyeing wool, silk, acrylic fibres. The outstanding characteristics of the basic dyes are the brilliance, excellent substantivity, good brightness and intensity of their colours.

The environmental issues surrounding the presence of colour in effluent is a continuous problem for dye stuff manufacturers, dyers, finishers, and water companies [4]. Therefore, the treatment of these pollutions is very important [5]. Dye is a natural or synthetic colouring material, whether soluble or insoluble that has an affinity to the substrate to which it is applied. They are widely used in textile, paper, leather, and mineral processing industries to colour their product.

Dyes can also cause severe damage to human beings such as the malfunction of kidney, reproductive system, liver, brain and the central nervous system [6]. In this present research methylene blue also known as methylthioninium chloride is a medication and a basic dye, which is used in the determination of the adsorption efficiency by the use of an adsorbent.

Adsorption process is an attractive and effective alternative treatment for dye removal from wastewater. In addition, it has been found to be superior to other techniques of wastewater treatment in terms of cost, simplicity of design, ease of operation, and insensitivity to toxic substances [7]. Activated carbon is the most common adsorbent for the removal of many organic contaminants. From this carbon the best porous adsorbent can be obtained (activated carbon) with unique properties for industrial usage. Activated Carbon (AC) is the common term used for a group of adsorbing substances having a large internal pore structures that make the carbon more adsorbent [8]. Activated carbon can be manufactured from virtually all carbonaceous materials. However, the abundance and availability of agricultural wastes makes them good sources of raw materials for activated carbon production Activated carbon (AC) is widely used as an adsorbent in the treatment of gas and liquid phases application as it contains porous structure. Most of the industrial sectors such textile industries, pharmaceutical, mining, petroleum, nuclear, water treatment uses Activated carbon (AC) in their Processing units [9] [10].

Application of AC in such industries is highly demanded due to the surface chemistry and unique characteristics of this carbon adsorbent [11]. Generally, the raw materials for the production of activated carbon are those with high carbon but low inorganic contents such as wood, lignite, peat, coal [12]. AC is inexpensive and hence very widely used adsorbent material.

Characteristics of activated carbon depend on the physical and chemical properties of the raw materials as well as method of activation [13].

This research work investigated the use of agricultural wastes (*Gmelina* wood wastes) to produce activated carbon and compare it with that of the raw *Gmelina* wood sawdust in the removal of methylene blue from textile wastewater.

Gmelina trees are abundant in the environment of this study. The mature plants are harvested and processed as timber for building and other woodworks. The sawdust's generated while processing the wood are hitherto handled as wastes. This work, therefore, demonstrates that these wastes could be turned into wealth by converting them into activated carbon for the removal of dyestuff (methylene blue) from textile effluents.

2. Materials and Methods

Preparation of the Adsorbents

The sawdust's of *Gmelina* wood were obtained from Nkwo market sawmill at Nnewi, in Anambra State of Nigeria. The sawdust's collected were washed vigorously with clean water to remove dusts, dirt's, and other foreign bodies. After washing, it was then sundried for seven (7) days. The sawdust's were sieved into a particle size of 0.35 mm mesh size. The sieved sample was kept in covered plastic containers. Some of the sieved samples were then carbonized using muffle furnace at a temperature of 500˚C for 3 hrs. After carbonization, the sawdust's which were converted to char were taken out from the furnace and allowed to cool at room temperature. The carbonized material was impregnated using 0.1 M of sulphuric acid as the activating agent. It was then heated up for 1 hr and was allowed to cool at room temperature. Then it was washed until the pH of the sample became neutral. The Sample was dried in a hot air oven at 100˚C.

2.1. Experimental Methods

Bulk density determination:

Bulk density is an important characteristic of activated carbon as it is a measure of the amount of adsorbate the adsorbents can hold per unit volume under specified conditions. Bulk density of the raw and activated carbon were determined using a known weight of raw and activated carbon sample. It was filled up into a measuring cylinder whose volume was 10 ml and was tapped on a hard surface for 1 minute to compact the carbon. The reduced compacted volume of the sample in the measuring cylinder was measured and bulk density calculated:

$$\text{Bulk density}\left(\text{g/cm}^3\right) = \frac{\text{weight of dry material}\left(\text{g}\right)}{\text{volume of packed dry material}\left(\text{cm}^3\right)} \tag{1}$$

pH determination:

4 g of activated carbon was suspended in 100 ml of distilled water, heated to 50˚C with continuous stirring for 15 minutes and was allowed to cool at room temperature. The pH was measured using pH meter.

Electrical conductivity:

4 g of activated carbon was suspended in 100 ml of distilled water, stirred for 20 minutes and the conductivity was measured.

2.2. Characterization of Adsorbent

Proximate analysis:

Proximate analysis, as defined by ASTM, is the determination by prescribed methods of moisture, volatile matter, ash contents and fixed carbon. Proximate analysis gives useful information about the physical properties of the biomass. The proximate analysis of the raw *Gmelina* sawdust was analysed to determine its moisture content, volatile matter, ash contents and fixed carbon.

Elemental analysis (Ultimate):

The elemental analysis of the raw GWS was determined. Elemental analysis are carried out to determine the organ genic elements *i.e.* Carbon, hydrogen, oxygen, sulphur and nitrogen. These elements are characteristic properties of an organic compound.

Iodine number:

The characterization of the adsorbents (raw and activated carbon) was obtained by determining their iodine number. Iodine number is a measure of the micro-pore content of the adsorbent. A high number indicates higher micro-porosity of the sample.

Scanning electron microscope (SEM):

SEM is a type of microscope which uses a beam of highly energetic electrons to scan a sample and produce its image. The surface morphological changes (porous structure) before and after adsorption of the raw sawdust and activated carbon were analysed using the scanning electron microscope.

2.3. Adsorption Experiment

Batch adsorption experiments were performed to determine the following parameters such as; effect of contact time and initial dye concentration, effect of pH, effect of temperature and effect of adsorbent dosage. Batch studies were conducted by weighing 0.2, 0.4, 0.6, 0.8 g of activated carbon and was interacted with 20 ml of methylene blue dye of a known concentration of 10 mol/dm^3 in a beaker at temperature of 70˚C, 100˚C, 130˚C, and 160˚C at different time intervals of 10, 20, 30, and 40 minutes, it was then filtered using a Whatman filter paper, the process was repeated at different concentration of 2, 4, 6, mol/dm^3 at constant temperature (100˚C) and adsorbent dosage of 0.8g. The absorbance of the filtrate was determined using a UV-Vis spectrophotometer at wave length of 650 nm. The amount of MB uptake onto activated GWS and raw GWS was calculated using the mass balance equation.

$$Q_e = \frac{C_o - C_e}{W} v \tag{2}$$

The percentage (%) dye removal was calculated using the following equation.

$$\text{Removal}(\%) = \frac{C_o - C_e}{C_o} \times 100 \tag{3}$$

where Q_e is the amount of MB adsorbed by GWS raw and activated carbon (mg/g), C_o and C_e are the initial and final dye concentrations (mg/L) respectively, V is the volume of solution (ml) and W is the adsorbent weight (g).

3. Results and Discussion

The characterization results are illustrated in Table 1 and Table 2. Figure 1 and Figure 2 show the surface morphology of the adsorbents before and after adsorption.

Physio-chemical characteristics describe the suitability of adsorbent for a particular process. The results of the characterization in Table 1 show that the percentage ash contents of the sample were low which indicates that the carbon yield of the sample was very high.

As shown in Table 2 the pH of the activated carbon was 7.00 and that of the raw GWS was 7.13 indicating that the pH is neutral. For most application activated carbon pH of 6 - 8 is acceptable [14]. Percentage yield is the amount of

Table 1. Characterization results for proximate and elemental (ultimate) analysis of *Gemlina* biomass (raw *Gmelina* sawdust).

Proximate analysis	Raw *Gmelina* Wood Sawdust
Moisture content (%)	9.30
Ash content (%)	1.1
Volatile matter (%)	99.00
Fixed carbon (%)	23.34
Elemental (ultimate) analysis	
Carbon (%)	0.40
Sulphur (%)	0.01
Oxygen (%)	84.99
Hydrogen (%)	4.20

Table 2. Physio-chemical characterization of raw GWS (*Gmelina wood* saw dust) and activated GWS.

Parameters	Raw GWS	Activated GWS
Ph	7.13	7.00
Conductivity (ηS/cm)	98	396
Bulk density (g/cm^3)	0.099	0.25
BET surface area (m^2/g)	746.20	1011.80
Iodine number (mg/g)	62.04	74.60
Pore volume (ml)	0.002	0.005
Yield (%)	-	12.37
Burn off (%)	-	62.04

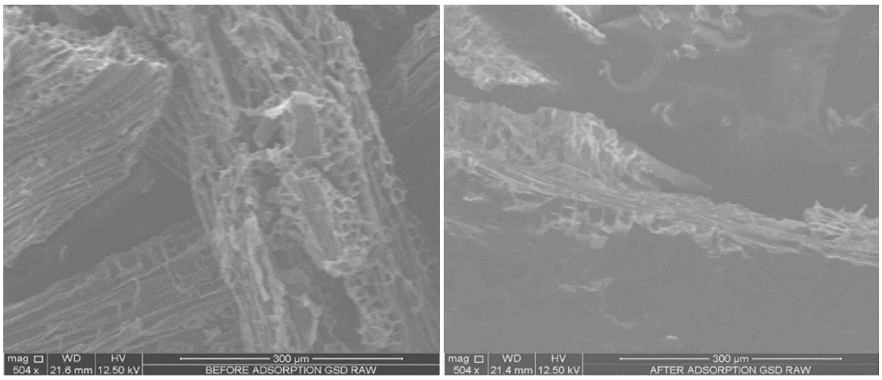

Figure 1. SEM before and after adsorption raw GWS (mag 504×).

carbon remaining after carbonization and activation treatment. Carbon with an adequate bulk density aids to improve the filtration rate by forming an even cake on the filter surface. The conductivity test is important because it indicates the presence of leach able ash which is considered to be impurity and undesirable in

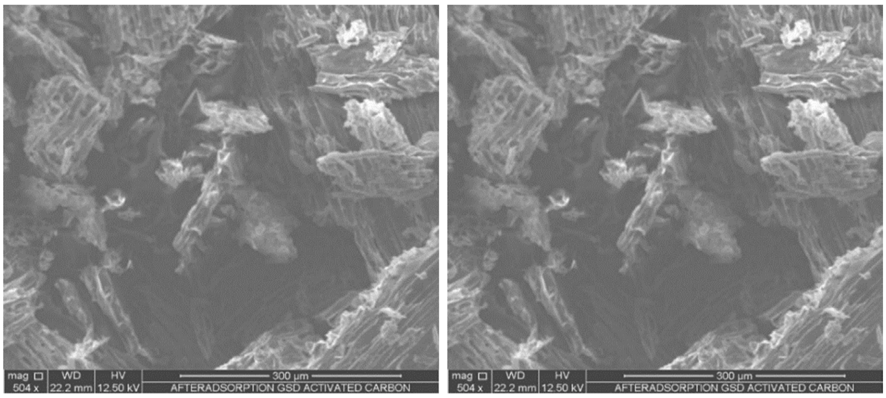

Figure 2. SEM before and after adsorption onto Activated GWS (mag.504×).

activated carbon [15]. The activated carbon showed the highest conductivity value of 396 ηS/cm which implies that the adsorbents contain less leach able ash.

In Table 2 the iodine number of activated GWS which was 74.60 mg/g indicates a higher micro porosity of the sample to that of the raw GWS which has a lower iodine number of 62.4 mg/g. The BET surface area of the activated GWS in Table 2 indicates a higher surface area to that of the raw GWS, hence providing more availability of surface for adsorption giving rise to better adsorption capacity.

Figure 1 and Figure 2 shows the micrograph of raw GWS analysed at the magnification of 540× which exhibits the surface of the raw GWS and activated carbon. Figure 1 indicates that the surface consisted of pores that seemed to have a rough surface and irregular arrangement. These pores would provide a template for the development of macro-pore in the resulting carbon [16]. Figure 1 showed that the adsorption of MB onto raw GWS was not high due to low porosity. Figure 2 Shows the activated GWS analysed at the magnification of 540×. The surface of the activated GWS shows a well-developed porous structure with a regular pore sizes and cavities which indicate that activation has taken place. Figure 2 shows the adsorption of MB onto activated GWS, indicating that the pores and surfaces of adsorbent were covered by MB dye. It is patent that the MB intake onto activated GWS was higher to that of raw GSD, indicating an increase in the pore structure of activated GWS [17].

3.1. Experimental Results

Experimental results obtained from the laboratory were used to calculate the percentage of dye removal at various temperatures and pH. From the results the graph of percentage of dye removal against adsorption parameters were obtained as shown below.

3.1.1. Effect of Contact Time

The effect of contact time on the adsorption of methylene blue (MB) onto activated GWS and raw GWS was studied, which shows that the percentage removal of MB was increasing as the contact time increases. The activated GWS has the highest percentage dye removal to that of the raw GWS due to the low number of vacant sites of the raw GWS.

The influence of contact time on the adsorption process of Methylene Blue (MB) onto raw *Gmelina* Wood Sawdust (GWS) is depicted in **Figure 3**. The percentage removal of MB is observed to increase with extended contact times. However, the raw GWS exhibits a comparatively lower percentage of dye removal in contrast to activated GWS, attributable to the limited number of available vacant sites on the surface of the raw GWS

Figure 4, illustrates the effect of contact time on the adsorption behavior of Methylene Blue (MB) onto activated *Gmelina* Wood Sawdust (GWS). The data portrays a consistent trend of increasing MB removal percentage as contact time is extended. Notably, activated GWS exhibits notably higher MB removal efficiency compared to raw GWS, primarily attributed to the enhanced presence of active sites and improved surface characteristics resulting from the activation process.

These observations underscore the significance of contact time in influencing

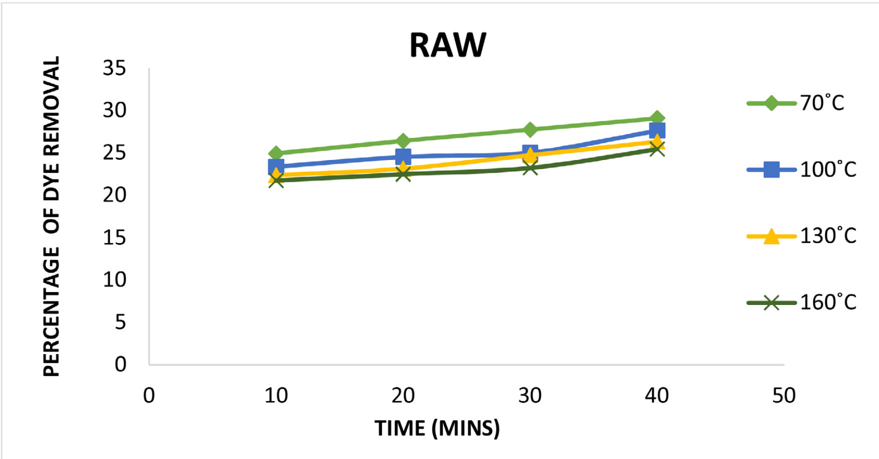

Figure 3. Effect of contact time on the adsorption of MB onto raw GWS.

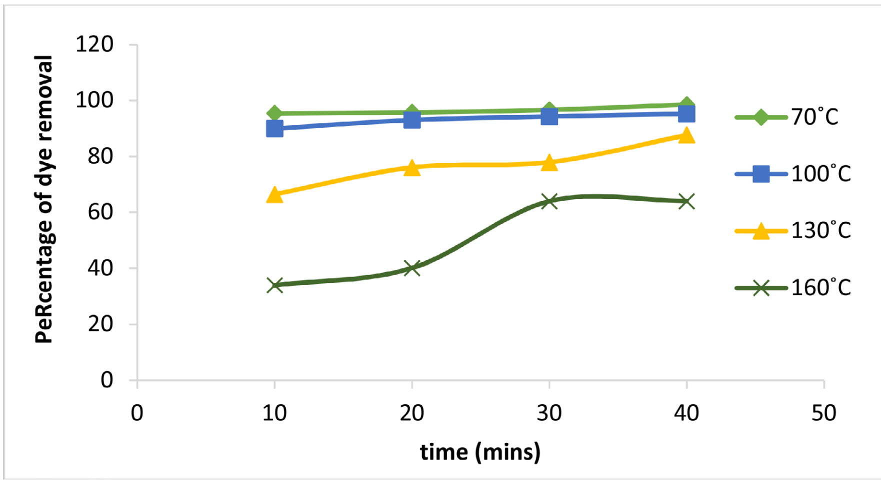

Figure 4. Effect of contact time on the adsorption of MB onto activated GWS.

the adsorption kinetics and highlight the favorable impact of activation on GWS in enhancing its adsorption capacity for Methylene Blue removal.

3.1.2. Effect of Adsorbent Dosage

The adsorption process of Methylene Blue (MB) onto both activated *Gmelina* Wood Sawdust (GWS) and raw GWS was systematically conducted by varying the adsorbent dosage from 0.2 g to 0.8 g, while maintaining a constant pH of 5.0. The outcomes of this investigation are elucidated in Figure 5 and Figure 6, revealing the intricate relationship between adsorbent dosage and MB dye removal efficiency.

Figure 5 illustrates the influence of varying adsorbent dosages on the adsorption process of MB onto raw GWS. The data portrays a consistent trend, where an increase in adsorbent dosage corresponds to an enhancement in the percentage of MB dye removal. It is noteworthy that raw GWS exhibits an observable increase in MB removal percentage with escalating adsorbent dosage. However, compared to activated GWS, the raw variant demonstrates relatively lower removal efficiency due to fewer accessible adsorption sites and a smaller surface area at higher dosages.

Figure 6 showcases the impact of varying adsorbent dosages on the adsorption behavior of MB onto activated GWS. The results depict a similar pattern of increasing MB removal percentage with the elevation of adsorbent dosage. Notably,

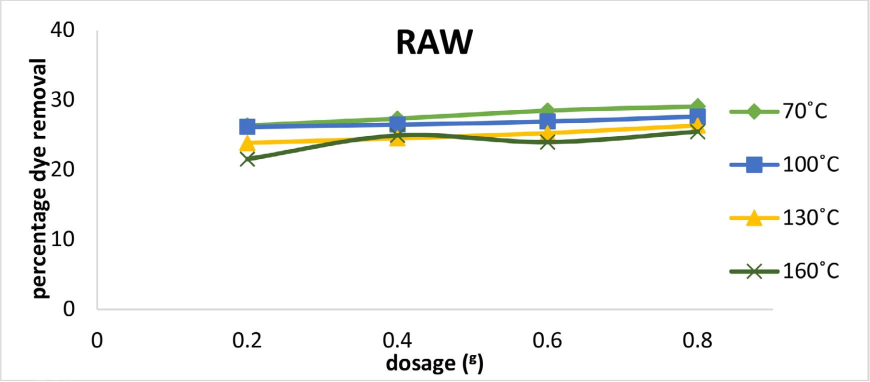

Figure 5. Effect of adsorbent dosage on the adsorption of MB onto raw GWS.

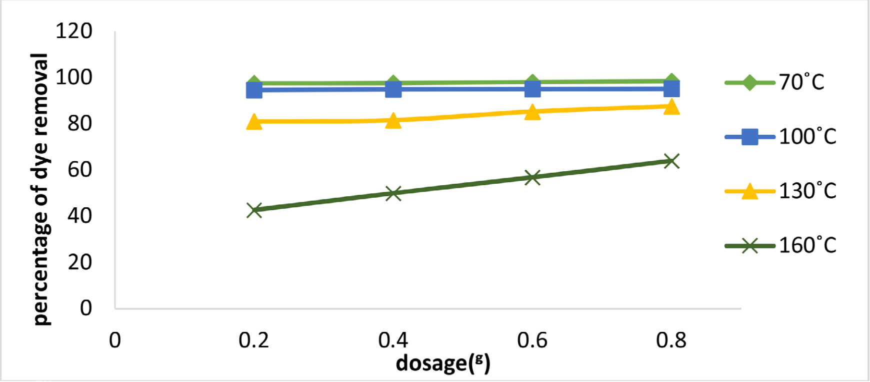

Figure 6. Effect of adsorbent dosage on the adsorption of MB onto activated GWS.

activated GWS exhibits significantly higher MB removal efficiency than raw GWS across all dosage levels. This discrepancy arises from the larger number of available adsorption sites and the greater surface area presented by activated GWS at elevated dosages.

In summary, the findings emphasize the pivotal role of adsorbent dosage in influencing the adsorption process, highlighting the positive correlation between dosage increase and MB dye removal efficiency. Furthermore, the pronounced superiority of activated GWS in comparison to raw GWS reinforces the advantageous impact of activation on adsorption capacity, underscoring the potential of activated GWS as a potent tool for pollutant removal from textile effluents.

3.1.3. Effect of Contact Time and Initial Dye Concentration

The investigation of contact time's influence on activated *Gmelina* Wood Sawdust (GWS) and raw GWS, in conjunction with varying concentrations of Methylene Blue (MB), constitutes a significant aspect of this study. Figure 7 and Figure 8 provide insight into the interplay between contact time, dye concentration, and the percentage removal of MB dye, shedding light on their combined

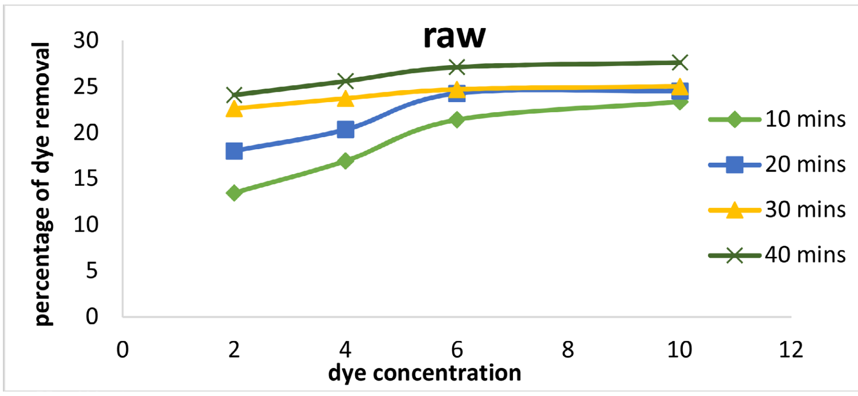

Figure 7. Effect of contact time and initial dye concentration on the adsorption of MB onto Raw GWS.

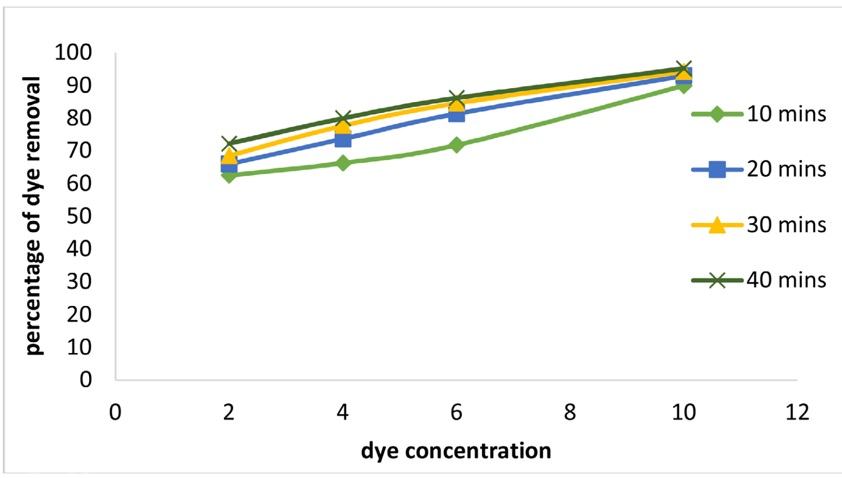

Figure 8. Effect of contact time and initial dye concentration on the adsorption of MB onto activated GWS.

impact on the adsorption process.

Figure 7 portrays the dynamic relationship between contact time and initial dye concentration during the adsorption of MB onto raw GWS. Notably, the percentage removal of MB dye exhibits a consistent upward trend as contact time progresses from 10 to 40 minutes. Similarly, the increase in dye concentration from 2 mol/dm^3 to 10 mol/dm^3 contributes to elevated dye removal efficiency. This phenomenon can be attributed to the higher initial dye concentration facilitating a more potent driving force for mass transfer between the aqueous and solid phases. Notably, while raw GWS exhibits enhanced dye removal with heightened contact time and concentration, the activated GWS outperforms its raw counterpart across all conditions.

Figure 8 elucidates the intricate interaction between contact time, initial dye concentration, and MB adsorption onto activated GWS. As evident, the percentage removal of MB dye displays a commendable increase as contact time extends from 10 to 40 minutes. Simultaneously, the rise in dye concentration enhances the removal efficiency. This behavior is attributed to the combined effect of contact time and initial dye concentration intensifying the driving force for effective mass transfer. Notably, the activated GWS outperforms the raw variant in terms of MB removal efficiency across all conditions.

The experimental outcomes underscore the substantial impact of contact time and dye concentration on the adsorption kinetics, while also emphasizing the marked superiority of activated GWS over raw GWS in enhancing MB dye removal. This reinforces the enhanced adsorption capacity facilitated by activation, further substantiating the promise of activated GWS for the efficient treatment of textile effluents contaminated with Methylene Blue.

3.1.4. Effect of Temperature

In order to scrutinize the impact of temperature on the adsorption process, this study explored the adsorption behaviour of Methylene Blue (MB) onto both activated *Gmelina* Wood Sawdust (GWS) and raw GWS, within a temperature range of 70˚C to 160˚C. The experimental investigation aimed to elucidate the intricate relationship between temperature and the percentage removal of MB dye, shedding light on how this influential variable affects the adsorption dynamics.

Figure 9 provides a comprehensive visualization of the response of the adsorption process to varying temperatures for raw GWS. As discernible from the data, an intriguing trend emerges: with the elevation of temperature, the percentage removal of MB dye experiences a gradual decrease. This observation is noteworthy as it suggests a temperature-dependent effect on the adsorption process. Remarkably, among the two materials studied, raw GWS manifests the lowest MB dye removal percentage, indicating its inferior performance in comparison to activated GWS across the range of temperatures examined.

Figure 10 unveils the response of the adsorption process to different temperatures when utilizing activated GWS. The outcomes mirror those observed with

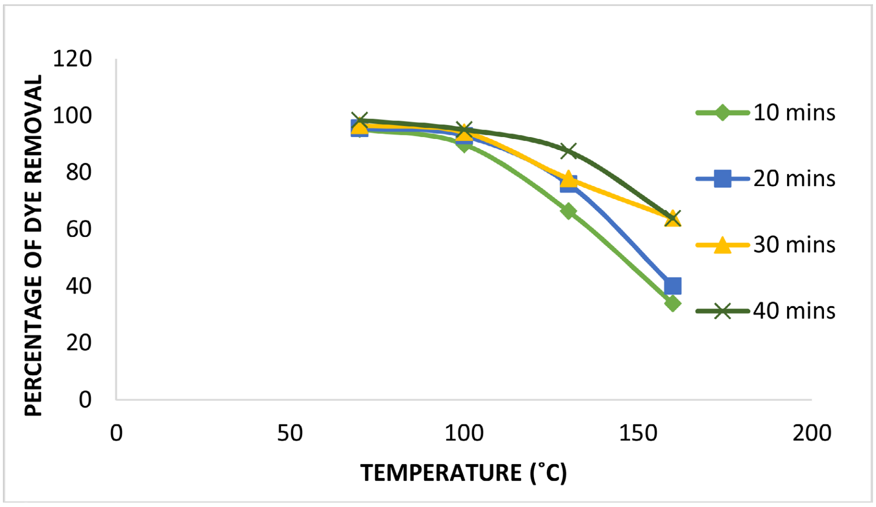

Figure 9. Effect of temperature on the adsorption of MB onto raw GWS.

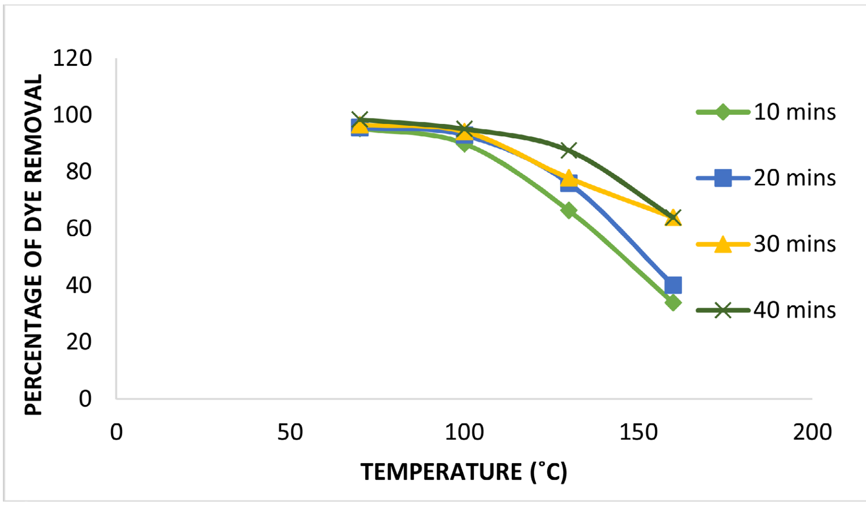

Figure 10. Effect of temperature on the adsorption of MB onto activated GWS.

raw GWS, demonstrating a consistent decrease in the percentage removal of MB dye as the temperature escalates. However, activated GWS maintains a higher removal efficiency even at elevated temperatures compared to its raw counterpart.

Collectively, these findings underscore the intricate interplay between temperature and the adsorption dynamics of MB onto GWS. The inverse relationship observed between temperature and dye removal underscores the necessity for cautious consideration when selecting optimal operational conditions for adsorption-based treatment processes. The pronounced contrast in performance between raw and activated GWS emphasizes the significance of activation in enhancing adsorption efficiency and stability under varying temperature conditions.

3.1.5. Effect of pH

The pH of the dye solution stands as a critical determinant influencing the overall adsorption capacity, as acknowledged within the literature [10]. The current study delved into the ramifications of pH variations while maintaining a constant temperature of 100˚C, coupled with different dosages and time intervals. Insightful exploration of this parameter is presented through Figure 11 and Figure 12, which delineate the complex interplay between pH, adsorption dosage, time, and the percentage removal of Methylene Blue (MB) dye.

Figure 11 encapsulates the intricate influence of pH variations on the adsorption process of MB onto raw GWS. Observations from the data reveal an upward trend in the percentage removal of MB dye as pH escalates from 5 to 10. This pH-dependent enhancement in removal efficiency is significant and aligns with the fundamental principles governing adsorption phenomena. Further analysis of the data underscores that the peak adsorption capacity occurs at a pH of 7.0. This specific point corresponds to the zero-point charge (pHzpc) of the adsorbent, where the electrical charge density on the adsorbent surface attains neutrality. Notably, this neutral charge condition provides an ideal environment for the adsorption process to thrive due to the presence of favourable electrostatic forces.

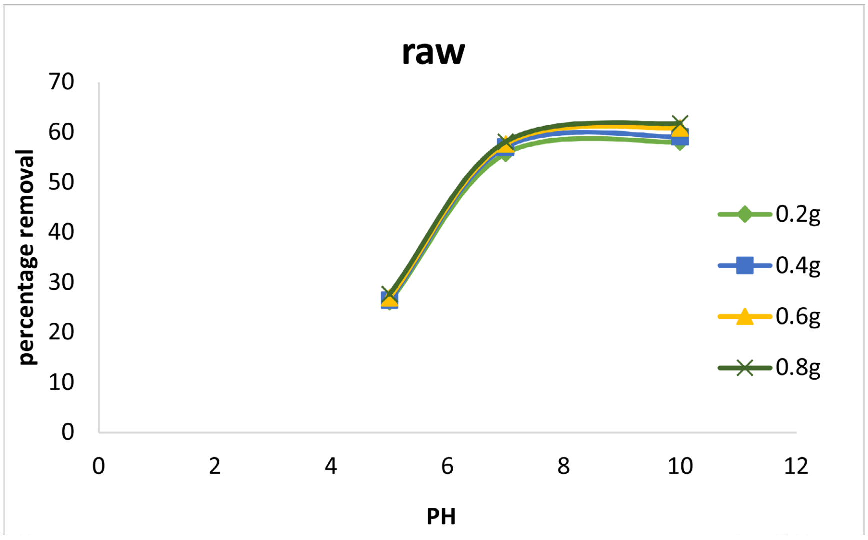

Figure 11. Effect of pH on the adsorption of MB onto raw GWS.

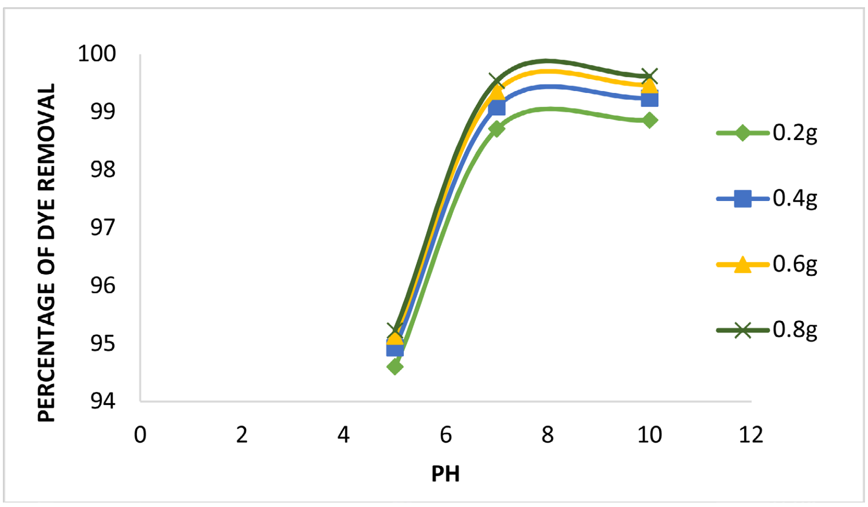

Figure 12. Effect of pH on the adsorption of MB onto activated GWS.

Figure 12 presents an insightful examination of pH's impact on the adsorption behavior of MB onto activated GWS. Evidently, a similar trend unfolds, where the percentage removal of MB dye rises progressively with increasing pH from 5 to 10. Correspondingly, the peak adsorption efficiency occurs at pH 7.0. The explanation lies in the phenomenon of electrostatic charge interactions: at the zero-point charge, the adsorbent's surface is electrically neutral, facilitating the most favorable conditions for adsorption. Above this pH, the adsorbent's surface becomes negatively charged, enhancing the attraction of positively charged dye cations through electrostatic forces. Conversely, below the zero-point charge, electrostatic repulsion between the adsorbent and the adsorbate reduces dye uptake.

In summary, this study's meticulous exploration of the pH variable underscores its pivotal role in influencing adsorption capacity, further elucidating the correlation between pH, adsorption kinetics, and the electrostatic interactions driving the process. These findings provide valuable insights into optimizing the operational conditions for the effective removal of Methylene Blue from textile effluents using *Gmelina* Wood Sawdust-based adsorbents.

4. Conclusion & Discussion

In conclusion, this comprehensive study has provided valuable insights into the adsorptive removal of Methylene Blue (MB) from textile effluents using *Gmelina* Wood Sawdust (GWS) as a raw material for activated carbon production. The investigation was guided by a range of adsorption parameters, including contact time, adsorbent dosage, initial dye concentration, temperature, and pH. The findings collectively contribute to our understanding of the intricate dynamics that govern the adsorption process and its potential applications for water treatment.

The characterization results, as depicted in Table 1 and Table 2, have unveiled the intrinsic physio-chemical properties of both raw GWS and activated GWS. These parameters underscore the suitability of the adsorbent for adsorption processes, with particular attention to factors such as pH, conductivity, bulk density, surface area, and pore volume. The relatively high carbon yield indicated by low ash content in raw GWS reinforces its potential as a precursor for activated carbon production.

The pH parameter emerged as a significant driver of adsorption capacity, with Figure 11 and Figure 12 revealing the relationship between pH and percentage dye removal. The pivotal role of pH was underscored by the peak adsorption occurring at pH 7.0, aligning with the zero-point charge of the adsorbent's surface. This balance in charge facilitates effective electrostatic interactions and enhances adsorption efficiency.

The explorations into contact time, initial dye concentration, adsorbent dosage, and temperature have collectively enriched our understanding of these factors' influence on adsorption kinetics and capacity. Figures 3-8 present intricate patterns that highlight the delicate interplay between these parameters. Notably, activated GWS consistently outperformed raw GWS, owing to its enhanced surface characteristics and porosity resulting from the activation process.

Temperature, a crucial operational parameter, demonstrated an inverse relationship with dye removal efficiency. **Figure 9** and **Figure 10** substantiated the cooling effect of temperature on the adsorption process, reinforcing the need for strategic temperature control to optimize the efficiency of dye removal using GWS-based adsorbents.

This study contributes to the broader field of environmental remediation by showcasing the potential of activated GWS as an effective and sustainable adsorbent for Methylene Blue removal from textile effluents. The environmentally friendly nature of using agricultural waste for activated carbon production underscores the feasibility of eco-conscious solutions for water treatment challenges. Moreover, the insights provided into the optimization of adsorption parameters pave the way for the development of more effective and efficient water treatment strategies.

Finally, the findings of this study underscore the promise of activated GWS as a valuable adsorbent material, further enhancing the arsenal of tools available for tackling water pollution and promoting environmental sustainability. Future research endeavors may delve deeper into optimizing adsorption conditions, exploring diverse pollutant removal, and extending the application of activated GWS-based adsorbents to various other pollutant types, thus advancing our capacity to safeguard and restore our precious water resources.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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