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Characterization of Functional Groups in Sengon Biochar Under Various Pyrolysis Temperatures

Karakterisasi Gugus-Gugus Fungsional Biochar Sengon pada Perlakuan Berbagai Suhu Pirolisis

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ABSTRACT

The decline in soil quality due to pollution and the depletion of nutrients can be addressed by using biochar as a soil conditioner. This study utilized sengon biochar pyrolyzed at temperatures of 300°C, 500°C, and 700°C to analyze differences in functional group characteristics and their ability to adsorb ions. The objective of this study was to identify the functional groups of biochar at various pyrolysis temperatures and to determine the optimal temperature for enhancing the soil's ion adsorption capacity. The methods employed included functional group characterization using FTIR and ion adsorption testing using gentian violet and eosin red dyes. The results showed that biochar at 300°C retained dominant hydroxyl (-OH) and carbonyl (C=O) functional groups. Biochar at 500°C exhibited increased aromatic structure with dominant aromatic C=C groups while still retaining hydroxyl groups. Biochar at a pyrolysis temperature of 700°C loses many functional groups and is dominated by aromatic carbon. The best ion adsorption capacity is found in biochar at 500°C, followed by biochar at 700°C, and finally biochar at 300°C. Keywords: Analysis, organic materials, adsorption, ion.
Keywords: Analysis, Organic Matter, Adsorption, Ion

ABSTRAK

Menurunnya kualitas tanah akibat pencemaran dan berkurangnya unsur hara dapat diatasi dengan penggunaan biochar sebagai bahan pembenah tanah. Penelitian ini menggunakan biochar sengon yang dipirolisis pada suhu 300°C, 500°C, dan 700°C untuk menganalisis perbedaan karakteristik gugus fungsional serta kemampuannya dalam menjerap ion. Tujuan penelitian ini adalah mengidentifikasi gugus fungsional biochar pada berbagai suhu pirolisis serta menentukan suhu optimal untuk meningkatkan kemampuan tanah menjerap ion. Metode yang digunakan mencakup karakterisasi gugus fungsional menggunakan FTIR dan uji adsorpsi ion menggunakan pewarna gentian violet dan eosin red. Hasil penelitian menunjukkan bahwa biochar suhu 300°C memiliki gugus fungsional hidroksil (-OH) dan karbonil (C=O) yang masih dominan. Biochar suhu 500°C mengalami peningkatan struktur aromatik dengan dominasi gugus C=C aromatik dan masih memiliki gugus hidroksil. Biochar pada suhu pirolisis 700°C kehilangan banyak gugus fungsional dan didominasi oleh karbon aromatik. Kemampuan menjerap ion terbaik ada pada biochar suhu 500°C, kemudian biochar suhu 700°C, dan terakhir biochar suhu 300°C.

Kata kunci: Analisis, Bahan Organik, Adsorpsi, Ion

INTRODUCTION

Sustainable agriculture requires effective soil management, particularly the ability of soil to absorb ions for fertilizer efficiency and nutrient availability, but inorganic agricultural activities have degraded soil quality. Biochar, an environmentally friendly soil conditioner made from biomass such as sengon wood waste, has high potential due to its physicochemical properties and therefore warrants further research as a solution to improve soil quality. The effectiveness of biochar is highly dependent on its surface functional groups (-OH, -COOH, C=O, C=C) and pore structure, which change during pyrolysis (Darajat *et al*., 2021; Janu *et al*., 2021). This study analyzed the functional groups and ion adsorption capacity of sengon biochar produced by pyrolysis at 300°C, 500°C, and 700°C using FTIR to support sustainable soil management.

Biomass is organic material from living or dead organisms, or waste such as sengon wood. The production of biochar from sengon wood waste involves environmentally friendly combustion because the carbon comes from photosynthesis, so it does not add to atmospheric CO_2 and has low sulfur content (Ridhuan *et al*., 2018). Unmanaged wood waste causes air pollution (CH_4, CO_2 gases) and soil fertility decline (Waluyo, 2018), o converting it into biochar through pyrolysis, producing a carbon-rich solid material with 70-80% carbon content, high porosity, and large surface area, is an effective solution. Sengon biochar can enhance nutrient-water absorption, remediate heavy metals/pollutants, improve soil fertility, function as water filtration, and store carbon long-term (Nurida *et al*., 2013; Lehmann & Joseph, 2015).

Sengon biochar comes from *Albizia chinensis* wood waste. This tree can improve soil porosity, has an optimal harvest age of 5–7 years, and has a fairly high cellulose and lignin content (Fajrin *et al*., 2020). Sengon grows optimally in fertile soil with a pH of 5.5–7. The lignin content of sengon trees increases through optimal care, resulting in lightweight and economical wood (Prijono & Saputra, 2024). The physical properties of sengon biochar include soft particles, dark brown color, and high porosity, enabling it to store water and nutrients (Moru, 2021). Biochar quality is generally influenced by raw materials and pyrolysis conditions, where cellulose, hemicellulose, and lignin determine physical-chemical properties such as resistance to degradation and pore size (Iskandar & Rofi'atin, 2017). High-lignin sengon wood biomass decomposes into stable carbon during pyrolysis, producing biochar with high organic carbon content that increases soil carbon, provides habitat for soil fauna, raises pH, and enhances ion adsorption capacity. Biochar produced at higher temperatures can increase carbon content and micro porosity (Zhang *et al*., 2017).

Figure 1. Sengon Biochar

Pyrolysis is the heating of biomass without oxygen, which can break down volatile compounds into stable carbon while producing syngas and bio-oil (Herlambang *et al*., 2020). Pyrolysis consists of slow pyrolysis (300–700°C, resulting in 35% biochar), fast pyrolysis (400–600°C, resulting in bio-oil), flash pyrolysis (>600°C), and torrefaction (200–300°C), with slow pyrolysis producing high-porosity biochar for ion adsorption (Qureshi *et al*., 2019). Pyrolysis at 300°C produces biochar with high volatility, pyrolysis at 500°C enhances carbon stability and retains many functional groups, while 700°C yields nearly pure carbon with better stability but loses many functional groups and becomes hydrophobic (Prasetiyo *et al*., 2022; Deswardani *et al*., 2020).

Functional groups are atomic groups that determine the chemical properties of biochar, such as -OH, -COOH, aromatic, and aliphatic groups—playing a vital role in pollutant adsorption (Dai *et al*., 2021). Low-temperature pyrolysis retains oxygen groups (hydrophilic), while high temperatures leave stable aromatic structures (Ahmad *et al*., 2014). The benefits of -OH functional groups include water/ion adsorption, -COOH functional groups help adjust soil pH, and aromatic/aliphatic groups enhance stability/adsorption of heavy metals (Schmidt *et al*., 2017).

Pyrolysis temperature significantly affects functional groups: low temperatures (300°C) increase polar groups (-OH, -COOH) that absorb water, while high temperatures (≥500°C) reduce functional groups but increase carbon stability (Darajat *et al*., 2021; Nirlasari *et al*., 2022). Biochar functional groups are identified through FTIR (Fourier Transform Infra-Red) analysis using infrared light absorption spectra (Schneider *et al*., 2012). Ion adsorption by soil occurs through four mechanisms: electrostatic cation exchange, specific adsorption on oxide minerals, precipitation, and complexation with organic matter (Sparks, 2003; Stevenson, 1994).

Ion adsorption testing using charged dyes such as gentian violet and eosin red involves shaking biochar in distilled water for 30–60 minutes at a shaking speed of 150–200 rpm and analyzing the filtrate (Kooli *et al*., 2018). Ion adsorption testing was conducted using charged dyes such as gentian violet and eosin red, with biochar agitation in distilled water for 30–60 minutes, at a machine speed of 150–200 rpm, and analysis of the filtrate (Kooli *et al*., 2018). This study aims to determine the differences in functional groups in sengon biochar produced from pyrolysis at temperatures of 300°C, 500°C, and 700°C, as well as how these temperature variations affect the biochar's ability to adsorb ions.

Previous research by Hendrawan *et al*. (2019) showed that carbonization temperature and activator type ($ZnCl_2$, $CaCl_2$, and CH_3COOH) significantly affect the characteristics of sengon wood biochar, with the best results at 600°C. However, that study focused more on the combination of temperature and activator type. In this study, the focus is specifically on the effect of pyrolysis temperature variations without the addition of activators. This study examines changes in functional groups and analyzes ion adsorption potential, considering that 300°C still retains volatile functional groups, while 500°C and 700°C indicate further carbonization and the formation of more stable aromatic structures.

MATERIALS AND METHODS

This study was conducted over a period of two months, from March to April 2025, at two locations: the Land Resources Laboratory, Department of Soil Science, Faculty of Agriculture, UPN "Veteran" Yogyakarta, for ion adsorption capacity testing, and the Integrated Laboratory, University of Islam Indonesia, for biochar functional group analysis. The main equipment used included an analytical balance for precise weighing of biochar; measuring cups, pipettes, and beakers for measuring solution volumes; 100

ml Erlenmeyer flasks as mixing containers; a shaker for homogenization; filter paper and funnels for separating filtrates; a UV-Vis spectrophotometer (measuring absorbance at λ 520 nm for eosin red and 590 nm for gentian violet); and FTIR for functional group characterization. The main materials consisted of sengon biochar produced by pyrolysis at 300°C, 500°C, and 700°C, indicator solutions (gentian violet and eosin red), and distilled water as a solvent.

The research was conducted by analyzing the functional groups of sengon biochar, testing the ability of sengon biochar to adsorb ions, and analyzing the relationship between the functional groups of sengon biochar and its ability to adsorb soil ions. First, the functional groups of biochar were analyzed using FTIR. Biochar was taken from three pyrolysis temperatures, namely 300°C representing low temperature, 500°C representing medium temperature, and 700°C representing high temperature. All three were analyzed to identify functional group transformations (-OH, C=O, C-O, C-H) and aromatic stability (Cha *et al*., 2016; Tomczyk *et al*., 2020). Each temperature level significantly alters the chemical composition through thermal degradation of lignocellulosic components (Amalina *et al*., 2022). Second, calculating the absorption capacity of biochar began with sample preparation: 1 gram of biochar was mixed with 100 ml of distilled water. Some samples were added with gentian violet, and others with eosin red at concentrations of 10, 20, 30, 40, and 50 ppm. The mixture was then stirred for 30 minutes using a stirrer at a speed of 120 rpm, after which it was filtered, and the filtrate was collected to measure its absorbance using a spectrophotometer. After obtaining the spectrophotometer results, the concentration of gentian violet and eosin red absorbed by biochar was then calculated using this formula:

$$\text{Absorbed Concentration} = \frac{Initial\ Concentration - Final\ Concentration}{Initial\ Concentration}$$

The final analysis of this study includes: (1) Identifying FTIR spectrum peaks at specific wave numbers to compare changes in functional groups between temperature treatments. Additionally, conducting a literature review on the utilization of biochar at each temperature treatment according to its functional groups; (2) comparing the spectrophotometric absorbance results to evaluate the ion adsorption performance of biochar at the three pyrolysis temperatures.

RESULTS AND DISCUSSIONS

A. Functional Groups of Sengon Biochar at Various Pyrolysis Temperatures

FTIR (Fourier Transform Infra-Red) analysis is useful for determining the effect of pyrolysis temperature on the functional groups of sengon biochar. Based on the analysis conducted, the FTIR results are presented in Figure 2. Based on Figure 4. Graph of Sengon Biochar Functional Groups, the FTIR spectrum shows the presence of various chemical functional groups in biochar produced at three different pyrolysis temperatures, namely 300°C (blue), 500°C (purple), and 700°C (green). At a pyrolysis temperature of 300°C, an absorption peak at 3427.50 cm^{-1} was detected, indicating the presence of hydroxyl groups (–OH). Additionally, there is absorption at 2924.86 cm^{-1}, indicating aliphatic C–H groups, as well as carbonyl groups (C=O) at 1699.22 cm^{-1}. Aromatic groups (C-H) at 782.01 cm^{-1} and aromatic groups (C=C) were detected at 1601.57 cm^{-1}. When the pyrolysis temperature was increased to 500°C, the spectrum showed absorption at 3434.06 cm^{-1}, also indicating the presence of hydroxyl groups (–OH). Aromatic groups appear at 1590.68 cm^{-1},

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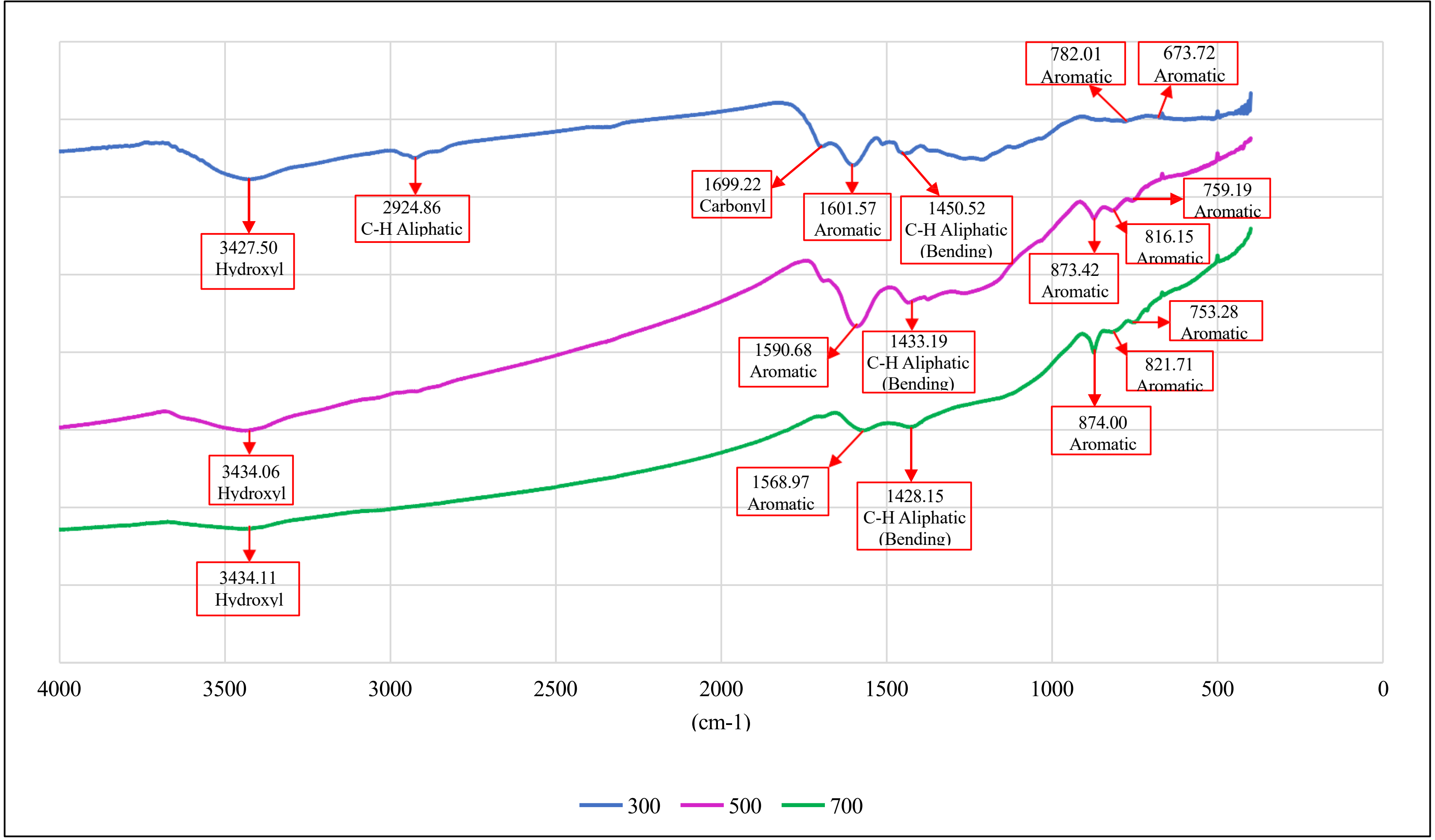

Figure 2. Graph of Sengon Biochar Functional Groups

and aliphatic C–H groups appear at 1433.19 cm^{-1}. Additionally, there are other aromatic groups, namely aromatic C-H groups appearing at the peak of 873.42 cm^{-1}. Meanwhile, the pyrolysis results at 700°C show absorption peaks at 3434.11 cm^{-1} (hydroxyl), 2924.86 cm^{-1} (aliphatic C–H), 1568.97 cm^{-1} (aromatic C=C), and 874.00 cm^{-1} (aromatic C-H). This indicates that hydroxyl and aromatic groups remain present despite the increase in pyrolysis temperature; however, the intensity and diversity of the groups suggest changes in the chemical structure of the biochar as the temperature increases.

Biochar at 300°C is dominated by polar groups such as –OH, –COOH, and C=O, indicating that oxygen and organic compounds have not been fully decomposed or decarbonized. At 500°C, hydroxyl groups decrease, carbonyl groups are no longer detected, and aromatic C=C groups become dominant because the increased pyrolysis temperature can remove most oxygen groups through dehydration and decarboxylation processes, but makes the biochar carbon more stable and increases pore size, which supports ion adsorption in soil (Janu *et al.*, 2021). Meanwhile, the dominance of aromatic groups becomes more evident at a pyrolysis temperature of 700°C. According to Sarwono (2016), this is because high temperatures cause the decomposition of almost all oxygen groups, leaving behind an aromatic carbon structure. Based on the identified functional groups of biochar, a literature review was conducted with the following results:

Table 1. Results of Observations of Functional Groups in Biochar

	300°C	500°C	700°C
Functional group dominance	Hydroxyl, carbonyl, aromatic[1]	Hydroxyl, aromatic[1]	Aromatic[1]
Characteris-tic	Hydrophilic, small pores[2]	Less hydrophilic, medium pores[6]	Hydrophobic, large pores[8]
Benefit	Soil ameliorant, water absorption [3] , habitat for soil organisms, absorbs inorganic pollutants[4]	Increase ion absorption and absorb organic and inorganic pollutants[7]	Hydrophobic organic pollutant absorbent, increases soil pH[9]
Advantages	Increase water absorption[3]	Carbon is more stable and resistant to degradation[8]	Stable and degradation resistant carbon[10]
Disadvanta-ges	Short term carbon, less stable[5]	Poor water absorption[6]	Hydrophobic[8]

Sources: [1] FTIR Test Results 2025
[2]Darajat *et al.*, 2021
[3]Rahayu & Khabibi, 2016
[4]Iskandar & Rofiatin, 2017
[5]Hendrawan *et al.*, 2019
[6]Ahmad *et al.*, 2014
[7]Ridhuan *et al.*, 2018
[8]Deswardani *et al.*, 2020
[9]Sarwono, 2016
[10]Nirlasari *et al.*, 2022

FTIR analysis showed that pyrolysis temperature affected the composition of functional groups in sengon biochar. Biochar at a pyrolysis temperature of 300°C, had many hydroxyl (-OH), carboxyl (-COOH), and carbonyl (C=O) groups which were polar. Biochar at a pyrolysis temperature of 500°C showed an increase in carbon functional groups and the loss of some polar groups. Biochar at a pyrolysis temperature of 700°C showed that most of its functional groups underwent further decomposition and were dominated by aromatic carbon groups.

B. Functional Groups of Sengon Biochar at Various Pyrolysis Temperatures

The addition of gentian violet and eosin red dyes into distilled water mixed with biochar is useful for representing the ability of biochar to absorb ions. Gentian violet is positively charged while eosin red is negatively charged. Both of these dyes interact with biochar through interactions between functional groups and pore adsorption. The following are the results of biochar's ability to absorb dyes, presented in Table 2 and Figure 3:

Table 2. Results of Sengon Biochar Adsorption on Gentian Violet and Eosin Red

Initial Consentra-tion (ppm)	Pyrolysis Temperature (°C)					
	Gentian Violet			Eosin Red		
	300	500	700	300	500	700
10	39.57	70.00	61.30	1.85	6.46	8.00
20	82.83	82.83	58.91	6.31	5.54	27.85
30	76.96	72.61	61.01	9.33	24.21	22.67
40	66.41	68.59	83.80	31.62	22.38	35.85
50	65.30	96.61	69.65	25.60	38.22	11.14

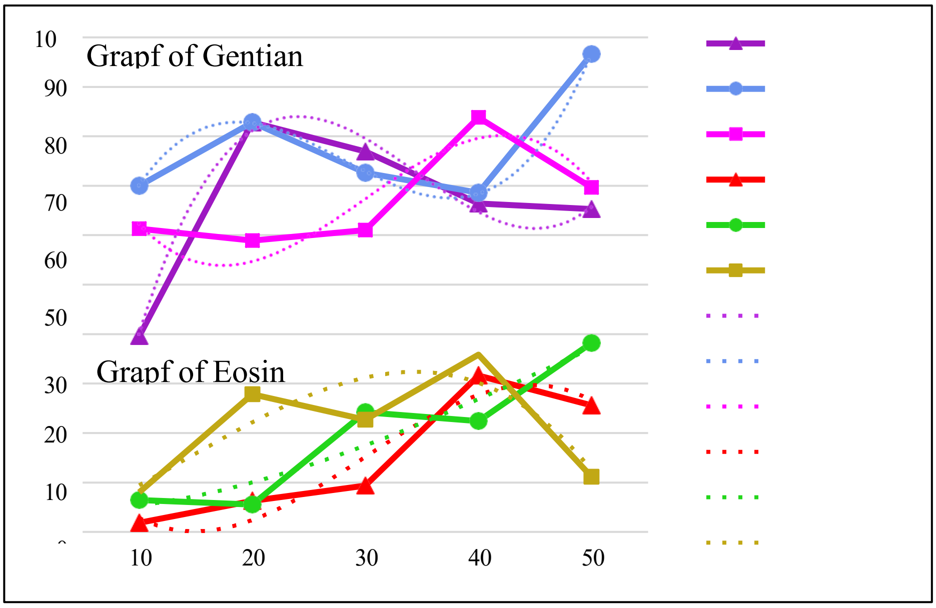

Figure 3. GV and ER Absorption Graph

The ability of sengon biochar to adsorb ions was tested using cationic dyes Gentian Violet (GV) and anionic Eosin Red (ER). For GV, biochar at a temperature of 300°C showed an adsorption of 39.57% at a concentration of 10 ppm, increasing drastically to 82.83% at 20 ppm due to increased electrostatic interactions (Inyang & Dickenson, 2015), then decreasing to 76.96% at 30 ppm, 66.41% at 40 ppm, and 65.30% at 50 ppm due to saturation of active sites (pore space and functional groups) and the large number of volatile substances attached to the biochar due to the low pyrolysis temperature (Ahmad *et al*., 2014; Kusman *et al*., 2024; Darajat *et al*., 2021). Biochar at 500°C has better adsorption capacity. This adsorption is influenced by functional groups and the addition of pore size due to high temperatures has evaporated volatile substances (Janu *et al*., 2021). The ion adsorption of biochar at 500°C was 70.00% at 10 ppm, increased to 82.83% at 20 ppm, decreased to 72.61% at 30 ppm and 68.59% at 40 ppm due to saturation of active sites, then increased sharply to 96.61% at 50 ppm. This increase is due to the formation of a GV molecular layer between biochar granules (Chen *et al*., 2021) and the transition from chemical to physical adsorption (Hendrawan *et al*., 2019). The adsorption of gentian violet on biochar at 700°C shows a non-linear pattern. Adsorption is 61.30% at 10 ppm, then decreases to 58.91% at 20 ppm due to the saturation of the monolayer capacity, then increases to 61.01% at 30 ppm as multilayer formation occurs, and at 40 ppm increases again to 83.80% due to the accumulation of GV molecules forming a dense multilayer structure on the surface, and finally decreases to 69.65% at 50 ppm due to the instability of the multilayer structure causing some molecules to detach. This trend aligns with the monolayer-multilayer transition mechanism and molecular release in high-temperature biochar as reported in Chen *et al*. (2021). Adsorption at 700°C is more influenced by the pore structure because many of its functional groups have been lost (Nirlasari *et al*., 2022). Meanwhile, the absorption of Eosin Red (ER) by biochar also varies. The ion adsorption of biochar at a pyrolysis temperature of 300°C increased from 1.85% at 10 ppm to 6.31% at 20 ppm, then increased again to 9.33% at 30 ppm, and reached 31.62% at 40 ppm due to non-electrostatic interactions such as hydrophobic forces and multilayer formation (Inyang & Dickenson, 2015; Chen *et al*., 2021), then decreased to 25.60% at 50 ppm due to saturation of active sites. Biochar at 500°C showed 6.46% absorption at 10 ppm, then decreased to 5.54% at 20 ppm, then increased to 24.21% at 30 ppm due to ER molecules crowding each other to fill the pore space , then decreased to 22.38% at 40 ppm due to saturation of active sites, and increased again to 38.22% at 50 ppm. This increase was driven by high porosity and accumulation of ER molecules in the pore space and between biochar grains (Inyang & Dickenson, 2015). Biochar at 700°C, which predominantly works through physical adsorption because its functional groups have been largely degraded (Nirlasari *et al*., 2022). Biochar at a temperature of 700°C has an adsorption of 8.00% at 10 ppm), then increases to 27.85% at 20 ppm, but decreases to 22.67% at 30 ppm due to active sites starting to saturate, then increases to 35.85% at 40 ppm due to molecular aggregation that clogs the pore space and intergranular space as well as Van der Waals force bonds (Domingues, 2020), and drops drastically again to 11.14% at 50 ppm due to saturation of the pores and interparticle space (Inyang & Dickenson, 2015).

Overall, the biochar adsorption performance is strongly influenced by the pyrolysis temperature which determines the presence of functional groups and its pore characteristics (active sites). GV adsorption is consistently greater than ER due to the strong electrostatic interaction between the (+) charge of GV and the (-) charged biochar surface (Kooli *et al*., 2018), as well as the smaller molecular size of GV (408 g/mol) which easily enters the micropores vs ER (692 g/mol) (Torres- Zúñiga *et al.*, 2014). The GV curve at 500°C fits the polynomial model well (R^2=0.9997), reflecting the predictability of cation adsorption, while ER at 700°C has sufficient validity (R^2=0.7356) (Montgomery, 2017). The sorption fluctuations confirmed the dependence on charge synergy, adsorbate size, and biochar structure evolution, with 500°C biochar being optimal for GV and 700°C being better for ER (Nirlasari *et al.*, 2022).

The highest adsorption for gentian violet occurred in biochar at 500°C pyrolysis temperature and for eosin red the highest adsorption was in biochar at 700°C pyrolysis temperature. Biochar at 300°C pyrolysis temperature showed moderate adsorption. Biochar at 500°C pyrolysis temperature produced high adsorption in both solutions more evenly so that it was most suitable for increasing soil ion adsorption. Thus, biochar at 500°C temperature was considered most suitable for increasing ion adsorption in soil widely.

CONCLUSIONS

The results of FTIR analysis showed that pyrolysis temperature affected the functional groups in sengon biochar. Biochar at a pyrolysis temperature of 300°C still contained many polar groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O). Biochar at a pyrolysis temperature of 500°C experienced an increase in carbon groups and some polar groups began to disappear. Biochar at a pyrolysis temperature of 700°C experienced further decomposition and the biochar structure was dominated by aromatic carbon groups. Based on the ion adsorption test, biochar at a temperature of 500°C was able to optimally adsorb dyes, with the highest adsorption of gentian violet and high adsorption that was evenly distributed for both types of ions. Meanwhile, biochar at 700°C was more effective in adsorbing eosin red.

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