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Brunauer-Emmett-Teller, Fourier-transform infrared, and scanning-electron-microscope analysis of biochar from marine organic waste

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ABSTRACT

Brunauer Emmet Teller (BET), Fourier Transform Infrared (FTIR), and Scanning Electron Microscope (SEM) study are important methods for characterizing biochar produced from marine organic waste. Each technique provides insights into the physical and chemical structure of biochar, which are essential for understanding its properties and potential as a soil amendment. The purpose of characterizing biochar from marine organic waste by BET method is to specify the superficies point, pore size, and total pore volume of the biochar, FTIR to identify the characterization of organic compounds, and SEM to understand the microstructure of the biochar. BET test results indicate that biochar from marine organic waste has a superficies point of 6.213m^2g^{-1}, a pore size of 21.690Å, and Barrett–Joyner–Halenda (BJH) adsorption and desorption pore volumes of 0.040cc g^{-1} and 0.035cc g^{-1}, respectively. This biochar demonstrates a higher adsorption capacity. FTIR tests reveal that the functional groups and chemical content of the biochar from marine organic waste include six types of vibrations with different wavenumbers and % transmittance values. SEM analysis at various magnifications shows that the biochar from marine organic waste (MOW) has a complex pore structure. The characterization of biochar derived from MOW illustrates its potential as a cost-effective soil amendment and environmental remediation material. Its microstructure suggests long-term stability in soil, supporting carbon sequestration and improved soil health.

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1. INTRODUCTION

Waste is a common problem faced by the entire world, particularly in Indonesia. As a developing country, waste management is a critical issue that requires increased attention due to the continuously growing population. Population growth rates have a major impact on the amount of waste generated by human activities. The amount of waste produced in a specific area is proportional to the population size, the variety of activities, and the level of consumption of material goods by the inhabitants (Manik et al., 2016).

Marine debris, which consists of both organic and inorganic solid materials that are not easily decomposable, is discarded, accumulates, and spreads across the surface of the sea and beaches. This pollution is carried by rivers, drainage systems, or waste disposal systems, and transported by water currents and wind from land, eventually ending up in the sea (NOAA, 2016). According to NOAA (2013), marine debris includes plastics, metals, glass, rubber, wood, and clothing/fibers, among others. Inorganic waste is particularly problematic, as it does not degrade over time and is often ignored due to the absence of direct, noticeable effects on humans, such as unpleasant odors (Susilo et al., 2022). This makes it a critical issue to study, especially as the movement of water masses plays a major role in distributing debris over long distances. Coastal areas—transitional zones between land and sea—are rich in natural resources and scenic beauty (Apriliansyah et al., 2018; Johan, 2016; Johan et al., 2019; Johan et al., 2017), but they also face significant environmental challenges, especially pollution in the form of marine debris. The presence of such debris reduces river depths, degrades water quality, and adversely impacts the surrounding environment and human health (Um et al., 2018; Wahyudin & Afriansyah, 2020). The issue is closely linked to

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population growth, rising incomes, urbanization, industrialization, and changing consumption patterns, all of which contribute to increased waste production (Djaguna et al., 2019). Research by Enggara et al. (2019) also emphasizes that marine debris originates from human activities in daily life, making it a pressing environmental concern that reflects broader socio-economic development trends.

Brunauer Emmet Teller's (BET) theory is associated with gas adsorption on the surface of materials. This phenomenon is caused by van der Waals forces, which are produced by the adsorbent power plant and consist of atoms, ions, or molecules on the surface of the adsorbent. Adsorption can occur physically or chemically. Physical adsorption is governed by van der Waals interactions, while chemisorption involves a chemical reaction between the solid and the adsorbent or gas (Mohammed et al., 2022). The quantity of gas adsorbed on the adsorbent is often correlated with the material's surface area.

Fourier Transform Infrared (FTIR) Spectroscopy is a spectroscopic measurement method used to detect the molecular structure of compounds (Sulistyani, 2018). When measuring samples using an FTIR Spectroscopy, the results obtained are in the form of a spectrum. Based on this spectrum, compounds can be identified qualitatively and quantitatively (Andriansyah et al., 2021).

Scanning Electron Microscopy (SEM) is a type of electron microscope that allows you to create high-resolution images of the surface of a sample. The working principle of SEM involves utilizing backscattered electrons (electron beams) on the object's surface and capturing images by detecting the electrons emitted from the surface (Septiano, Susilo, et al., 2021). Advances in the use of SEM allow for the scanning of large areas and the collection of substantial data to characterize samples. This includes counting objects and gathering statistics about them, such as obtaining morphological images to determine size distribution (Kharin, 2020). SEM testing enables the acquisition of morphological images and the concentration of material mixtures (Septiano, Sutanto, et al., 2021).

Kuala Indah Beach is located in the Sei Suka Subdistrict of Batu Bara Regency, in the province of North Sumatra, Indonesia, and offers a unique appeal for tourists with its high natural resource potential. However, it faces significant waste management challenges, particularly concerning marine debris. The beach is predominantly affected by piles of organic marine waste such as driftwood, seaweed, stranded coral, and shell remnants. To address this issue, innovative solutions for managing this organic marine waste are necessary, one of which is converting it into biochar. This approach not only helps in waste management but also creates a valuable product that can be used as a soil amendment, improving soil fertility and supporting sustainable environmental practices.

The objective of analyzing the characteristics of biochar produced from marine organic waste using the BET method is to evaluate its superficies point, pore diameter, and pore volume. FTIR analysis is used to identify organic compounds, while SEM is employed to examine the microstructure of the biochar by utilizing the electrons emitted from the sample.

2. MATERIAL AND METHODS

This study was conducted from September 2022 to January 2023. The marine organic waste samples used in the research were collected from Kuala Indah Beach, Sei Suka District, Batu Bara Regency, North Sumatra Province, Indonesia (3°21'0" N and 99°28.2'0" E).

2.1. Equipment and Materials

The equipment used in this study includes the S BT 1 Faculty of Agriculture, the specific superficies point of the first sample measured using the BET (Brunauer–Emmett–Teller) for producing biochar, an analytical balance for weighing samples, a 20 mesh sieves for sifting the biochar with each opening measuring about 0.0331 inches or 0.841 mm, a camera for documentation, SEM JSM 6390A for analyzing the microstructure of biochar, NOVA 4200e Superficies point and Pore Size Analyzer for Brunauer Emmet Teller (BET) analysis to determine superficies point, pore size, and volume of biochar, and Thermo Scientific Nicolet iS-10 for Fourier Transform Infrared (FTIR) analysis to identify functional groups in biochar. The materials include marine organic waste as the raw material for biochar production.

2.2. Biochar Production

Biochar production using the retort technique involves utilizing a device that could be placed into the SBT 1 device, which refers to a specific biochar production device owned by the Faculty of Agriculture at Universitas Sumatra Utara. Dry biomass is placed in the can, which is then sealed tightly. The production of biochar from marine organic waste such as driftwood and branches typically requires heating at 400–600°C for about 2 hours, followed by a cooling period of approximately 2 hours under oxygen-limited conditions (total duration 4 hours). The retort technique is a method of biochar production that prevents the biomass from burning directly by allowing it to absorb heat indirectly from an external source, such as a stove. In this system, a large, specially modified metal tube is used, which includes an integrated liquid smoke production feature. This design ensures efficient pyrolysis while capturing by-products like liquid smoke. Biomass is heated within the thermolysis device, and additional heating is provided by a gas stove to accelerate the temperature rise in the pyrolysis tube, thus converting the biomass into biochar. The dry biomass is placed into the thermolysis tube and roasted with high-temperature heat from below, using a support stand for the tube (Prasetiyo et al., 2020).

2.3. BET (Brunauer-Emmet-Teller) Analysis

The superficies point of biochar was tested using the BET method. The Brunauer–Emmett–Teller (BET) analysis is a commonly used technique to evaluate the surface and textural properties of porous materials such as biochar. This method relies on the physical adsorption of gas molecules, typically Nitrogen, into the surface of a material at liquid nitrogen temperature. Several key parameters can be derived from BET analysis, including specific superficies point ($m^2 g^{-1}$), pore volume ($cc\ g^{-1}$), and pore size distribution (Å), which is essential to determine the effectiveness of biochar for various applications such as adsorption, soil amendment, and catalyst. The BET method is used to determine the diameter and volume of pores, as well as the specific surface range of the material. It is usually based on the rules for gas adsorption and desorption. Gas absorbers contain gas retention (such as nitrogen, argon, and helium) on the surface of a strong fabric characterized by a stable temperature. The amount of gas that can be adsorbed by a strong surface at a certain temperature and specific weight (nitrogen, argon, or helium), as well as the virtual surface of the gas atoms known, can be calculated to determine the strong and complete surface range. The surface represents the entire pore area per unit of test area, with the specific surface being the surface range per gram of test.

2.4. FTIR (Fourier Transform Infrared) Analysis

The functional groups in the biochar were tested using the Thermo Scientific Nicolet iS-10 FTIR method. FTIR Spectroscopy was used to recognize functional category and organic content in the marine organic waste-derived biochar, which operates in the mid-infrared region, typically within the wavenumber range of 4000-400 cm^{-1}. FTIR instrumentation utilizes infrared radiation to detect functional groups present in the sample. The FTIR results are presented as a graph with peaks indicating wavenumbers, which are then matched with reference wavenumbers to identify functional groups or chemical bonds in the material (Skoog et al., 2017).

2.5. SEM-EDX (Scanning Electron Microscope-Energy Dispersive X-Ray) Analysis

SEM-EDX combines two types of instruments: SEM and EDX. SEM (Scanning Electron Microscope) is used to observe surface structure of a solid sample through imaging. EDX (Energy Dispersive X-ray) analyzes the constituent arrangement or chemical characteristics of a material. SEM analysis helps in understanding the microstructure, including porosity and crack formation. The electron beam used in SEM is generated from a heated filament, known as the electron gun. Morphological structures of the compost were observed using advanced Scanning Electron Microscopy with 3 types: Hitachi SU-3500 and Jeol JSM-IT200.

3. RESULTS

Based on the BET test, the results of Biochar from Marine Organic Waste are presented in Table 1.

Table 1. Analysis BET of Biochar from Marine Organic Waste

Parameters	Results
Temperature	77.350K
Cross section	16.200 A^2
Liquid Density	0.808 g cc^{-1}
Superficies point DH Desorption	16.060 m^2g^{-1}
Pore Volume DH Desorption	0.035 cc g^{-1}
Pore Radius Dv (r) DH Desorption	19. 081 Å
Superficies point DH Adsorption	10.737 m^2g^{-1}
Pore Volume DH Adsorption	0.040 cc g^{-1}
Pore Radius Dv (r) DH Adsorption	21. 690 Å

Table 2. Textural Properties of Biochar from Marine Organic Waste

Properties	Quantity	Units
Superficies point	6.213	m^2 g^{-1}
BJH cumulative volume of adsorption	0.040	cc g^{-1}
BJH cumulative volume of desorption	0.039	cc g^{-1}
BJH pore radius	21.690 (mesopores)	(Å)

The results of the BET analysis, presented in (Table 1), indicate that at a temperature of 77.35 K using an adsorbate gas with a molecular cross-sectional area of 16.200 $Å^2$ and a liquid density of 0.808 g cc^{-1}, carbonization leads to an increase in the superficies point of the biochar. Superficies point DH Desorption (16.060 m^2g^{-1}) refers to the superficies point of the material that is measured when gas molecules are being desorbed (released) from the surface of the material. This is the superficies point available to gas molecules that can be removed from the material. Superficies point DH Adsorption (10.737 m^2g^{-1}), on the other hand, refers to the superficies point of the material when gas molecules are adsorbed (attached) to the surface of the material. This value generally tends to be lower because some of the surface may be blocked or unavailable during the adsorption process due to the adsorbed molecules occupying space (Ambroz et al., 2018). The difference between the two values suggests that the material has a higher available superficies point during desorption than during adsorption, which might imply that the material undergoes changes in its surface structure or pore accessibility when gas is adsorbed versus desorbed. It is happened because when pyrolysis is conducted at higher temperatures, the raw materials containing aromatic lignin, aliphatic alkyl groups, and ester groups result in a greater superficies point for the biochar. High pyrolysis temperatures can enhance the superficies point and lead to pore formation.

Nitrogen adsorption-desorption analysis is used to determine the pore size, pore volume, and superficies point of biochar using the BET method. According to Table 2, the superficies point of the biochar is 6.213 m^2 g^{-1}. The adsorption and desorption values for the pore volume of the marine organic waste biochar are determined using the BJH method. The adsorption pore volume is 0.040 cc g^{-1}, and the desorption pore volume is 0.039 cc g^{-1}. The pore size of the marine organic waste biochar is 21.690 Å, categorizing it as mesoporous. Enlarged pores can reduce the total pore volume of the biochar, resulting in macro-pores with a lower superficies point and reduced total pore volume.

The nitrogen isotherm graph shown in Figure 1 illustrates the characteristic behavior of mesoporous materials, evidenced by a hysteresis loop observed in the marine organic waste biochar. This hysteresis loop occurs at a relative pressure (P/Po) of approximately 0.60–1.00, indicating the filling of mesopores. This suggests that the marine organic waste biochar possesses mesopores. The presence of hysteresis or branching in the graph is further confirmed by the difference between the amount of nitrogen gas adsorbed

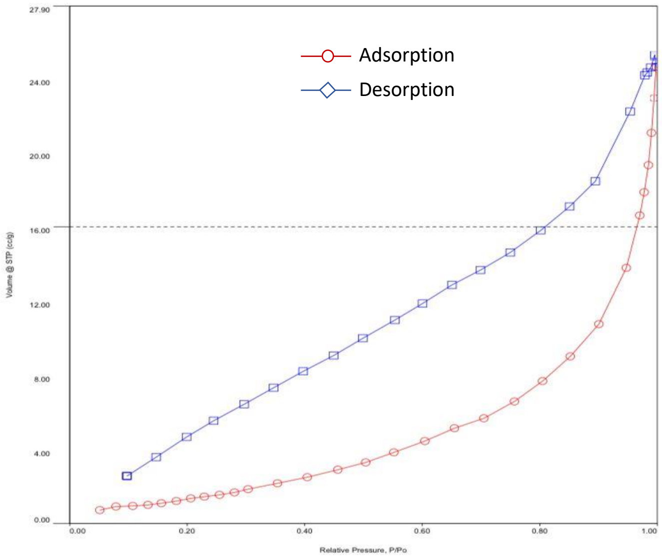


Figure 1. Linear Isotherm Graph of Biochar from Marine Organic Waste

Table 3. Selected Infrared Indicator Bands in Biochar of Marine Organic Waste Materials

Biochar Wave Numbers	Functional Groups
910.08	C—H Alkene
1029.32	C—O Alcohols, Ethers, Carboxylic Acids, Esters
1558.28	C=C Aromatic ring
1635.27-1652.51	C=C Alkene
3362.11	N—H amide, amine

and desorbed. Specifically, at the same relative pressure of 0.60-1.00, the amount of gas remaining on the material's surface during desorption is higher than the amount adsorbed initially. In other words, more gas is desorbed than was adsorbed. This hysteresis loop is attributed to condensation within the mesopores of the marine organic waste biochar. The red and blue lines in the biochar isotherm linear graph typically represent differences in experimental conditions or types of biochar used. The red line may indicate the adsorption results under specific conditions (e.g., higher temperature or pH), while the blue line represents a different set of conditions (e.g., lower temperature or pH). The difference between these lines provides insight into how variations in experimental conditions or biochar characteristics influence its adsorption capacity for contaminants. This graph is useful for understanding biochar's efficiency in adsorbing solutes at various concentrations, which is crucial for its applications in waste treatment or environmental remediation (Downie et al., 2012).

Based on the FTIR test of marine organic waste biochar, the results are shown in Table 3. Spectral peaks indicate wavenumbers are matched with reference wavenumbers to identify functional groups or chemical bonds present in a material, as Skoog Table (Skoog et al., 2017) . The infrared (IR) spectrum analysis of biochar produced from marine organic waste revealed several prominent absorption peaks, each indicating the presence of specific functional groups. A peak at 910.08 cm^{-1} corresponds to C—H bending vibrations typically found in alkenes, suggesting the presence of double bonds. The absorption at 1029.32 cm^{-1} is associated with C—O stretching, commonly found in alcohols, ethers, carboxylic acids, and esters, indicating the presence of polar oxygen-containing groups. A notable peak at 1558.28 cm^{-1} reflects C=C stretching within aromatic rings, signifying the presence of stable aromatic structures. Meanwhile, peaks in the range of 1635.27–1652.51 cm^{-1} also correspond to C=C bonds, but these are characteristic of non-aromatic alkenes. The broad absorption observed at 3362.11 cm^{-1} is indicative of N—H stretching, which is typically present in amides and amines, suggesting the incorporation of nitrogen-containing groups. These spectroscopic features provide a clear indication of the chemical structure of the biochar, confirming the presence of a variety of functional groups that influence its reactivity and potential application. For improved clarity, the IR spectra were vertically shifted along the absorbance axis in the presentation (Fig. 2).

Table 3 reveals that the marine organic waste biochar exhibits six spectral peaks corresponding to five functional groups. The peak at 910.08 cm^{-1} indicates the presence of the C-H Alkene group, with strong intensity. The peak at 1029.32 cm^{-1} corresponds to the C-O Alcohol, Ether, Carboxylic Acid, Ester groups, also with strong intensity. The C=C Aromatic Ring group is represented by the peak at 1558.28 cm^{-1} with variable intensity, and the C=C Alkene groups are found at wavenumbers 1635.27–1652.51 cm^{-1} with variable intensity. The peak at 3362.11 cm^{-1} represents the N-H Amide and amine groups with medium intensity.

The varying intensities of these functional groups are visible in Figure 2. The primary bands in the biochar material are labeled in the spectrum. The reduction of average spectra from different waste categories leads to a "difference spectrum," which highlights specific wavenumber regions that effectively differentiate between waste categories with different vibrations. These functional groups contribute to the cation exchange capacity (CEC) of the biochar and enhance its ability to adsorb heavy metals (Chen et al., 2011). The presence of phenolic groups, ethers, carboxylic acids, and esters ensures that biochar remains organic rather than becoming mineral carbon, thus retaining properties similar to other organic materials (Conte, 2014).

The SEM-EDX analysis results of biochar from marine organic waste are shown in Table 4. Based on Table 4 and Figure 3. The elemental compositions of marine organic waste biochar are carbon (C), oxygen (O), magnesium (Mg), aluminum (Al), silicon (Si), potassium (K), calcium (Ca), titanium (Ti), and iron (Fe). Among these elements, potassium (K), an essential macronutrient, is present in notably high concentrations.

The surface morphology of the sample can be observed using SEM. SEM allows the examination of the sample's surface morphology from three perspectives: the top surface, the side surface, and the internal structure. The SEM analysis reveals the morphology of the marine organic waste biochar at various magnifications: 1000x, 2500x, 5000x, and 10,000x, as shown in Figure 4.

In Figure 4, the SEM analysis of marine organic waste biochar at magnifications a. 1000x; b. 2500x; c. 5000x; and d.

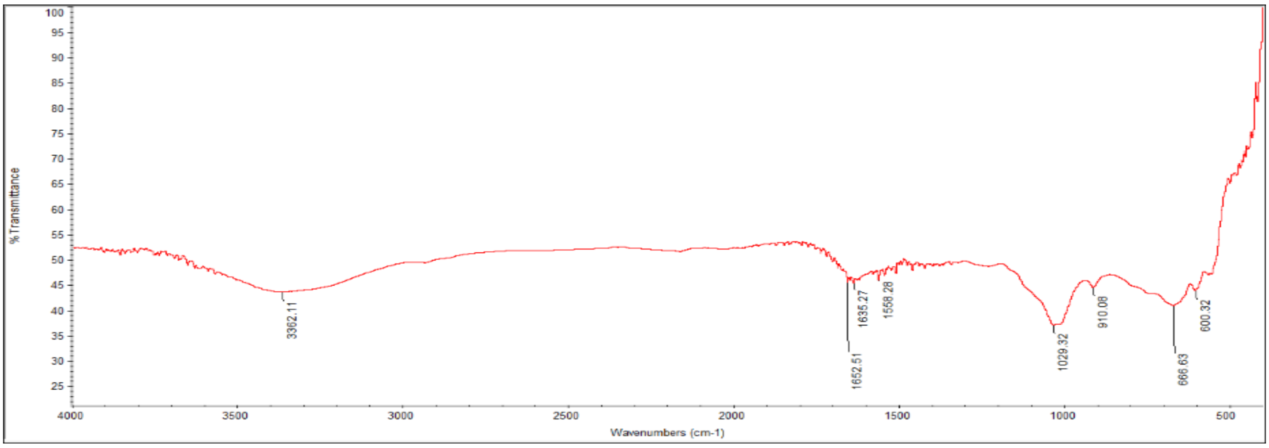


Figure 2. Averaged Infrared Spectra of Biochar from Marine Organic Waste Using the FTIR Test.

Table 4. SEM-EDX Analysis Results of Biochar from Marine Organic Waste

	Apparent Concentration	K Ratio	Wt (%)	Wt% Sigma	Atomic %	Standard Label
C	23.70	0.237	33.28	0.47	42.91	C Vit
O	129.16	0.434	49.43	0.38	47.85	SiO_2
Mg	2.16	0.014	0.59	0.03	0.37	MgO
Al	19.88	0.142	4.66	0.06	2.67	Al_2O_3
Si	44.43	0.351	10.03	0.09	5.53	SiO_2
K	2.49	0.021	0.50	0.02	0.20	KBr
Ca	1.65	0.014	0.34	0.02	0.13	Wollastonite
Ti	0.40	0.004	0.10	0.02	0.03	Ti
Fe	4.50	0.045	1.07	0.05	0.30	Fe
Total			100.00		100.00	

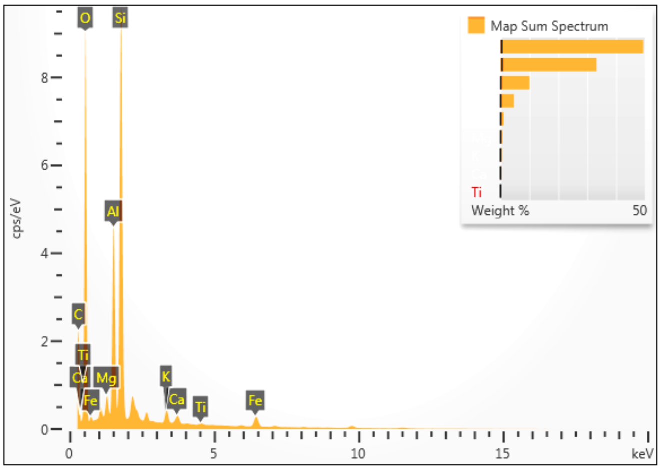


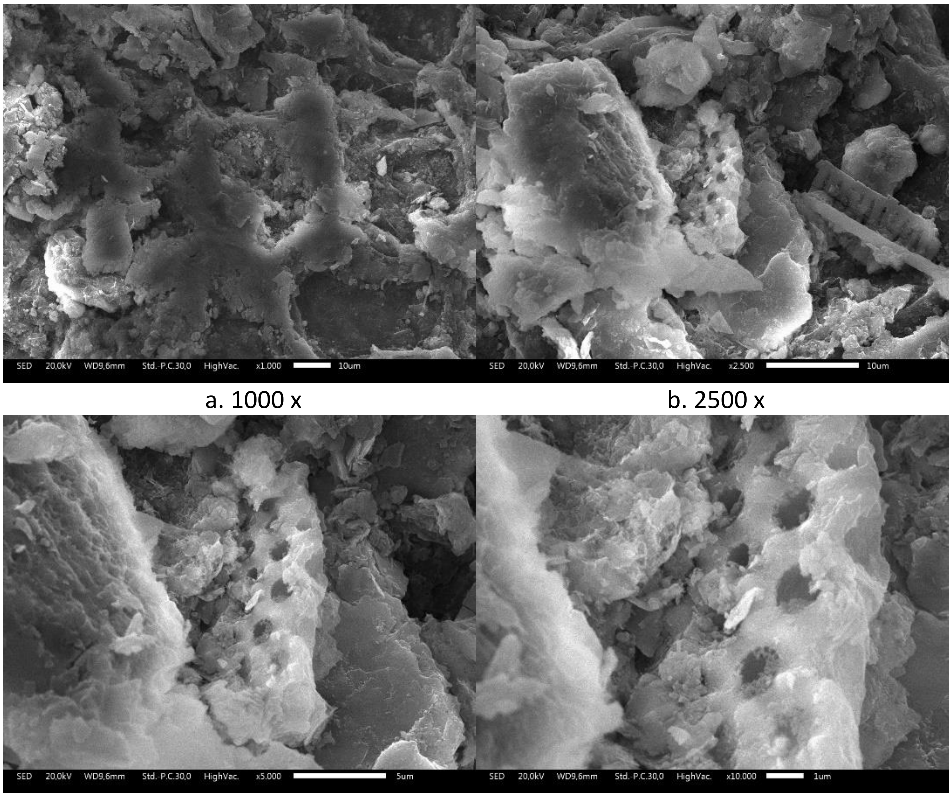
Figure 3. EDX Graph of Biochar from Marine Organic Waste

10000x shows that the microstructure is denser and less porous. The number of pores is minimal, with large, irregularly shaped pores. In the retort technique, biomass is not heated directly, causing substances on the biomass surface to evaporate more slowly. This slow evaporation leads to a gradual cracking of the biomass surface, resulting in larger and fewer pores. At higher pyrolysis temperatures, more pores are created. Optimal heating conditions allow substances in the surface pores of the biomass to disappear and evaporate, resulting in a higher superficies point and an increased number of pores.

4. DISCUSSION

The superficies point of marine organic waste biochar is 6.213 m^2 g^{-1}. High-quality biochar typically has a larger superficies point and more pores, which enhances heavy metal absorption and helps in pollutant removal. The presence of micro, meso, and macropores in larger quantities in biochar can improve soil physical properties by providing new habitats for microorganisms. Pores in biochar offer microorganisms new habitats and spaces for activity and water retention (Ding et al., 2016). The superficies point is determined using adsorption isotherms. Specific superficies point is crucial as it facilitates the absorption of substances like organic compounds and heavy metals. Generally, feedstock and pyrolysis temperature affect the superficies point due to the release of volatile properties. The superficies point of biochar varies depending on the production technique and feedstock used.

The superficies point of biochar is influenced by the type of biomass feedstock, pyrolysis conditions, and pre-and post-processing. High pyrolysis temperatures increase the superficies point and carbonization fraction of biochar, which affects its capacity for nutrient, water, and pollutant absorption, depending on its application (Wang et al., 2018). Based on the classification by the International Union of Pure and Applied Chemistry (IUPAC), pores can be divided into three categories: micropores (less than 2 nm), mesopores (2-50 nm), and macropores (> 50 nm) (Fahmi et al., 2018). Biochar is typically characterized by high porosity and wide -



a. 1000 x b. 2500 x

c. 5000 x d. 10.000 x

Figure 4. SEM Analysis Results of Marine Organic Waste Biochar with Magnification a. 1000x; b. 2500x; c. 5000x and d. 10000x

pore distribution, with pore sizes ranging from micropores to macropores. The pore size of marine organic waste biochar is 21.690 Å, which falls into the mesopore category. Mesopores play a role in liquid-solid adsorption, thereby increasing the adsorption capacity of biochar. Higher temperatures result in more interactions with carbon, leading to more pore formation. This results in the breaking of existing macropores into mesopores or micropores, decreasing the average pore radius. The properties of biochar are influenced by the type of biomass feedstock used and the specific conditions under which it is produced (Kinney et al., 2012; Mukherjee & Lal, 2013). The proportion of lignin, cellulose, and hemicellulose in the biomass affects the biochar produced through pyrolysis. The pyrolysis temperature greatly affects the amount of carbon lost and contained in the biochar and determines the physical properties.

The feedstock also affects biochar quality. For example, biomass containing lignin, such as wood, results in a smaller superficies point when pyrolyzed using the retort technique. Higher pyrolysis temperatures and feedstock containing aromatic lignin, aliphatic alkyl groups, and esters produce biochar with a larger superficies point (Rashid et al., 2021). High pyrolysis temperatures can increase superficies point and create more micropores. Pore enlargement can reduce the total pore volume of biochar, resulting in fewer macropores with a lower superficies point and total pore volume.

Functional groups in marine organic waste biochar include C—H alkene, C—O alcohol, ether, carboxylic acids, esters, C=C aromatic ring, C=C alkene, and N-H amide, amine. The presence of functional groups provides biochar with the potential for negative surface charges upon hydrolysis in soil. These negative charges can enhance biochar's ability to bind exchangeable plant nutrients. With such a structure, biochar can retain water, and its functional groups may contribute to cation or anion exchange, benefiting plant growth (Thangarajan et al., 2015). The absorption of metal and non-metal ions (including nutrients) occurs chemically through functional groups and physically through nano, micro, and macropores.

Marine organic waste biochar produced using the retort technique has a denser surface, fewer and larger pores, and irregular sizes. The retort technique heats biomass indirectly, causing substances on the biomass surface to evaporate more slowly, resulting in larger and fewer pores. Optimal heating conditions allow substances in the surface pores of the biomass to evaporate, increasing superficies point and the number of pores (Downie et al., 2012).

Marine organic waste biochar contains a variety of nutrients. Biochar significantly influences soil physical and chemical properties (C, N, P, K, CEC, pH, water holding capacity), affecting soil microbiota and plant root interactions (Warnock et al., 2007). Nutrient content varies with feedstock type. Typically, biochar produced at high pyrolysis temperatures has higher nutrient content than biochar produced at low temperatures. The increased nutrient content is due to the carbonization and volatilization of feedstock, while higher pyrolysis temperatures increase nutrient concentration in biochar, as nutrients do not dissipate during combustion. Higher burning temperatures lead to increased concentrations of cations such as K, Cu, Mn, Mg, Na, and Zn, depending on the biomass used (Yuan et al., 2019).

Biochar is a carbon-rich product. According to the International Biochar Initiative (IBI, 2014), the carbon content of marine organic waste biochar falls into Class 2 (>30%, <60%), indicating its capacity to retain carbon for a long period. Hussain et al. (2017) stated that implementation of biochar into the soil has many benefits such as its effect on physical properties (increasing porosity, water holding capacity, soil aggregation), chemical holding water, soil aggregate components), chemical (enhancement of pH, cation exchange capacity, soil organic carbon, nutrient retention and nutrient availability), and soil biology (microbes and earthworms). Improvement of soil properties then affects plant agronomic performance, growth, and production.

5. CONCLUSION

The characterization of biochar derived from marine organic waste illustrates its potential as a cost-effective soil amendment and environmental remediation material. Featuring a mesoporous structure, a specific superficies point of 6.213 m^2 g^{-1}, and the presence of key functional groups and essential elements such as potassium and calcium, this biochar exhibits moderate adsorption capacity and nutrient retention properties. Its microstructure suggests long-term stability in soil, supporting carbon sequestration and improved soil health. These findings underscore the dual benefit of addressing coastal organic waste while producing a value-added product for agriculture. Future efforts should focus on optimizing pyrolysis conditions and conducting field trials to maximize its environmental and economic impact.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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