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The Effect of Water on The Changes in Physical, Chemical, and Microstructural Properties of Oil Palm Empty Fruit Bunch Biochar

Dampak Air Terhadap Perubahan Sifat Fisik, Kimia, dan Struktur Mikro Biochar dari Tandan Kosong Kelapa Sawit

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Abstract Water is essential to life, and immersion treatment has been shown to significantly alter the properties of biochar, particularly by converting its hydrophobic nature into a hydrophilic one and others. This transformation leads to various changes in the material's physicochemical characteristics. In this study, biochar produced through pyrolysis of oil palm empty fruit bunches (EFB) using a kiln method was analyzed to assess its physical properties before and after immersion in distilled water. Surface morphology and elemental composition were evaluated using Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM-EDX), while specific surface area was measured using the Brunauer–Emmett–Teller (BET) method. Additional analyses, including pH, bulk density, water holding capacity, and moisture content, were conducted at the National Research and Innovation Agency (BRIN) and the Soil Biology Laboratory, Faculty of Agriculture, University of North Sumatra. The results demonstrated that water immersion induced notable changes in biochar characteristics. The pH of the biochar slightly decreased from 10.09 in dry EFB biochar to 9.54 in the soaked sample. While the soaked biochar exhibited higher concentrations of most nutrient elements, the carbon (C) content remained higher in the dry biochar at 65.06%. BET analysis revealed that the surface area of dry biochar (79.446 m^2/g) was substantially greater than that of the soaked biochar (38.783 m^2/g). Conversely, the soaked biochar showed superior performance in terms of bulk density (0.34 g/cm^3), water holding capacity (10.51%).

Keyword: Biochar, Immersion Treatment, Oil Palm Empty Fruit Bunches, Physicochemical Properties, Water Retention

Abstrak Air berperan penting dalam memodifikasi sifat biochar, terutama melalui perlakuan perendaman yang mengubah sifat hidrofobik menjadi hidrofilik dan banyak sifat lainnya. Penelitian ini bertujuan untuk mengkaji pengaruh perendaman air terhadap biochar yang dihasilkan dari pirolisis tandan kosong kelapa sawit (TKKS) menggunakan metode kiln. Sifat fisik dan kimia biochar dianalisis sebelum dan sesudah perendaman dalam air suling. Morfologi permukaan dan komposisi unsur ditentukan dengan SEM-EDX, sedangkan luas permukaan spesifik diuji menggunakan metode Brunauer–Emmett–Teller (BET). Analisis tambahan meliputi pH, bobot isi, kapasitas menahan air, dan kadar air, yang dilakukan di BRIN dan Laboratorium Biologi Tanah, Universitas Sumatera Utara. Hasil penelitian menunjukkan bahwa perendaman menyebabkan perubahan nyata pada sifat biochar. Nilai pH menurun dari 10,09 (biochar kering) menjadi 9,54 (biochar terendam). Biochar terendam memiliki konsentrasi unsur hara lebih tinggi, namun kandungan karbon tetap dominan pada biochar kering (65,06%). Analisis BET mengungkap penurunan luas permukaan dari 79,446 m^2/g (kering) menjadi 38,783 m^2/g (terendam). Sebaliknya, biochar terendam menunjukkan kinerja lebih baik pada bobot isi (0,34 g/cm^3) dan kapasitas menahan air (10,51%). Temuan ini menegaskan peran penting air dalam mengubah sifat fisikokimia biochar.

Kata Kunci*:* Biochar, Perendaman, Tandan Kosong Kelapa Sawit, Sifat Fisikokimia, Retensi Air

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Penulis yang tidak disertai dengan catatan kaki instansi adalah peneliti pada Pusat Penelitian Kelapa Sawit

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INTRODUCTION

Empty Fruit Bunches (EFB), a lignocellulosic by-product of palm oil milling, represent a significant waste management challenge due to their large annual production and environmental impacts when disposed of through open burning or landfill accumulation. EFB consists mainly of cellulose, hemicellulose, and lignin, making them suitable for thermochemical conversion such as pyrolysis to produce biochar, bio-oil, and syngas (Ichriani *et al*., 2013; Rezki *et al*., 2024).

Pyrolysis transforms the unstable organic polymers in EFB into a stable, carbon-rich biochar through thermal decomposition in limited oxygen, resulting in increased fixed carbon content and altered surface functional groups, including alcohol, ketone, carbonyl, and carboxyl groups (Savitri *et al*., 2023). These chemical transformations, such as decreased H/C and O/C molar ratios and increased aromaticity with higher pyrolysis temperatures, enhance the stability and sorptive properties of the resulting biochar. Chemical characterization of biochar—including elemental composition, pH, cation exchange capacity, and surface functionality—is essential because these properties determine its interaction with soil nutrients and microorganisms, influence nutrient retention and cation exchange capacity, and affect soil pH and water dynamics when applied as a soil amendment (Dady *et al*., 2021; Blankson *et al*., 2025).

In agricultural applications, well-characterized biochar has been shown to improve soil physical and chemical properties, potentially increasing soil fertility and crop yield due to improved structure and nutrient cycling, though results may vary with soil type and crops (Rafly, 2022; Sari, 2023). Conditioning or pre-soaking biochar before field application has been discussed in the broader biochar literature as a practice to reduce initial phytotoxicity, enhance microbial colonization, and improve water retention; however, specific empirical studies on EFB biochar conditioning remain limited in the palm oil biomass context. The conversion of abundant EFB waste into biochar therefore supports waste valorization, enhances soil health, and contributes to sustainable agricultural systems, aligning with circular economy principles in the utilization of agro-industry waste.

MATERIALS & METHODS

This research was conducted at the Faculty of Agriculture, Universitas Sumatera Utara, Medan, situated at an elevation of approximately 25 meters above sea level. Microstructural and elemental analyses of the biochar were conducted at BRIN (the National Research and Innovation Agency). The study took place from March 2024 to October 2024.

The materials used in this study included oil palm empty fruit bunches (EFB) as the raw material for biochar production, sacks for collecting the EFB, plastic sheets for placing the biochar samples, markers for labeling the samples, distilled water (aquadest) as the solution for pH measurement, and various chemical reagents required for laboratory analysis. This research employed an experimental method through direct trial with a descriptive design, in which the biochar was produced using the kiln method. After production, the biochar was soaked in distilled water for a period of seven days.

Biochar was produced using the Super BTKO pyrolysis unit owned by the Soil Chemistry and Biology Laboratory, Faculty of Agriculture, University of Sumatera Utara. This device is capable of producing biochar using two methods: retort and kiln. Constructed from copper, the apparatus consists of two chambers. The larger outer chamber is used for biochar production via the kiln technique. In comparison, a smaller inner chamber, placed inside the main tube, is used for biochar production via the retort method. The system is equipped with a gas burner at the base, which provides heat to the biomass placed above it, The temperature used in this study was 400–500 degrees Celsius with 2 to 3 hours of heating. (Hidayat & Pramuga, 2024)

The soaking process involved weighing 20 grams of biochar that had been sieved using a 20-mesh screen. The biochar was then placed into an Erlenmeyer flask and mixed with 100 mL of distilled water (Aquadest). The flask was sealed with cling wrap and incubated at room temperature for seven days to allow the biochar's surface properties to transition from hydrophobic to hydrophilic. After the incubation period, the biochar was filtered using filter paper to separate the solid from the liquid.

Figure 1. Dry biochar (a), biochar soaked in water for 7 days
Gambar 1. Biochar kering (a), Biochar yg direndam air 7 hari

The equipment used in this study included the SBT 1 unit at the Faculty of Agriculture for producing biochar, an analytical balance for weighing samples, a pH meter for measuring pH, a 20-mesh sieve for filtering the biochar, a shaker for homogenizing samples, and a camera for documentation purposes. The Scanning Electron Microscope (SEM) JSM 6390A was used to observe the surface morphology and nutrient content of the biochar. At the same time, the NOVA 4200e Surface Area and Pore Size Analyzer was employed for Brunauer–Emmett–Teller (BET) analysis to determine the specific surface area of the biochar. Additional tools and instruments necessary for the research were also utilized.

The bulk density of the biochar was measured using a 100 mL graduated cylinder. First, 55 mL of biochar was prepared for measurement. Before placing the biochar into the cylinder, its mass was determined using an analytical balance. The biochar was then poured into the graduated cylinder, which was tapped gently for 15 minutes to allow the particles to settle and compact. After compaction, the final volume was recorded. The bulk density of the biochar was calculated using the following formula:

$$\text{Bulk density} = \frac{\text{biochar mass}}{\text{total volume}}$$

The water holding capacity (WHC) of the biochar was determined by soaking the biochar for two days using a 1:5 ratio (biochar to distilled water). After the soaking period, the mixture was filtered using filter paper to remove excess water, and the retained biochar was then weighed. The water holding capacity was calculated using the following formula:

$$\text{WHC (\%)} = ((\text{Ws} - \text{Wi}) / \text{Wi}) \times 100$$

Where:

- Wi = initial dry weight of the biochar (g)
- Ws = saturated weight of the biochar after soaking (g)

The moisture content of the biochar was measured by weighing 10 grams of biochar and placing it in a heat-resistant crucible. The sample was then placed in an oven at 105°C for 3 hours. After drying, the crucible was transferred to a desiccator for 30 minutes to cool down, and then the sample was reweighed. The moisture content was calculated using the following formula:

$$\text{Moisture content} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \text{ x } 10$$

RESULTS AND DISCUSSION

pH Biochar

Based on the pH analysis results, it can be observed that the pH values of dry EFB biochar and water-soaked EFB biochar are different, as shown in Table 1 below.

Table 1. pH Values of Dry and Water-Soaked EFB Biochar
Tabel 1. Nilai pH Biochar TKKS Kering dan Terendam Air

Application	Replication			Average
	1	**2**	**3**	
Dry Biochar	10.10	9.82	10.36	10.09±0,27a
Soaked Biochar	9.53	9.51	9.58	9.54±0,04a

Note: Values with the same letter do not show a significant difference according to the Wilcoxon (signed-rank) test
Ket : Angka dengan huruf yg sama tidak berbeda nyata menurut uji Wilcoxon

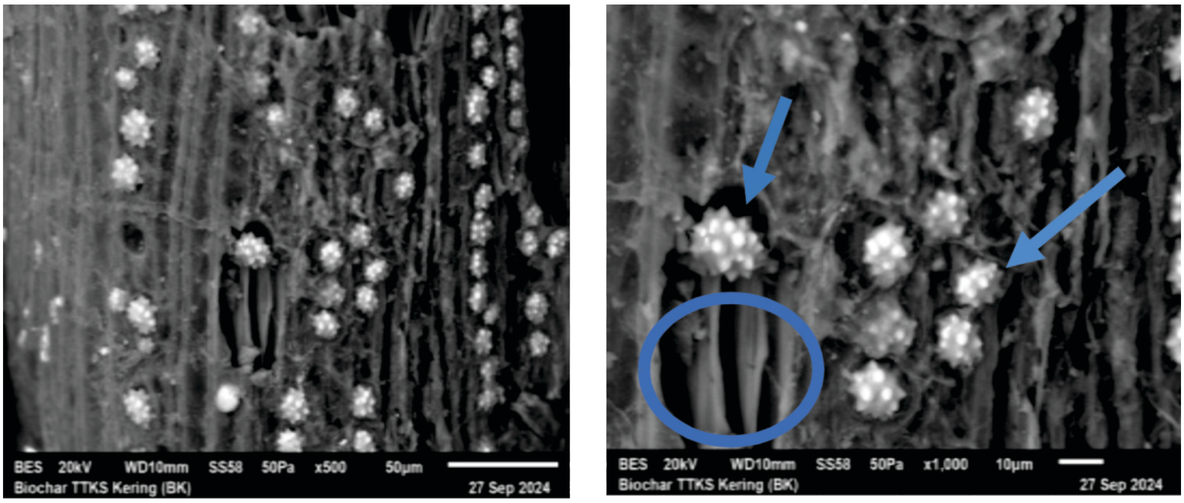
Table 1 shows that the average pH value of dry oil palm empty fruit bunch (EFB) biochar is higher (10.09) compared to that of water-soaked EFB biochar (9.54). This difference is attributed to the leaching of alkaline minerals such as calcium (Ca), potassium (K), and magnesium (Mg) during the soaking process. These minerals, which contribute to the alkaline nature of biochar, are partially dissolved in water and subsequently removed, reducing the ash alkalinity and lowering the pH. This finding is consistent with (Dayoub *et al.* 2024), who stated that biochar ash contains basic oxides of metals that can leach out during soaking, thereby decreasing the pH. Furthermore, the higher pH observed in kiln-produced dry biochar is likely due to the retention of these alkaline substances, which remain intact in the absence of water leaching. Mukhlis *et el.* (2023) also supported the fact that the alkaline pH of biochar is influenced by the presence of alkali and alkaline earth metals in the biomass feedstock, which remain stable during pyrolysis and contribute to biochar's basicity.

The application of biochar can significantly alter soil pH, which in turn affects the surrounding environment and soil processes where it is applied. Because many biochars are alkaline, their incorporation into acidic soils typically raises soil pH, improving conditions for nutrient availability, microbial activity, and overall soil fertility; this improvement can increase the solubility of essential nutrients such as phosphorus, calcium, and magnesium, thereby enhancing plant growth and reducing soil acidity (Yao *et al.*, 2025; Blankson *et al.* ,2025).

Surface Morphology of Biochar Observed by Scanning Electron Microscopy (SEM)

Based on the analysis using Scanning Electron Microscopy (SEM), the surface morphological structures of dry and water-soaked EFB biochar can be observed in Figures 2 and 3 at magnifications of 500× and 1000×, respectively.

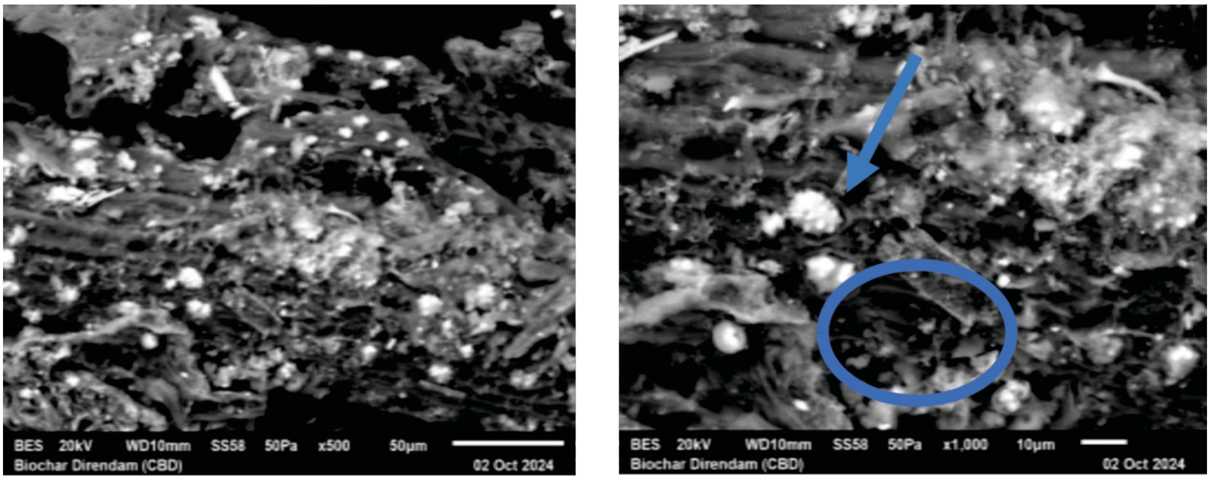
Scanning electron micrograph (SEM) of dry oil palm empty fruit bunch (OPEFB) biochar (×1000 magnification). The image reveals a well-developed porous structure with visible and intact microchannels. White crystalline mineral deposits (indicated by arrows) are observed on the biochar surface, likely representing inorganic residues formed during pyrolysis. These mineral aggregates appear embedded within the carbon matrix, suggesting potential active sites for cation exchange and microbial colonization.These pores and structured surfaces are important features that contribute to water retention, aeration, and microbial colonization in soil. In contrast, the soaked EFB biochar image shows a more compacted, irregular surface morphology, with some collapsed pore structures and more dispersed mineral particles. This indicates that soaking alters the biochar's physical microstructure, potentially reducing porosity while increasing the availability of dissolved nutrients.



(a) (b)

Figure 2. SEM images of dry EFB biochar at (a) 500× and (b) 1000× magnification. The arrows indicate adsorbed minerals and the circles denote preserved pore structures.

Gambar 2. Citra SEM biochar TKKS kering pada perbesaran (a) 500× dan (b) 1000×. Tanda panah menunjukan mineral yg terabsorpsi dan bulatan menunjukan pori yg utuh



(a) (b)

Figure 3. SEM images of water-soaked EFB biochar at (a) 500× and (b) 1000× magnification. The arrows indicate adsorbed minerals and the circles denote damaged pore structures.

Gambar 3. Citra SEM biochar TKKS terendam air pada perbesaran (a) 500× dan (b) 1000×. Tanda panah menunjukan mineral yg terabsorpsi dan bulatan menunjukan pori yg berantakan

Despite the loss of some pore integrity in the soaked biochar, the exposure of more mineral surfaces may enhance nutrient exchange and short-term cation availability for plants. Thus, both dry and soaked biochar exhibit beneficial characteristics for soil fertility: the dry variant supports long-term physical soil improvement due to its stable structure, while the soaked form may provide more immediate nutrient benefits (Lehmann & Joseph, 2015; Dayoub *et al*., 2024). For land application soeked is a good option. As such, understanding the microstructural differences is crucial in tailoring biochar applications for specific agronomic purposes (Lehmann & Joseph, 2025; Ayoub *et al*., 2024).

Elemental Composition of Biochar Analyzed by Scanning Electron Microscopy–Energy Dispersive X-Ray (SEM-EDX)

Figures 4 and 5 represent an Energy Dispersive X-ray Spectroscopy (EDS or EDX) spectrum, which is typically used to determine the elemental composition of a sample. The x-axis shows the X-ray energy in kiloelectronvolts (keV), while the y-axis represents the counts (intensity), indicating the number of X-rays detected for each energy level.

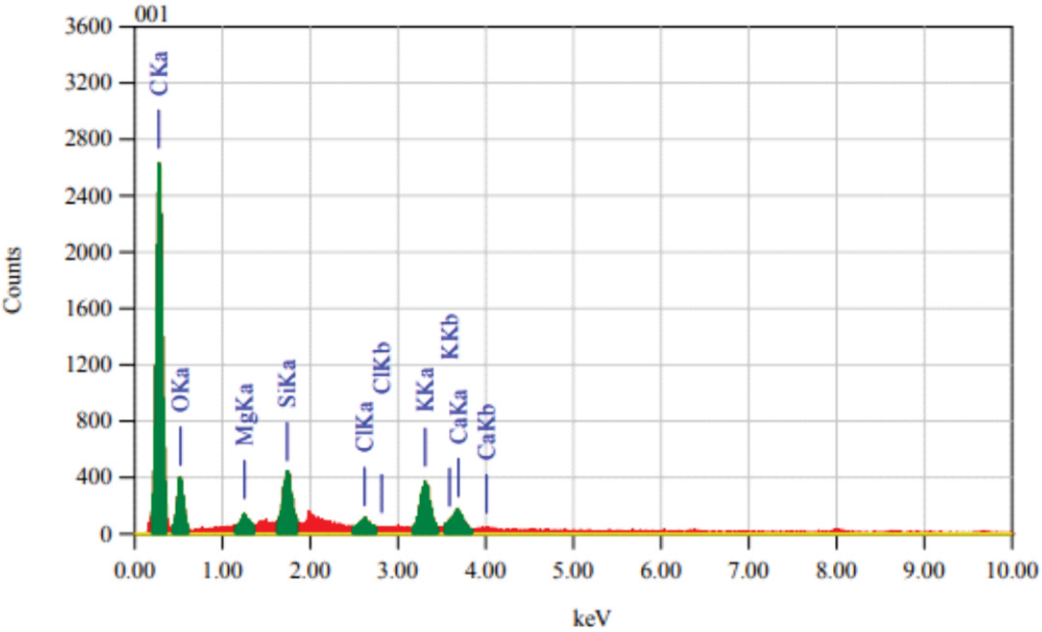


Figure 4. Energy Dispersive X-ray (EDX) spectrum of dry oil palm empty fruit bunch (OPEFB) biochar.
Gambar 4. Spektrum Energi Dispersif X-Ray pada biochar kering tandan kosong kelapa sawit

In Figure 4, several characteristic peaks can be observed, corresponding to specific elements present in the sample. The major peaks are identified as C (carbon), O (oxygen), Mg (magnesium), Si (silicon), Cl (chlorine), K (potassium), and Ca (calcium). The most intense peak, located around 0.3 keV, corresponds to carbon (C Kα), indicating that carbon is the dominant element in the sample. The strong presence of oxygen (OKα) suggests that the material likely contains oxides or oxygen-containing functional groups. The presence of Si, Mg, K, and Ca indicates mineral or ash components, which are typical in materials derived from biomass residues such as compost or biochar (Lehmann & Joseph, 2015; Luo *et al*., 2020).

The EDS spectrum Figure 4 reveals that the sample is rich in carbon and oxygen, confirming its organic nature, while the presence of Si, K, Ca, Mg, and Cl suggests mineral contributions that can influence nutrient availability and sorption capacity in agricultural applications.

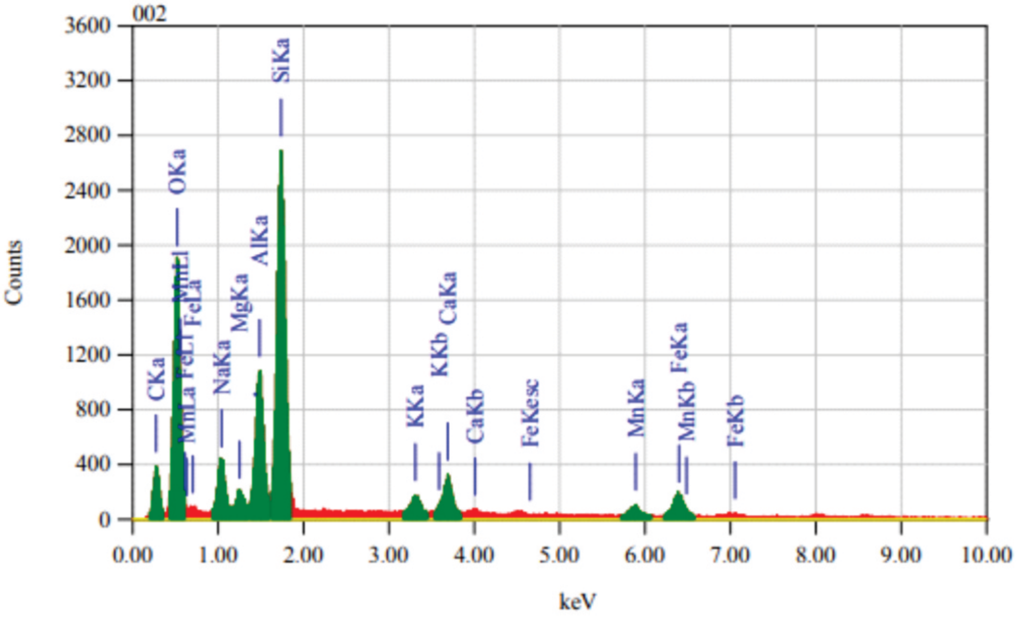


Figure 5. Figure X. Energy Dispersive X-ray (EDX) spectrum of soaked oil palm empty fruit bunch (OPEFB) biochar
Gambar 5. Spektrum Energi Dispersif X-Ray pada biochar tandan kosong kelapa sawit yg direndam.

The EDX spectrum, Figure 5 of the water-soaked oil palm empty fruit bunch (OPEFB) biochar, revealed carbon (C) and oxygen (O) as the predominant elements, indicating that the biochar maintained a carbon-rich matrix even after soaking. The strong C and O peaks at approximately 0.28 keV and 0.52 keV, respectively, reflect the dominance of carbonized organic matter together with surface oxygen-containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O). ((Lehmann & Joseph, 2015).

The presence of oxygen suggests partial oxidation of the biochar surface during soaking (Fig.5), which may enhance its cation-exchange capacity and reactivity toward nutrients or microbial colonization (Ahmad *et al*., 2014; Jindo *et al*., 2014). Minor peaks of silicon (Si), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), and manganese (Mn) were also detected, representing mineral residues originating from the ash fraction of the palm biomass (Zahra et al., 2021). Among these, K and Ca are macronutrients that can improve soil fertility, while Fe and Mn act as essential micronutrients (Steiner *et al*., 2017). Compared with the dry biochar, the soaked sample exhibited lower carbon and higher oxygen and mineral contents, confirming that water immersion enhanced surface oxidation and mineral enrichment (Zhao *et al*., 2017). This compositional change suggests that soaked biochar may provide greater immediate nutrient availability and surface activity when applied to soil (Lehmann *et al*., 2021).

Table 2 presents the elemental composition (expressed as weight percent) for two variants of biochar derived from oil palm empty fruit bunches (OPEFB): a "dry" biochar and a "soaked" biochar, which underwent water soaking before analysis. Carbon (C) dominates the dry biochar at 71.5 wt%, decreasing to 58.0 wt% in the soaked sample; this decline likely reflects increased relative proportions of mineral and oxygenated components following soaking (i.e., oxidation or leaching). Oxygen (O) increases from 19.8 to 25.0 wt% upon soaking, which is consistent with the formation or enrichment of surface‑oxygen functional groups (such as –OH, C=O, –COOH) that occur during exposure to water and/or mild oxidation. Silicon (Si) rises from 2.8 to 3.5 wt%, reflecting a modest relative enrichment of silica bodies (phytoliths) inherent in palm fibres after the organic fraction is partially leached or altered. Potassium (K) increases from 2.5 to 3.8wt %, implying that K-bearing mineral residues or soluble salts remained or were concentrated after soaking. Calcium (Ca) likewise increases from 2.2 to 2.8 wt%, indicating that mineral ash fractions contribute to alkalinity and buffering capacity in the biochar matrix. Magnesium (Mg) slightly decreases from 1.2 to 1.0 wt%, which may suggest selective leaching or redistribution of Mg during soaking. Interestingly, several elements appear only in the soaked biochar: iron (Fe) is detected at 1.4 wt%, manganese (Mn) at 0.2 wt%, sodium (Na) at 0.5 wt%, and aluminium (Al) at 0.3 wt%; these may stem from mineral ash constituents or ingress of aqueous ions during soaking. Chlorine (Cl) is detected at 0.5 wt% in the dry biochar but is absent in the soaked biochar, likely because Cl– salts were leached out during the water-soaking step. The totals sum to 100% for both variants, indicating a closed-mass basis for the EDX analysis.

Table 2. Elemental composition of dry and water-soaked OPEFB biochars based on EDX analysis
Tabel 2. Komposisi unsur dari Biochar kering dan yg sudah direndam pada analisis EDX

Element	**Symbol**	**Dry Biochar (wt%)**	**Soaked Biochar (wt%)**	**Description**
Carbon	C	**71.5**	**58.0**	Main element in the biochar matrix; represents aromatic carbon structure formed during pyrolysis.
Oxygen	O	**19.8**	**25.0**	Associated with surface oxygenated functional groups (–OH, C=O, –COOH); higher in soaked biochar due to surface oxidation.
Silicon	Si	2.8	3.5	Derived from silica bodies (phytoliths) in oil palm fibers; relatively higher in soaked biochar.
Potassium	K	2.5	3.8	Major nutrient element; retained after pyrolysis and relatively concentrated in the soaked biochar.
Calcium	Ca	2.2	2.8	Mineral ash contributes to alkalinity and pH buffering.
Magnesium	Mg	1.2	1.0	Secondary nutrient element; part of the mineral ash fraction.
Iron	Fe	—	1.4	Detected in soaked biochar; possible mineral residue from pyrolysis ash.
Manganese	Mn	—	0.2	Trace element; potential micronutrient.
Sodium	Na	—	0.5	Minor soluble salt is retained after soaking.
Aluminium	Al	—	0.3	Trace mineral from ash residue.
Chlorine	Cl	0.5	—	Slight presence in dry biochar; absent after soaking due to leaching.
Total	—	**100.0**	**100.0**	—

Taken together, the data illustrate how water-soaking modifies the biochar elemental composition, primarily by enriching oxygenated functional groups and concentrating mineral/ash-derived elements, while reducing the relative carbon content. These modifications may influence the biochar's chemical reactivity, surface functionality, nutrient retention, and suitability as a soil amendment. For instance, increased surface oxygen content is known to enhance nutrient sorption and microbial colonisation (e.g., Ibrahim *et al*., 2021). Furthermore, enrichment of K and Ca post-soaking supports the role of biochar as a nutrient reservoir and pH buffer in soils (Maulana *et al*., 2024).

Analysis on surface area, pore volume, and pore size of the biochar

Based on the results of BET analysis, data on surface area, pore volume, and pore size of the biochar surface from dry and water-soaked EFB (Empty Fruit Bunch) biochar were obtained, as presented in Table 3 below.

Table 3. BET Analysis of Dry and Soaked EFB Biochar
Tabel 3. Analisis BET biochar TTKS kering dan yg direndam air

Parameter	Treatment	
	Dry EFB Biochar	Soaked EFB Biochar
Surface area	79.446 m²/g	38.763 m²/g
Pore Volume		
(BJH Adsorption cumulative volume)	0.051 cc/g	0.065 cc/g
(BJH Desorption cumulative volume)	0.044 cc/g	0.057 cc/g
Pore Size		
(BJH Desorption pore radius)	19.250 Å	19.358 Å

Based on the BET analysis results presented in Table 3, water soaking significantly altered the surface properties of EFB biochar. The surface area of dry biochar was notably higher (79.446 m²/g) compared to the soaked biochar (38.763 m²/g), suggesting that water immersion reduces surface area, potentially due to pore collapse or blockage by soluble compounds. Conversely, the cumulative pore volume increased after soaking, with soaked biochar showing higher values for both BJH adsorption (0.065 cc/g) and desorption (0.057 cc/g) compared to the dry biochar (0.051 cc/g and 0.044 cc/g, respectively). The average pore radius slightly increased from 19.250 Å in the dry sample to 19.358 Å after soaking. These changes indicate that water treatment may affect the pore structure, enhancing water-accessible pore space while reducing surface area, which can influence biochar's performance as a soil amendment (Li *et al*., 2020)

The incorporation of biochar into agricultural soils has been demonstrated to enhance soil fertility by improving physical, chemical and biological soil properties. For instance, several reviews report that biochar's high porosity, large surface area and functional groups enable it to increase soil porosity and aggregation, reduce bulk density, raise available water capacity, and thus support more favourable root environments (Batista *et al*., 2018). Chemically, biochar often elevates soil pH (especially in acidic soils), enhances cation exchange capacity (CEC), and reduces nutrient leaching, thereby increasing nutrient retention and availability to plants (Beusch, 2021).

Bulk Density Values of Dry and Soaked EFB Biochar

The difference between dry and soaked empty fruit bunch (EFB) biochar primarily lies in their physical condition, as shown by bulk density in Table 4.

Table 4. Bulk Density Values of Dry and Soaked EFB Biochar
Tabel 4. Nilai Kerapat lindak biochar TTKS kering dan direndam air

Treatment	Replication			Average
	1	2	3	
Dry EFB Biochar	0.28	0.28	0.28	0.28±0,00a
Soaked EFB Biochar	0.34	0.35	0.33	0.34±0,01a

Note: Values with the same letter do not show a significant difference according to the Wilcoxon (signed-rank) test
Ket: Angka dengan huruf yg sama tidak berbeda nyata menurut uji Wilcoxon

Dry EFB biochar refers to biochar that has not been pre-treated with water or any solution before application. It retains its natural porous structure and has a lower bulk density due to the presence of air-filled pores. In the current study, the bulk density of dry EFB biochar was recorded at 0.28 g/cm³. In contrast, soaked EFB biochar is biochar that has been pre-saturated with water or nutrient-rich solutions, resulting in the filling of its internal pore spaces. This soaking process increases the overall mass per unit volume, as reflected by a higher bulk density of 0.34 g/cm³. Pre-soaking biochar before soil application is widely recommended, as it reduces the risk of nutrient immobilization in the soil and enhances immediate nutrient availability for plant uptake (Lehmann & Joseph, 2015). Moreover, soaking improves the biochar's interaction with soil microbes and minimizes potential phytotoxic effects caused by dry biochar absorbing water and nutrients from the surrounding soil and plant roots (Carril *et al.*, 2023). Thus, the choice between dry and soaked biochar should consider both the desired soil amendment effects and the logistical aspects of field application.

Water Holding Capacity of Dry and Soaked Biochar

The data presented in Table 5 show a significant difference in the water holding capacity (WHC) between dry and soaked Empty Fruit Bunch (EFB) biochar. The WHC of dry EFB biochar ranged from 55.6% to 63.5%, with an average of 59.13%, indicating that the biochar in its dry form can hold a large amount of water relative to its dry weight. In contrast, soaked EFB biochar showed a much lower WHC, ranging from 9.65% to 11.1%, with an average of 10.51%.

This stark contrast is attributed to the hydrophobic nature of fresh or dry biochar, which, after exposure to air or storage, may develop surface properties that enhance water absorption upon rehydration. Initially, biochar is often hydrophobic due to aromatic surfaces and unoxidized carbon residues formed during pyrolysis. However, dry biochar—especially if not previously wetted—may absorb large volumes of water once that hydrophobicity is overcome, resulting in higher WHC measurements (Adhikari *et al.*, 2023; Edeh *et al.*, 2022).

Conversely, soaked biochar, which has been saturated beforehand, tends to show lower measured WHC values in gravimetric tests because its pores are already filled with water and are less reactive to additional moisture. This is a methodological artifact, often encountered when WHC is measured by re-saturating already-wetted material (Reynaldi *et al.*, 2024). Despite this, pre-soaking is beneficial in agronomic applications because it *reduces the initial hydrophobic barrier*, improves *water retention dynamics*, and prevents the biochar from competing with plant roots for moisture during early soil incorpora. (Carril *et al*., 2023). Thus, while the dry biochar shows higher WHC values in laboratory tests, pre-soaking biochar enhances its practical performance in the field by promoting immediate interaction with soil moisture and nutrients. This has implications for biochar activation protocols and field application strategies.

Table 5 Water Holding Capacity of Dry and soaked Biochar EFB (%)
Tabel 5. Daya pegang air dari biochar TTKS kering dan direndam air

Treatment	Replication			Average
	1	2	3	
Dry EFB Biochar	63.50	55.60	58.30	59.13±3,00a
Soaked EFB Biochar	10.08	11.10	9.65	10.51±0,73a

Note: Values with the same letter do not show a significant difference according to the Wilcoxon (signed-rank) test
Ket : Angka dengan huruf yg sama tidak berbeda nyata menurut uji Wilcoxon

CONCLUSION

Soaking induces morphological changes in biochar, transforming its compact structure into a more fragmented form and enlarging the surface pores. This process leads to a reduction in total pore area, thereby facilitating the release of previously fixed elements within the biochar matrix. Additionally, soaking increases bulk density and alters the hydrophobic nature of the biochar to hydrophilic, resulting in enhanced water retention and moisture-holding capacity—particularly in biochar derived from oil palm empty fruit bunches. The results of this study indicate that for biochar application, the biochar should ideally be soaked first in water or in a nutrient-containing solution as an additional treatment

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