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Adsorption of Lead (Pb^{2+}) Using Biochar Derived from Bamboo Waste Pyrolysis

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ABSTRAK

Meningkatnya aktivitas industri dan urbanisasi telah menyebabkan akumulasi logam berat yang menimbulkan risiko tinggi bagi kesehatan manusia dan ekosistem. Adsorpsi menggunakan biochar dari limbah bambu merupakan solusi alternatif sebagai adsorben. Penelitian ini mengevaluasi kinerja biochar hasil pirolisis limbah bambu pada berbagai suhu (300–600°C) untuk adsorpsi ion timbal (Pb^{2+}). Pirolisis dilakukan di bawah atmosfer gas nitrogen untuk mencegah oksidasi selama dekomposisi termal. Analisis Fourier Transform Infrared spectroscopy (FTIR) menunjukkan peningkatan stabilitas gugus fungsi karbonil (C=O) dan karbon–nitrogen (C–N) seiring dengan peningkatan suhu, yang berkontribusi pada afinitas yang lebih kuat terhadap ion logam. Analisis Brunauer–Emmett–Teller (BET) menunjukkan bahwa biochar yang diproduksi pada suhu 400°C menunjukkan karakteristik permukaan yang paling baik, dengan luas permukaan 178,56 m^2/g, volume pori 0,091 cm^3/g, dan diameter pori rata-rata 2,05 nm. Sampel ini juga menunjukkan kapasitas adsorpsi Pb^{2+} tertinggi, yaitu 52,4 mg/g. Meskipun porositasnya lebih tinggi, biochar yang diproduksi pada suhu 600°C menunjukkan efisiensi adsorpsi yang menurun akibat keruntuhan struktur pori dan penurunan kandungan karbon. Temuan ini menunjukkan bahwa biochar yang disintesis pada suhu 400°C memiliki potensi yang kuat untuk digunakan dalam aplikasi remediasi lingkungan, khususnya dalam mitigasi kontaminasi timbal dalam sistem air.

Kata kunci: Adsorpsi, Limbah Bambu, Biochar, Logam Berat, Pirolisis

ABSTRACT

The increasing of industrial activities and urbanization have led to the accumulation of heavy metals, which pose a high risk to human health and ecosystems. Adsorption using biochar from bamboo waste is an alternative solution as an adsorbent. This study evaluated the performance of biochar from pyrolysis of bamboo waste at various temperatures (300–600°C) for adsorption of lead (Pb^{2+}) ions. The pyrolysis was conducted under a nitrogen gas atmosphere to prevent oxidation during thermal decomposition. Fourier Transform Infrared (FTIR) analysis revealed an increase in the stability of carbonyl (C=O) and carbon–nitrogen (C–N) functional groups with increasing temperature, which contributed to a stronger affinity for metal ions. Brunauer–Emmett–Teller (BET) analysis showed that biochar produced at 400 °C exhibited the most favorable surface characteristics, with a surface area of 178.56 m^2/g, a pore volume of 0.091 cm^3/g, and an average pore diameter of 2.05 nm. This sample also demonstrated the highest Pb^{2+} adsorption capacity of 52.4 mg/g. Despite higher porosity, the biochar produced at 600 °C showed diminished adsorption efficiency due to pore structure collapse and decreased carbon content. The findings suggest that biochar synthesized at 400 °C has strong potential for use in environmental remediation applications, particularly in mitigating lead contamination in water systems.

***Keywords*:** Adsorption, Bamboo Waste, Biochar, Heavy Metal, Pyrolysis

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1. INTRODUCTION

The Increasing of industrial activities and urbanization have led to increased concentrations of heavy metals in the environment, especially in water resources. Heavy metal pollutants such as lead (Pb) are very dangerous due to their high toxicity and persistent nature in the environment (H. Luo et al., 2022). These pollutants can accumulate in the body of organisms and cause health problems such as impaired kidney function, nervous system, and cancer (Zaynab et al., 2022). In addition, heavy metals also have negative impacts on the environment, such as decreased water quality, damage to aquatic ecosystems, and disruption of the food chain (Hama Aziz et al., 2023). Heavy metals that accumulate in sediments or organism tissues can disrupt the balance of the ecosystem and endanger the sustainability of biodiversity (Rubalingeswari et al., 2021). Therefore, the development of effective methods to remove heavy metals from the environment becomes very important.

Adsorption is one of the methods often used to remove heavy metals from water due to its high efficiency, relatively low cost, and ability to be applied in various conditions (Bilal et al., 2021). The adsorption process was chosen because it has the advantage of handling low concentrations of heavy metals and its ability to minimize additional waste generated during the treatment process (Yizhuo Wang et al., 2022). In addition, this method is flexible to be applied in various scales, from laboratories to large industries. The adsorption process can use materials from carbon materials (biochar) produced from biomass conversion (Jamilatun, Elisthatiana, et al., 2020). Biochar is a carbon material produced from the pyrolysis of biomass under conditions of little or no oxygen. This material has high porosity, large surface area, and an abundance of active functional groups, making it suitable for adsorption applications (Aini et al., 2023; Pham et al., 2022). The biochar as raw materials are very diverse, such as agricultural waste such as rice husks, corn husks, and bamboo waste. The use of bamboo waste as a raw material for biochar has great potential, considering the nature of bamboo which grows quickly and is abundant, as well as its chemical composition which is rich in cellulose, hemicellulose, and lignin (Liang et al., 2023).

Previous studies have demonstrated that biochar derived from a variety of biomass sources has been effectively utilized for the adsorption of heavy metals. For instance, biochar from corn waste exhibited high adsorption capacity for Pb(II) ions due to its optimized pore structure and substantial surface area (Yun et al., 2022). Similarly, biochar derived from palm oil mill waste effectively removed Cd(II) through ionic interactions between heavy metal ions and surface functional groups (Goh et al., 2019). Rice husk-based biochar also showed significant potential in removing various heavy metals via ion exchange and physical adsorption mechanisms (Li et al., 2022).

While these studies demonstrate the versatility of biomass-derived biochar, the potential of bamboo waste—an abundant and fast-growing biomass—has not yet been fully explored. Bamboo-based biochar possesses a high carbon content and favorable chemical composition (cellulose, hemicellulose, lignin), making it a promising candidate for adsorbent application (Guo et al., 2024). Research indicates that pyrolysis temperature significantly affects the physicochemical properties of bamboo biochar, such as surface area, pore volume, and functional group stability (A Aladin, B Modding, 2020). Moreover, nitrogen doping during pyrolysis has been shown to enhance adsorption capacity by introducing nitrogen-containing functional groups (e.g., C–N, N–H) that can coordinate with metal ions (Zheng et al., 2019). Despite these findings, there remains a clear research gap concerning the optimization of pyrolysis conditions specifically for bamboo biochar. Furthermore, there is limited understanding of how the structural modifications induced by nitrogen doping influence the binding mechanisms for specific heavy metals, particularly Pb (II) and Cd (II). Therefore, this study seeks to address these gaps by evaluating the adsorption performance of bamboo biochar synthesized at various pyrolysis temperatures.

This study aims to evaluate the performance of biochar from bamboo waste in the pyrolysis process in absorbing heavy metals such as lead. This study includes the analysis of the physical and chemical properties of biochar, including surface area, pore volume, average pore diameter, and characterization of functional groups using Fourier Transform Infrared Spectroscopy (FTIR). In addition, this study also compares the adsorption efficiency of biochar at various pyrolysis temperatures to determine the optimal temperature.

2. EXPERIMENTAL SECTION

2.1. Material and Devices

Bamboo waste as the main raw material in this study was obtained from the Kampung Bambu Group (Deling Studio) in Mojorejo Village, Ponorogo, East Java. Meanwhile, nitrogen gas as the inner gas was obtained from CV. Gasindo, Ponorogo Regency, East Java. The supporting equipment such as an oven with an oven memmert UN 55 and a grinder type miller DE200G was supported by the chemistry laboratory at Département of agro-industrial technology, Universitas Darussalam Gontor. The adsorption experiment utilized lead nitrate [$Pb(NO_3)_2$] as the source of lead ions, obtained from CV Nitra Kimia, Indonesia. This compound was selected due to its high solubility in water and stability in solution, which makes it suitable for adsorption studies. All chemicals used in this study, including $Pb(NO_3)_2$, methanol, and dithizone, were of analytical grade (pro analysis) to ensure precision and reproducibility. Adsorption testing uses UV-Vis spectrophotometer with the types of Genesys 10s. Additional laboratory equipment includes a magnetic stirrer, pH meter, dropper pipette, beaker, measuring flask, analytical balance, glass funnel, spatula, sieve, etc.

2.2. Biochar Preparation

Biochar was produced through the pyrolysis of bamboo waste using a quartz tube furnace reactor. Prior to pyrolysis, bamboo waste was dried under direct sunlight to reduce its moisture content to below 10%, followed by mechanical shredding to ensure uniform particle size. Both moisture content and particle size are known to influence the pyrolysis process, as high water content lowers the calorific yield by consuming energy for evaporation, while particle size affects heat transfer efficiency during thermal decomposition (Aguilar et al., 2015). Materials with high water content tend to reduce the calorific value of the pyrolysis product because some of the energy is spent to evaporate the water. In addition, the particle size of bamboo affects the heat transfer during the pyrolysis process. The characteristics of bamboo waste used in this study can be seen in Table 1. A total of 50 grams of bamboo waste was placed into a quartz tube furnace reactor for the pyrolysis process. The pyrolysis was conducted was conducted at temperatures ranging from 300 °C to 600 °C under a constant flow of nitrogen gas (500 mL/min), which acted as an inert carrier to prevent unwanted oxidation reactions and promote thermal decomposition into bio-oil, syngas, and biochar. The detailed configuration of the pyrolysis setup is presented in Figure 1.

Table 1. Characteristics of Bamboo Waste

No	Characteristics	Bamboo Waste
1	Nitrogen (%)	0.18
2	Water content (%)	5.5
3	Ash content (%)	2.62
4	Cellulose (%)	54.27
5	Hemicellulose (%)	26.32
6	Lignin (%)	5.94

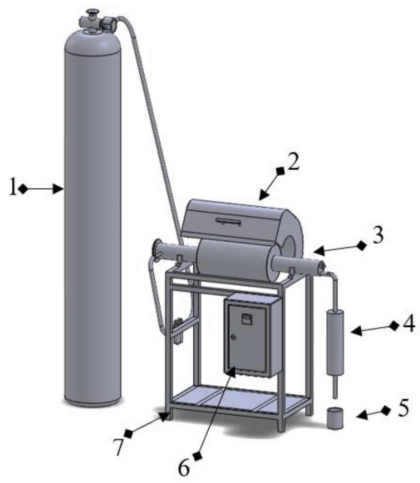

Figure 1. The Quartz Tube Furnace Reactor Configuration

Based on Figure 1, the pyrolysis apparatus consists of several key components: a nitrogen gas tank (1), a reactor cover (2), a reactor with a bamboo waste sample holder (3), a condenser (4), a bio-oil storage container (5), an electrical control system (6), and a support stand (7). The quartz tube furnace reactor used in this study has specific dimensions: a length of 700 mm, a diameter of 60 mm, a stand height of 600 mm, and a stand width of 500 mm. The sample holder within the reactor has a length of 300 mm. The reactor is equipped with a heating jacket designed to minimize heat loss and ensure consistent temperature throughout the pyrolysis process. Additionally, the reactor features a condenser for efficient cooling and condensation of the volatile products, facilitating the collection of bio-oil. The nitrogen gas flow into the reactor is precisely controlled using a rotameter, which ensures accurate and steady gas flow during the pyrolysis process.

2.3. Characteristics of Biochar

The characteristics of biochar from bamboo waste were carried out using BET (Brunauer-Emmett-Teller) and FTIR (Fourier Transform Infrared Spectroscopy). BET (Brunauer-Emmett-Teller) testing was carried out to determine the specific surface area of biochar from pyrolysis of bamboo waste weighing 1.0988 grams. Before analysis, the sample underwent a gradual degassing process to a temperature of 300 °C to remove adsorbed gas or water vapor. Furthermore, nitrogen gas was used as an adsorbate at liquid nitrogen temperature (77.35 K) using a NOVA 800 device. The analysis was carried out in NOVA Mode with adsorption isotherm measurements at several partial pressures to calculate the specific surface area, pore volume, and pore size distribution. This process lasted for 494.65 minutes, using a 9 mm type analysis cell with filler rod.

Meanwhile, FTIR (Fourier Transform Infrared Spectroscopy) testing is an analysis method used to identify functional groups and chemical structures in a sample through the interaction of molecules with infrared radiation. In this method, an infrared spectrum is generated based on the absorption of energy by chemical bonds at various infrared wavelengths, which form a unique fingerprint for each compound. This method uses an FTIR instrument, in accordance with the IKM.F.1 standard procedure, to ensure the validity and accuracy of the test results. The analysis is carried out by placing the sample in the infrared radiation path, which then produces spectrum data in the form of a graph of absorbance or transmittance against wavelength. This data is used to determine the chemical composition or identify functional groups present in the sample.

2.4. Biochar Adsorption on Heavy Metals (Pb)

The testing of bamboo waste biochar on lead (Pb) metal was carried out using a UV-Vis spectrophotometer. The stages carried out were determining the wavelength, making a standard solution, making a lead solution with varying concentrations, and an absorption test using a UV-Vis spectrophotometer. The determination of wavelength is done by making a standard solution of Pb 5 and 25 ppm, each as much as 20 mL, put into a beaker. Then add 0.0015% dithizone as much as 5 mL and stir and both will be measured for absorbance values between 500 - 560 nm and the highest peak of the graph will be used as the wavelength. This study used a wavelength of 516 nm. The preparation of a standard curve or standard solution was done by mixing Pb solutions of 1, 2, 3, 4 and 5 ppm as much as 20 mL into a beaker. Each solution was added with 5 mL of 0.0015% methanol solution and stirred until a pink complex was formed. Then measured with a UV-Vis spectrophotometer with a wavelength of 516 nm. Testing the variation of Pb solution concentration on biochar absorption was carried out by mixing 0.125 grams of biochar into 100 ppm metal solution as much as 10 ml. The solution was stirred using a centrifuge for 10 minutes at a speed of 250 rpm. Then the solution was filtered using filter paper. Do the same procedure for concentrations of 200 ppm and 300 ppm. The absorption test was carried out by inserting 0.750 ml of dithizone solution into 3 mL of Pb and biochar mixture solution then stirred until homogeneous and inserted into a cuvette to be tested using a UV-Vis spectrophotometer.

3. RESULTS AND DISCUSSION

3.1. FTIR Analysis of Biochar from Pyrolysis

The results of FTIR analysis on biochar from bamboo waste pyrolysis showed significant changes in the structure of functional groups with increasing pyrolysis temperature from 300 °C (BC-300), 400 °C (BC-400), to 600 °C (BC-600). The results of FTIR analysis can be seen in Figure 2. At low temperature (BC-300), the spectrum from FTIR peak at 3051 cm^{-1} showed that the presence of aliphatic C–H stretching vibrations and the presence of volatile organic compounds are still dominant. The peak at 2872 cm^{-1} and the peak at 1595 cm^{-1} indicate the presence of N-H stretching vibrations in the amine group strongly and moderately which identifies the presence of nitrogen in the pyrolysis process. (Byambaa et al., 2023). The peak around 1118 cm^{-1} and the range from 875 to 751 cm^{-1} reflects carboxylic or ester groups, which indicate that biochar at this temperature still has polar groups were reactive enough for the adsorption of heavy metal ions.

In BC-400, the intensity of the O–H stretching group at 3049 cm^{-1} began to decrease that indicated the decomposition of most of the organic matter. The appearance of a consistent peak at 2310 cm^{-1} in all biochar samples indicated the presence of carbonyl groups (C=O) which were stable with pyrolysis. In addition, the peaks at 1191 cm^{-1} and 1120 cm^{-1} indicated the presence of nitrogen-carbon (C–N) functional groups. This group is important because it can increase adsorption capacity through coordination bonds with heavy metal ions (Su et al., 2022). The peak range of 877–756 cm^{-1} indicating aromatic vibrations indicates an increase in the polarity of the biochar structure, which favors interaction with heavy metal ions. In BC-600, further thermal decomposition causes the intensity of the aliphatic C–H group at 2830 cm^{-1} to weaken further, indicating the formation of a more conjugated aromatic carbon structure. The new peak appearing at 1217 cm^{-1} indicates the presence of nitrogen-carbon (C-N) functional groups in the medium scale. This peak is produced from the pyrolysis process. While the peak1147 cm^{-1} related to carbon-oxygen groups such as C–O–C or ether groups indicates that this biochar has better hydrophilic properties for metal ion adsorption. In addition, the peak at 915 cm^{-1} indicates more stable polarized aromatic groups, which increase the adsorption capacity through ion-dipole interactions or ion exchange mechanisms.

The difference in temperature of bamboo waste pyrolysis affects the structure and distribution of functional groups on the biochar surface, which has a significant impact on the adsorption capacity of heavy metals. BC-300 tends to have more volatile organic groups and is potentially degraded when interacting with heavy metals, while BC-400 shows a balance between polar and aromatic groups. BC-600 has a more dominant and stable aromatic structure with the presence of polarized oxygen and nitrogen groups that increase the affinity for heavy metal adsorption (Hotová et al., 2020). Based on previous research, biochar with nitrogen showed an increase in adsorption capacity due to the presence of C–N groups which can form coordination bonds with heavy metal ions (Jiang et al., 2022). In addition, the more dominant carbonyl groups and ether groups in BC-600 provide stronger hydrophilic properties, which is also in line with the results from (Tomczyk et al., 2020).

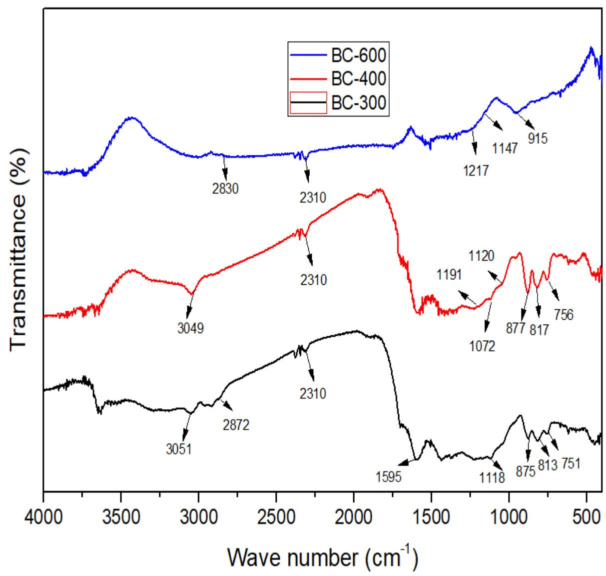

Figure 2. FTIR Analysis of Biochar

3.2. Pore Analysis and Surface Properties of Biochar from Pyrolysis

The surface characteristics of biochar produced from bamboo waste at various pyrolysis temperatures were analyzed using the BET (Brunauer-Emmett-Teller) method, as presented in Table 1. The parameters measured included surface area, total pore volume, and average pore diameter. These properties are very important in determining the adsorption capacity of biochar against heavy metals. The results of BET analysis showed that pyrolysis temperature has a significant effect on the physical properties of biochar. Biochar produced at a temperature of 300°C (Biochar-300) has a very small surface area, which is 1.018 m^2/g and a total pore volume of 0.0014 (cm3/g). The average pore diameter is not available or not measurable. This indicates that at that temperature, porosity has not developed, possibly due to the suboptimal thermal decomposition of bamboo biomass. A similar thing was also reported by (Elnour et al., 2019; Tomczyk et al., 2023), which biochar produced at low temperatures has less developed porosity because the carbonization process has not reached the stage of forming micropore and mesoporous structures. At temperature of 400°C (Biochar-400), The surface area increased significantly to 178.559 m^2/g, accompanied by a total pore volume of 0.091 cm^3/g and an average pore diameter of 2.050 nm. This significant increase indicates that the pyrolysis temperature of 400°C is the optimal temperature to activate the pore structure of bamboo-derived biochar. The formation of mesopores at this temperature increases its potential for adsorption applications (Barszcz et al., 2024).

However, the increasing of pyrolysis temperature from 500°C (BC-500) to 600°C (BC-600) caused a decrease in surface area to 30.423 m^2/g and 52.807 m^2/g, respectively. The total pore volume also decreased to 0.018 cm^3/g and 0.032 cm^3/g, while the average pore diameter slightly increased to 2.354 nm and 2.447 nm. This decrease is likely due to the collapse of the pore structure and densification of the material at higher temperatures, which reduces the number of active sites for adsorption. The highest pyrolysis temperatures can cause carbon agglomeration which reduces the porosity of the biochar and its effectiveness as an adsorbent (Jamilatun et al., 2023).

Biochar at 400°C showed the best surface characteristics for heavy metal adsorption because it had the highest surface area and pore volume. The moderate average pore diameter also indicated its suitability for adsorbing heavy metal ions, which are generally in the mesoporous size range. Previous research from (Huang et al., 2014) confirmed that biochar with a dominant mesoporous structure is more effective in adsorbing heavy metals through pore diffusion and chemical bonding mechanisms. Pyrolysis temperature plays an important role in optimizing the surface properties of bamboo-derived biochar. Biochar-400, characterized by its superior surface, is the most potential candidate for heavy metal adsorption applications in environmental remediation. In addition, the adsorption capacity of biochar through improving the surface chemical properties, such as more reactive functional groups (Yu et al., 2018).

Table 2. Biochar Surface Characteristics

No	Biochar	Surface Area (m2/g)	Total Pore Volume (cm3/g)	Average Pore Diameter (nm)
1	BC-300	1.018	0.0014	-
2	BC-400	178.559	0.091	2.050
3	BC-500	30.423	0.018	2.354
4	BC-600	52.807	0.032	2.447

3.3. Morphological Characteristics and Chemical Composition of Biochar

Based on analysis results of the EDX (Energy Dispersion X-Ray), the element composition of biochar with nitrogen as gas innert produced from bamboo waste using variations in pyrolysis temperature (300°C, 400°C, 500°C, and 600°C) showed significant differences in the chemical composition of biochar. The chemical composition of bamboo waste biochar can be seen in Table 3. The carbon content reaches its highest value at a temperature of 400°C of 93.26%, then decreases to 86.00% at 600°C. This indicates that at a temperature of 400°C there is an optimal pyrolysis process that produces maximum carbon from organic material. While at a temperature of 600°C there is further oxidation releasing carbon in the form of gas. In contrast, the oxygen (O) content decreased drastically from 10.61% at 300°C to 4.83% at 400°C, before increasing again to 11.13% at 600°C. This decrease indicates the release of functional oxygen groups during pyrolysis, while the increase at high temperatures indicates the formation of oxide compounds or the adsorption of oxygen from the environment (Q. Luo et al., 2024). The content of minor elements such as magnesium (Mg) and silicon (Si) tends to be stable at low temperatures but increases sharply at 600°C to 1.21% and 1.48%, respectively. This reflects the dominance of mineral compounds at high temperatures after volatilization of organic matter. The aluminium (Al) content was only detected at a temperature of 300°C at 0.08%, while the potassium (K) content was relatively stable at around 1.00% at a temperature of 300°C to 500°C but decreased significantly to 0.17% at 600°C due to the volatilization of potassium compounds (H. Zhao et al., 2015). These element composition changes reflect the chemical transformation of organic and inorganic materials in BC during the pyrolysis process. At low to medium temperatures, carbon is more dominant, while at high temperatures, the mineral content increases along with the further decomposition of organic materials (B. Zhao et al., 2018). These compositional variations can affect the properties of BC, such as adsorption capacity and thermal stability, which are important for applications in environmental remediation and soil quality improvement.

Table 3. Chemical Composition of Biochar

Elements	BC-300 (Wt %)	BC-400 (Wt %)	BC-500 (Wt %)	BC-600 (Wt %)
C	86.91	93.26	90.87	86.00
O	10.61	4.83	7.73	11.13
Mg	0.14	0.09	0.08	1.21
Al	0.08	-	-	-
Si	1.26	0.81	0.27	1.48
K	0.99	1.01	1.04	0.17

Figure 3 shows the results of Scanning Electron Microscopy (SEM) analysis for biochar (BC) at various pyrolysis temperatures (BC-300, BC-400, BC-500, and

BC-600). The morphological structure of biochar changes during the pyrolysis process. BC-300 shows that the biochar structure is still relatively dense with small pores that are scattered. This is influenced by the decomposition of organic material that has not yet taken place optimally. (Yurou Wang et al., 2024). Therefore, the original structure of the biochar raw material is still intact. The pyrolysis process at low temperatures produces little physical change because organic volatiles have not been released much. BC-400 shows that biochar pores begin to form in greater numbers than BC-300. The surface structure becomes more decomposed but still shows robustness with more uniform pores. The formation of these pores is caused by the release of more intense volatile compounds at temperatures of 400°C. Pyrolysis at a temperature of 400 to produce biochar with a good pore structure (Khater et al., 2024). BC-500 shows that the pores of biochar are increasingly developing with larger sizes and more even distribution. The structure of the carbon layer looks more organized due to the evaporation of large amounts of volatile compounds, leaving a more stable carbon matrix. The increase in the number and size of pores at this temperature increases the specific surface area. BC-600 showed a very high porosity level with more obvious damage to the biochar pore structure. The pores formed looked larger and more complex, indicating almost complete decomposition of organic materials. However, the damage to the structure at high temperatures can cause a decrease in the mechanical strength and stability of the carbon structure. In addition, high temperatures can cause some pores to collapse, which can reduce the adsorption efficiency when used as an adsorbent material (Jamilatun, Mufandi, et al., 2020; Zhang et al., 2022).

3.4. Evaluation of Adsorption on Heavy Metal (Pb)

In this study, a comparison of Pb concentration (100 ppm, 200 ppm, and 300 ppm) and biochar application from bamboo waste on BC-400 and BC-600 was conducted. The results of the analysis showed that Pb concentration and type of biochar can affect the adsorption capacity which can be seen in Figure 4. BC-400 showed the highest Pb metal absorbance capacity at all solution concentrations when compared to BC-600. This condition is in line with the results of biochar characteristic testing in the previous section. This relationship is influenced by the structure and chemical composition of biochar, especially in BC-400 and BC-600, each of which has different morphological and chemical characteristics due to pyrolysis temperature treatment. In BC-400, the pore structure that begins to develop with even pore distribution and high carbon content (93.26%) provides optimal adsorption capacity. This structure provides many active sites to bind Pb ions, while the high carbon content increases the affinity for heavy metals through hydrophobic interactions. BC-400 has an optimal balance between the amount of Pb ions available in solution and the adsorption capacity on the biochar surface. The stable structure and less damage by pyrolysis temperature allows BC-400 to maintain adsorption efficiency even though the concentration of Pb ions increases. In contrast, BC-600 has a more developed pore structure with a high degree of porosity, indicating lower adsorption efficiency than BC-400. This decrease may be due to the saturation of active sites on the BC-600 surface due to increased porosity and decreased carbon content (Gray et al., 2014). The more fragile structure due to high pyrolysis temperature can also reduce the stability of the interaction between Pb and the biochar surface.

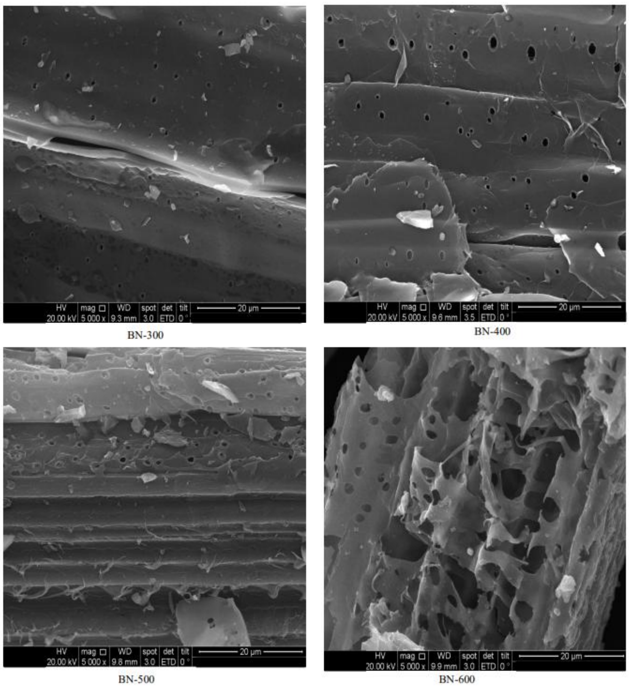

Figure 3. Morphological Structure of Bamboo Waste Biochar

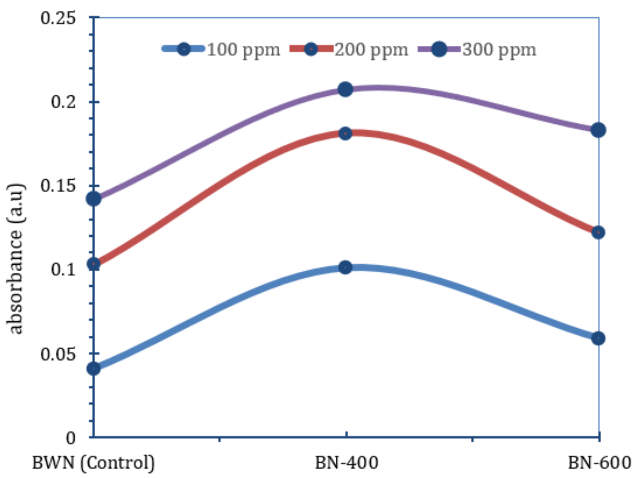

Figure 4. Effect of Solution Concentration

4. CONCLUSION

This study shows that biochar from bamboo waste through pyrolysis process has high potential as a heavy metal (Pb) adsorbent. Pyrolysis temperature plays a significant role in determining the physical and chemical characteristics of biochar. Biochar at a temperature of 400°C (BC-400) showed the best performance with a surface area of 178.56 m^2/g, pore volume of 0.091 cm^3/g, and an average pore diameter of 2.05 nm. The carbon content of BC-400 reached 93.26%, which is the highest value compared to biochar at other temperatures. The high carbon content provides stability to the biochar structure and increases the affinity for heavy metals through hydrophobic interactions and chemical bond formation. FTIR analysis showed that active functional groups such as carbonyl (C=O) and nitrogen-carbon (C–N) were dominant in BC-400, which increased the adsorption capacity through the coordination mechanism with heavy metal ions. At higher pyrolysis temperature (600°C), although the porosity increased, there was a decrease in the surface area (52.81 m^2/g) and carbon content (86.00%), which caused the adsorption efficiency to decrease due to the damage of the pore structure and the saturation of active sites.

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