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Comparative Efficacy of Two Bamboo-Derived Activated Carbons for Hospital Wastewater Remediation

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Abstract. Liquid medical waste containing pathogens and hazardous chemicals can pollute the environment and endanger human health. The increasing volume of waste during the COVID-19 pandemic adds urgency to find effective and sustainable treatment methods. However, environmentally friendly and efficient solutions are still limited. This study aims to explore the utilization of activated carbon from two local bamboo species, Gigantochloa apus (GA) and Bambusa vulgaris (BV) as alternative adsorbents in the treatment of liquid medical waste. Two-year-old bamboo was traditionally carbonized and activated using 0.3 M sodium chloride solution. The 50 mesh charcoal powder was tested using BET surface area analysis with QUADRASORB evo™ instrument, morphology using FESEM (FEI Quanta 650), and pollutant reduction efficiency through pH, TDS (HAIK EZ 9909), COD (HACH DBR 200 closed reflux method), and BOD (Winkler method with BOD 6 VELP system) measurements. The results showed that GA activated carbon exhibited a much higher adsorption capacity due to its larger BET surface area compared to BV. In addition, pH and Total Dissolved Solids (TDS) analysis showed that wastewater treated with GA activated carbon exhibited a greater reduction in TDS levels. The study also evaluated the reduction of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), which confirmed that GA provided higher pollutant removal efficiency than BV. These findings underscore the potential of GA and BV as effective adsorbents for medical wastewater treatment, offering a sustainable solution to improve water quality and reduce environmental impacts associated with liquid medical waste.

Keywords: bamboo charcoal, activated carbon, adsorption, water quality, liquid medical waste.

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1. Introduction

The liquid medical waste produced by medical faculties poses considerable risks to human health and the environment. This trash comprises pathogens, dangerous chemicals, and other agents that can elevate the risk of infection and contamination [1,2]. Contact with such trash may occur by direct exposure or aerosol transfer, and inadequate management presents risks of adverse effects on public health, along with heightened healthcare expenses due to illnesses associated with this waste.

Consequently, it is imperative to comprehend the hazards linked to liquid medical waste and to execute efficient management strategies, encompassing the adoption of innovative technologies for filtration and biological treatment, alongside consistent monitoring and assessment of waste quality to mitigate exposure risks and environmental repercussions [3,4].

Indonesia possesses considerable promise as a biomass resource for reducing carbon emissions using traditional carbonization techniques. Indonesia presents a promising array for biomass production, featuring 125 species of biomass, including GA and BV [5]. Efficient carbonization processes, encompassing anoxic environments, are crucial for biomass production. The swift proliferation of biomass facilitates efficient land utilization and environmental preservation [6,7]. Biomass can be utilized in soil analysis to reduce contaminants such as COD and TSS [8]. The activation of biomass- derived carbon can be enhanced through the use of chemicals such as KOH or ZnCl2, hence increasing its surface area and adsorption capacity [9,10]. Bamboo, characterized by its cellulose, hemicellulose, and lignin, possesses potential as a sustainable energy source [11]. Nonetheless, obstacles in biomass production encompass quality and species of bamboo. Additional study is required to enhance output and augment bamboo's carbon adsorption capacity.

The utilization of GA and BV as carbon sources in aqueous soil analysis encounters several hurdles, including existing research deficiencies and recent developments in this field. Liquid medical waste poses a considerable issue in soil management, especially during the COVID-19 epidemic, which has amplified the quantity of soil samples required for examination [12]. Therefore, utilizing GA and BV as adsorbent materials in soil analysis may yield significant solutions. The absence of targeted studies on the effects of GA and BV on soil analysis, the use of inconsistent methods, and a limited understanding of the environmental factors that may influence soil analysis and adsorption mechanisms is evident.

Recent advancements underscore the utilization of GA and BV as adsorbent materials, the refinement of the carbonization method, and their applications in air analysis. The relevance of environmental management in soil analysis is emphasized, as evidenced by research by [13]. Addressing the current research gaps and furthering studies in this domain, the application of GA and BV as adsorptive materials in soil analysis may provide a viable solution to the issues associated with liquid medical waste treatment and environmental preservation.

This study seeks to investigate the application of GA and BV as adsorptive materials in aqueous analysis, emphasizing their impact on the role of organic matter in water quality and environmental health. The objective is to ascertain the distinct impacts of GA and BV on waste disposal and to optimize the carbonization process to improve carbon content and biomass usage efficiency. The study will assess the physical properties and composition of GA and BV as adsorptive materials. A range of assessments, including BET (Brunauer–Emmett–Teller), proximate analysis, pH, Total Dissolved Solids (TDS), Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD), will be utilized to furnish detailed information regarding the efficacy of GA and BV in water analysis and their roles in enhanced environmental management.

2. Methods

2.1 Materials

The GA and BV utilized in this study were 2-years-old bamboo with a stem diameter ranging from 3 to 5 cm and a stem height between 7 to 10 meters. Liquid medical waste was sourced from practicum trash at the medical faculty, comprising a heterogeneous mixture of Betazoid DAB Substrate Buffer, Trekkie Universal Link, TrekAvidin-HRP Label, Background Sniper, Staining Solution, and Coomassie Blue.

2.2 Process of charcoal production

This study employed traditional methods for the charcoal production process in a charcoal manufacturing facility. The homogenization process of GA and BV plants was conducted based on the criterion of selecting plants that were around 2 years old. The charcoal-making process commences with the chopping of GA and BV shoot into small sizes, followed by a thorough cleaning with flowing water to eliminate debris. After cutting, GA and BV are dried in the sun to remove moisture content. A cavity measuring 0.9 x 0.7 x 0.8 m^3 is created, then filled with combustible raw materials and arranged with bamboo segments. The cavity was covered with leaves and wood. The temperature profile during combustion was recorded to gradually rise from 100°C to peak at 500-600°C over two days. After burning, the charcoal was cooled, then pulverized using a blender and sieved using a series of 50-100 mesh sieves with a Rotap sifter (frequency 50 Hz, duration 15 min).

2.3 The bamboo charcoal activation

The activation process uses a 0.3 M NaCl solution (Merck). The choice of NaCl is based on economic considerations and environmental safety compared to KOH or $ZnCl_2$ which are corrosive and more dangerous. Charcoal powder (50 mesh size) was mixed with NaCl solution in a ratio of 1:10 (b/v) and stirred using a magnetic stirrer (SH-03, China) at 150 rpm for 48 hours. The mixture was filtered with batis cloth, dried in an oven (Sharp) at 100°C for 90 min, then cooled at room temperature.

2.4 Proximate Testing

Testing the water content, volatile compounds, ash, and bonded carbon in GA and BV activated material attempts to ascertain its chemical composition and physical properties. The water content testing procedure commences with the preparation of activated charcoal that has undergone activation, followed by weighing and drying in an oven at a temperature of 105 °C for one hour. Upon drying and cooling to ambient temperature, the activated carbon was reweighed, and this procedure was reiterated until the weight stabilized to ascertain the water content. Additionally, to assess the volatile matter content, 1 gram of activated carbon was placed in a crucible and subjected to heating in a furnace (Openbau Hofman, Germany) at 600°C for 10 minutes, subsequently cooled to ambient temperature for 1 hour. The volatile matter content was determined by the mass difference before and after heating. To determine the ash content, 1 gram of activated carbon was placed in a crucible and heated at 700°C for 4 hours, subsequently cooled, and the ash content was determined based on the final mass post- combustion. The binding carbon content test was conducted by evaluating data from activated carbon assessed for water, volatile matter, and ash content, thereby offering a detailed overview of the composition and properties of the produced activated carbon.

2.5 BET Testing

BET testing seeks to define the adsorbent by measuring the specific surface area and pore distribution of the briquette sample. The testing technique commences with the preparation of briquette specimens for each variant to be evaluated. The specimens are thereafter placed into the Quantachrome Instruments (QUADRASORB evo™, USA) for a degassing process designed to eliminate moisture that may influence the measurement outcomes. Upon completion of the degassing process, nitrogen (N_2) gas is introduced into the specimen at varying pressures. The data acquired from this method are subsequently kept for later study.

2.6 Compaction Process

Following activation and oven drying, the bamboo charcoal powder is subjected to compression. The combination of charcoal powder and tapioca starch adhesive solution (weight ratio 3:1) is compressed utilizing a hydraulic press machine (Nagasaki Jack-NSP 15, Indonesia). The compaction process is conducted at pressures of 10 MPa for GA1 and BV1 and also 12 MPa for GA2 and BV2, each with a duration of 180 seconds.

2.7 Testing the Moisture Content of Briquettes

Activated charcoal briquettes were measured and subsequently dried in an oven at 105°C for one hour. Upon reaching room temperature, the briquettes were reweighed. The drying and weighing process was reiterated until the briquette weight stabilized, which was subsequently utilized to ascertain the moisture content by calculating the difference between the original and final weights.

2.8 pH and TDS Testing

Measurements of pH and TDS were conducted on 100 mL of medical wastewater utilizing a pH meter and TDS meter (HAIK EZ 9909, China) prior to and subsequent to the incorporation of activated charcoal briquettes. Measurements were conducted immediately post-mixing and following settling intervals of 12, 24, 36, and 48 hours. The pH and TDS values were documented following the stabilization of the instrument readings.

2.9 COD-BOD Testing

Chemical Oxygen Demand (COD) levels were assessed utilizing the closed reflux method (HACH- DBR 200, USA). Following the measurement of the initial dissolved oxygen (DO) with a DO meter, 2.5 mL of filtered sBV wastewater was combined with 1.5 mL of 0.1 N potassium dichromate ($K_2Cr_2O_7$) standard solution and 3.5 mL of 20% sulfuric acid (H_2SO_4) solution in a digestion tube. The amalgamation was thereafter subjected to heating at 150°C for a duration of 2 hours within a heating block. Following cooling and precipitation to achieve a transparent solution, the absorbance was assessed at 420 nm or 600 nm, and the COD concentration was determined using a calibration curve. The Biological Oxygen Demand (BOD) was assessed via the dilution method in Winkler bottles (A1 and A2) utilizing the BOD Sensor System 6 (VELP Scientifica, Italy). Following the measurement of the initial dissolved oxygen in 2 mL of purified sBV at 20°C and pH 6-8, the sBV was incubated in bottle A2 with 20 mL of glucose-glutamic acid solution diluted to 1 liter at 20°C for a duration of 5 days. Following incubation, dissolved oxygen was remeasured to ascertain biochemical oxygen demand.

2.10 Surface Morphological Testing

For morphological analysis of both activated and sedimented charcoal in liquid medical wastewater, the first step is to separate the charcoal sediment from the waste. This is done by filtering the charcoal that has been exposed to the waste. Next, we carry out the drying process and perform morphological analysis using the FESEM FEI Quanta 650 instrument. We then proceed with further analysis.

3. Results and Discussion

3.1 Proximate Analysis

The proximate method is a standard way to find out what the main parts of solid fuels like charcoal are. These parts are the water content, the volatile matter content, the ash content, and the bound carbon content, which is the difference between 100% and the sum of the first three parts. The results of the proximate test are shown in Table 1 below.

Table 1. Results of Proximate Analysis of Activated Carbon

Activated Bamboo Charcoal	Water Content (%)	Volatile Matter Content (%)	Ash Content (%)	Fixed Carbon Content (%)
GA	0.5	1.16	2.92	95.42
BV	0.4	1.26	3.29	95.45

Overall, activated carbon from both bamboo species exhibited relatively low moisture levels. The GA activated carbon maintained a stable moisture level, while BV was slightly lower. The volatile matter content tended to be higher in BV activated carbon, with values varying depending on the mesh size. A similar trend was observed in ash content, with BV activated carbon having a slightly higher ash content than GA. However, the bound carbon content remained exceptionally high, indicating excellent carbon efficiency in the resulting activated carbon.

The ability of GA and BV activated carbon to release water was influenced by their pore structure, with BV having larger and more interconnected pores, as well as its chemical makeup, which includes higher amounts of cellulose and lignin, and physical properties such as texture and density, where BV is lighter and less dense. Additionally, genetic and anatomical variations in bamboo and the environmental conditions during growth further contributed to these differences. When intrinsic factors, such as structure and composition, interact with extrinsic environmental factors, BV-activated carbon retains less water, enhancing its efficiency in releasing water during the drying process. There are differences in the chemical makeup of the raw bamboo material, especially the amounts of lignin and hemicellulose, which is why BV has a higher volatile content than GA.

Lignin, a complex polymer that makes up the cell walls of plants, has a diverse and complex chemical structure [14,15]. When heated during the thermal activation process, the chemical bonds in lignin are broken, producing various volatile compounds, such as phenol, guaiacol, syringol, and various other aromatic compounds [15,16]. Along with releasing acetic acid, furfural, and other volatile compounds during the heating process, hemicellulose, a polysaccharide that breaks down more easily than cellulose, also helps create volatile compounds. Because BV has more lignin and hemicellulose than GA, more volatile compounds are made and released during the thermal activation process. This means that BV char has more volatile compounds. This difference comes from the fact that bamboo cell walls are made of different chemicals and have different structures [17,18]. These differences affect the material's thermal properties and cause different profiles of volatile compounds to form during the carbonization process.

The higher ash content in BV char compared to GA char is likely due to the higher mineral content in BV raw materials. When organic compounds like cellulose, hemicellulose, and lignin are burned, they break down into gases like CO2, water vapor, and other volatile compounds. However, inorganic minerals found in bamboo, such as silica (SiO_2), calcium (Ca), magnesium (Mg), potassium (K), and phosphorus (P), have much higher melting and boiling points and therefore do not decompose at the carbonization temperature [19,20]. These minerals remain as solid residues that form ash. So, the difference in ash content between the two types of charcoal is due to the different amounts of inorganic minerals in the two types of bamboo, not to the different levels of carbonization. Higher mineral content in BV leads to the formation of more ash after the carbonization process is completed. Different BV activated charcoals had different amounts of volatile matter and ash, but all of them had a high amount of bound carbon (over 95%), which showed that the thermal activation process worked. In this process, the raw material is heated to high temperatures under controlled conditions, usually with or without chemical activators [21,22]. This breaks down organic compounds like lignin, hemicellulose, and cellulose. This decomposition results in the release of volatile compounds, including various gases and vapors, and leaves behind a structured carbon framework.

The high percentage of bound carbon indicates that most of the organic material has been successfully converted into a structured, stable solid carbon form rather than being wasted as volatiles [23]. This carbon structure has important properties, namely a massive surface area and pores that allow efficient adsorption of various pollutants. So, small changes in the amounts of volatile matter and ash show that the raw materials or the conditions of the activation process were not exactly the same. However, the consistently high amounts of bound carbon show that the activated carbon is of good quality and works well for adsorption tasks like cleaning water or air.

3.2 Moisture Content of GA and BV Activated Carbon Briquettes at Different Pressures

The moisture content of charcoal briquettes from GA and BV compacted at different pressures is shown in Fig. 1. Higher briquette moisture content was consistently shown by GA compared to BV at both pressures. When the compaction pressure was raised from 10 MPa to 12 MPa, a reduction in moisture content was observed in both types of bamboo, with GA being affected more significantly.

Although all briquettes had relatively low moisture content (3.9%-5.1%), the significant difference between the two bamboo species suggests that BV may have a denser structure and absorb less water than GA. This difference can be attributed to the physical and structural characteristics of the two bamboo species. The looser cellular structure of GA with larger intercellular spaces compared to BV causes GA to absorb and retain more water. This supports the findings of [24],who highlighted the influence of the interaction of moisture and compaction pressure on the mechanical properties of the material.

According to the report by [25], increasing the compaction pressure made both types of bamboo less wet, especially GA. This meant that the interparticle cohesion and briquette density went up. Although the moisture content was relatively low, ranging from 3.9% to 5.1% in all BV, the difference in moisture content between GA and BV remained significant. This suggests that even at low moisture content, the structure and characteristics of the base material still have an important influence on the final product properties [26]. Other things that affect the amount of water in different materials are the amount of lignin, which is a natural binder [27], and the fact that GA is more hygroscopic, which means it can absorb more water from the air. So, to control the amount of water in the briquettes and make them burn more efficiently, the process needs to be optimized by adjusting the compaction pressure and the drying process, as explained by [28] through proximate analysis.

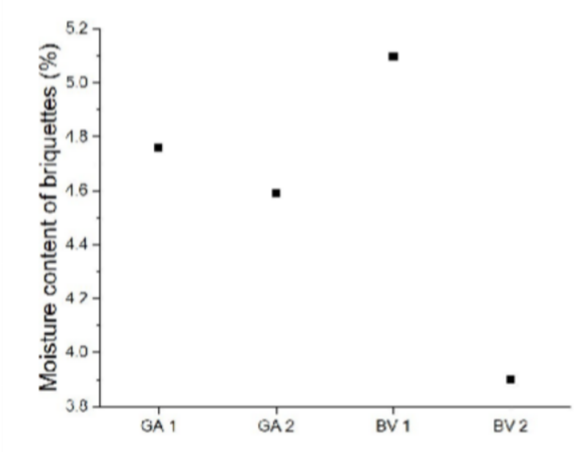

Figure 1. Comparison the Activated Carbon Briquettes Made with GA and BV Under Varying Pressures for Moisture Content

3.3 Comparative Analysis of BET Surface Area in Activated Carbon from GA and BV

Meanwhile, the BET surface area (m2/g) of activated carbon from GA and BV, respectively, was about 69 m2/g and 59 m2/g, as shown in Fig. 2, where it appears that GA has a much higher BET surface area, indicating a greater adsorption potential.

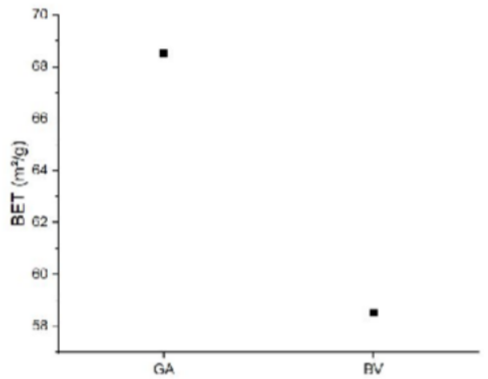

Figure 2. BET Surface Area Comparison of Activated Carbon from GA and BV

The difference in BET results on activated carbon from GA and BV showed significant values, ranging from 59 to 69 m^2/g. This indicates that activated carbon from GA has a greater adsorption potential compared to BV. Factors that influence this difference can be analyzed through the physical structure, carbonization process, and chemical composition of the bamboo [29]. The more prominent and longer shell structure of activated carbon, compared to BV, influences its porosity, allowing for more effective contaminant absorption [30]. The carbonization process used to produce activated carbon is also an important factor in determining the BET length. Under anaerobic conditions, the carbonization process reduces volatile components and increases carbon content. A well-conducted process can produce a greater

BET length [31].

Furthermore, the structural properties of activated carbon can be influenced by the atomic composition of GA and BV bamboo, despite the lack of specific references regarding the liquid and sulfate content. The factor such as the fungicidalroperties of activated carbon, can also affect the adsorption capacity [32]. The polar fungi group can improve the interaction between activated carbon and target molecules. This can make processes like cleaning the air and stopping contamination more efficient and effective. The study conducted by [33] highlights the use of bamboo in a variety of other applications, including water treatment, soil conservation, and waste processing, as well as the potential for briquettes produced from agroforestry biomass for energy generation.

3.4 GA and BV Activated Charcoal on pH and TDS in Medical Wastewater

The increase in pH of the medical wastewater over time when subjected to activated charcoal GA and BV compressed at 10 MPa and 12 MPa is illustrated in Fig. 3(a). Ion adsorption by the activated charcoal, indicated by the elevation in pH, is the primary mechanism in this instance. The ions found in the wastewater constituents are probably adsorbed by the charcoal, resulting in a rise in pH. A more pronounced elevation in pH was exhibited by charcoal from GA relative to BV, signifying a superior adsorption capacity. A deceleration of the pH elevation rate was resulted from increasing the compaction pressure from 10 MPa to 12 MPa. This was likely due to the reduced number of pores and surface areas available for ion attachment resulting from the elevated pressure.

The TDS concentrations in the medical wastewater decreased with mixing with activated charcoal GA and BV, followed by compaction at 10 MPa and 12 MPa, as illustrated in Fig. 3(b). A more pronounced reduction in TDS was exhibited by charcoal GA compared to BV, aligning with its superior BET surface area, as previously elucidated. A more significant decrease in TDS was led to by a compaction pressure of 10 MPa than 12 MPa, perhaps because of the increased surface area and pore size. The decrease in TDS indicates that ion adsorption is the primary mechanism for solute removal from medical waste; however, the composition remains mostly unknown.

The ion adsorption mechanism occurring on activated charcoal elucidates the reason for the increase in pH of medical wastewater when subjected to activated charcoal from GA and BV. Charcoal generated through carbonization and activation possesses a substantial surface area and a porous architecture, facilitating considerable contact with ions in liquid waste [26,34]. This signifies that specific ion in the liquid waste can be absorbed by activated charcoal, resulting in an elevation of pH. Activated charcoal from GA exhibited superior adsorption capability compared to BV, evidenced by a more pronounced increase in pH. This finding corroborates the research conducted by [35], which emphasized the effective adsorption capacity of bamboo charcoal for diverse pollutants, including ions in solution. The enhanced adsorption capacity may stem from an improved porosity structure and an increased BET surface area in GA charcoal, facilitating more ion adsorption.

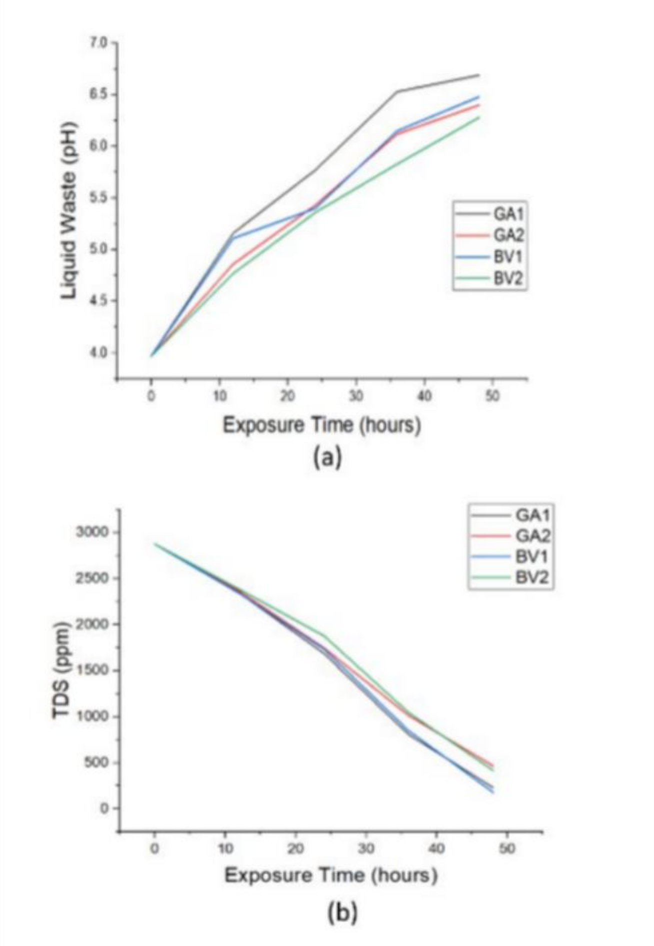

Figure 3. GA and BV Activated Charcoal on Medical Wastewater (a) pH (b) TDS Elevating the compaction pressure from 10 MPa to 12 MPa resulted in a reduction in the rate of pH increase.

This may result from the diminished surface area and pore availability for ion adsorption caused by increased compaction. [36] demonstrated that augmenting the density of activated carbon could diminish the adsorption capacity owing to the reduced accessibility of pore space to ions in solution. While increased compaction pressure may enhance the mechanical strength of activated carbon, it could compromise its ion adsorption capacity [6].

The reduction of TDS in wastewater upon interaction with activated carbon demonstrated that ion adsorption was the mechanism responsible for solute diminution. Kuok et al. demonstrated that bamboo carbon effectively diminished solute concentrations in water, signifying a robust adsorption capacity [37]. This update indicates that charcoal from GA had a more pronounced TDS decrease than BV, aligning with GA's superior BET surface area. This demonstrates the significant potential of bamboo activated carbon in medical wastewater treatment, particularly in efficiently mitigating pH increases and lowering total dissolved solids TDS.

3.5 BOD and COD Reduction in Medical Wastewater with GA and BV Activated Charcoal

Figure 4 illustrates the reduction in BOD and COD in medical wastewater treated with activated charcoal GA and BV, subjected to pressures of 10 and 12 MPa, respectively. The wastewater contained unspecified reagents. GA charcoal demonstrated superior efficacy in eliminating contaminants compared to BV charcoal. The impact of compaction pressure on COD and BOD removal efficiency was negligible within the measured range. The COD and BOD readings indicate the total decrease of organic pollutants.

The reduction of COD and BOD in liquid medical waste treated with activated charcoal from GA and BV demonstrates the efficacy of this activated charcoal in eliminating organic contaminants from waste. This alteration signifies a decrease in dissolved organic matter, a crucial parameter in assessing water quality. Various elements contributing to this phenomena encompass the adsorption method, the physical properties of activated charcoal, and the makeup of the waste material. The primary method for reducing COD and BOD is by adsorption.

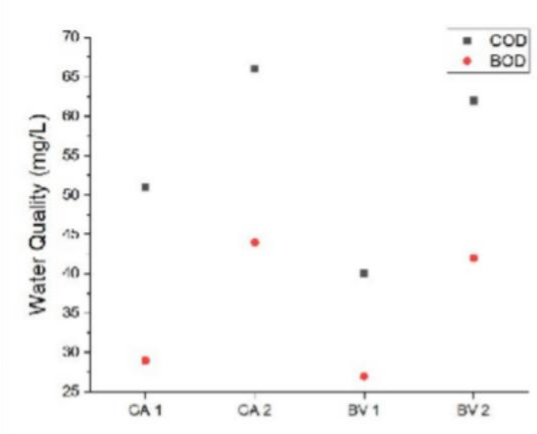

Figure 4. Medical Waste Water Decreased in BOD and COD after via GA and BV Activated Charcoal

Activated charcoal possesses a substantial surface area and numerous holes, enabling significant interaction with organic compounds in waste [38]. Research conducted by [39] indicated that activated charcoal derived from bamboo exhibits significant adsorption capacity for diverse pollutants, with findings revealing superior pollutant reduction efficacy in charcoal from GA relative to BV. The compaction pressure during the production of activated charcoal can influence its efficacy in reducing COD and BOD, albeit it did not significantly affect the measured range [40]. The various components of medical waste might alter the COD and BOD measurements, as different elements react and adsorb differently, affecting the interaction between the adsorbent and the pollutants. The biodegradation process that may occur during treatment with activated charcoal can also reduce COD and BOD levels. Activated charcoal provides microorganisms with a conducive environment for the decomposition of organic materials. The application of activated charcoal derived from GA and BV in medical waste treatment demonstrates significant promise for enhancing water quality and mitigating the environmental effects of wastewater.

3.6 SEM Analysis of Microstructural Changes in GA and BV Activated Charcoal Post-Adsorption

SEM images contrast the microstructures of GA and BV prior to and following the adsorption of medical wastewater as showed in Fig. 5. The image of GA before to adsorption 5(a) depicts its surface and pores in their initial state. The image is subsequently compared to the image of GA post-adsorption 5(b) to assess alterations, including potential pore obstruction or material accumulation. We replicate the identical procedure to contrast the pictures of BV prior to 5(c) and after to 5(d) adsorption. This comparison illustrates the impact of adsorption on the microstructure of both varieties of charcoal.

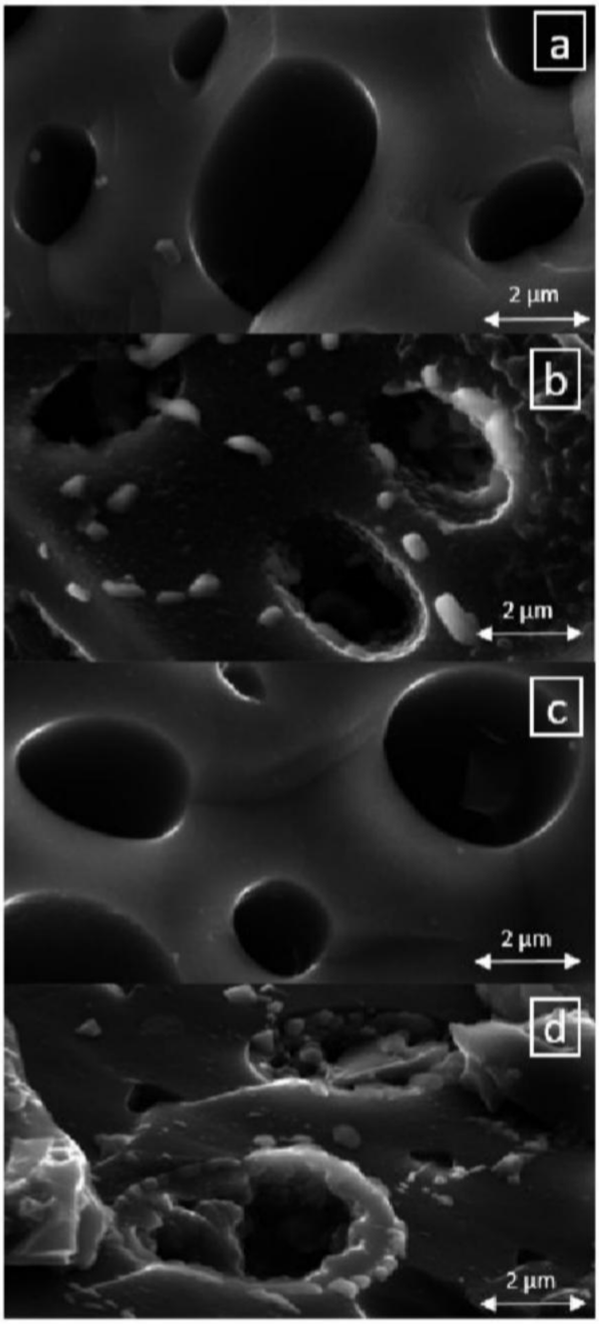

Figure 5. Surface Morpholgy (a) GA before adsorption (b) GA after adsorption (c) BV before adsorption (d) BV after adsorption

The activator functioCns as both an oxidizing and dehydrating agent, resulting in enlarged pores in both varieties of bamboo following the treatment. The activation process cleaves hydrocarbon bonds to open closed pores, facilitating the formation of a porous structure [17]. Impurity chemicals resulting from carbonization can be desiccated and dehydrated when the activator is employed. This eliminates the water that saturates the charcoal pores [41]. An essential component of the process is the utilization of NaCl as an activator, as it serves as an effective dehydrating agent that facilitates the rapid evaporation of impurities and inhibits tar formation, hence optimizing the pore structure in charcoal [42]. Subsequent to the cleaning process, many molecules may adhere to the pores of the charcoal [43]. The adsorbat and adsorbent interact via attraction-dispersion forces, a phenomenon known as physisorption. Molecules are interconnected by hydrogen bonding.

The compaction process significantly influences the pore size of activated carbon, in addition to activation. This occurs because increased holding time and pressure result in denser particles within the briquette, causing the pores to overlap and diminish, potentially compromising the structural integrity of the pores [44]. Increased pressure and extended holding time enhance the briquette's strength, rendering it less susceptible to breakage; yet, this adversely impacts its capacity to absorb solutions, as the liquid adsorbate encounters greater difficulty penetrating the minute pores.

3.7 Comparison of GA/BV carbon with commercial granular activated carbon GAC performance

Activated carbon produced from Gigantochloa apus (GA) and Bambusa vulgaris (BV) bamboo shows promising prospects as an alternative adsorbent material in the treatment of liquid medical waste, especially in areas with limited infrastructure and resources. To objectively evaluate its effectiveness, it is necessary to compare it with commercial granular activated carbon (GAC) that has been widely used in conventional water treatment systems.

In general, commercial activated carbon (GAC) has a higher specific surface area compared to activated carbon from GA or VB bamboo. GAC in the form of millimeter-sized granules is widely used because of its relatively low cost, suitable density (about 1500 g/m^3), and pore structure that supports adsorption efficiency [45]. In contrast, activated carbon from GA and BV bamboo activated using NaCl solution and conventional heating tends to have a smaller surface area and non-uniform pore distribution. This hinders the adsorption performance towards small-sized pollutants such as heavy metals and pharmaceutical compounds. However, efficiency tests showed that bamboo carbon was still effective in reducing Total Dissolved Solids (TDS) levels and improving wastewater pH. Despite slower adsorption rates than commercial GACs, GA and BV carbons still yielded positive results over longer contact times, making them suitable for small-scale or community sewage treatment with more flexible process times.

From the aspect of adsorption kinetics, GAC is designed to work rapidly, even reaching its maximum capacity in just a few hours due to its highly structured surface area and pores [46]. In contrast, bamboo carbon tends to exhibit gradual adsorption due to limited molecular access to active sites located deeper in the carbon structure. Nonetheless, this approach remains relevant for effluents with low contaminant concentrations or slow-flow systems.

The main advantages of GA/BV carbon are sustainability and cost efficiency. Bamboo as a raw material is rapidly renewable and grows abundantly in the tropics. The production process is simple, can be done with basic equipment, and is suitable for use in areas with limited access to advanced technology, such as remote villages or health care facilities [47]. In contrast, industrial-scale GAC production requires high temperatures, aggressive chemicals such as KOH or $ZnCl_2$, and specialized equipment, which results in high costs and potential environmental pollution. In addition, GAC has a limited lifetime, once saturated these materials are generally discarded, and if not managed properly, have the potential to release pollutants back into the environment.

Thus, overall, activated carbon from GA and BV bamboo offers a sustainable, economical and local resource-based alternative in the treatment of liquid medical waste. Although not yet as efficient as commercial GAC on an industrial scale, this approach is promising to be further developed as an environmentally friendly appropriate technology solution.

4. **Conclusion**

This study shows that the physical and chemical characteristics of activated carbon from GA and BV bamboos are influenced by anatomical structure and environmental factors, which impact the adsorption effectiveness in medical wastewater treatment. The ion adsorption mechanism on activated charcoal in medical wastewater improved the pH level, with GA charcoal showing better adsorption ability. However, although GA charcoal showed higher adsorption performance, these results are still laboratory in nature and do not include effectiveness tests against pathogens or an evaluation of the economics of the process. Differences in porosity, carbon content and microstructure influence the mechanism of interaction with pollutants. These findings offer the potential to utilize bamboo waste as a local material for adsorbents, but practical application requires further validation through pilot-scale trials, cost-benefit analysis, and testing under real-world conditions. Further studies are also needed to understand the long-term durability and regeneration potential of activated carbon in sustainable treatment systems.

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