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Evaluation of The Physical and Chemical Properties of Bio-Char Derived from The Pyrolysis of Moringa Oleifera Seeds

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Abstract

This study aims to assess the potential of bio-char derived from Moringa oleifera seeds through an evaluation of its physical and chemical properties. Moringa oleifera seeds were processed into fine powder, dried, and then subjected to pyrolysis at 400°C using a microwave reactor. Nitrogen gas was introduced before and during the pyrolysis process to create a low-oxygen environment. The pyrolysis continued until no more condensable vapors were detected, indicating that the thermal decomposition process had reached completion. The resulting bio-char was collected and analyzed to determine its physical and chemical characteristics, including proximate analysis (moisture content, ash content, volatile matter, and fixed carbon), calorific value, and density. The results showed that the bio-char from Moringa oleifera seed powder had a very high fixed carbon content of 79.13% and low volatile matter. The calorific value reached 25.04 MJ/kg, which is comparable to that of low-rank coal. Additionally, the bio-char had a density of 0.905 g/cm³, which is relatively high compared to most biomass-derived bio-chars. These characteristics indicate that bio-char from Moringa oleifera seeds holds significant potential for use as a solid fuel in the form of briquettes or pellets, as a biomass energy source, and as a long-term carbon storage medium for climate change mitigation.

INTRODUCTION

The global dependence on fossil fuels has been a major concern in recent decades. This is due to their non-renewable nature and adverse impact on the environment. Fossil fuels, including petroleum, coal and natural gas, were formed over millions of years and will run out if continuously exploited at current consumption rates. Fossil fuel reserves are limited, which are expected to be depleted in 50-70 years if no new fields are found as fossil energy sources (Yana et al., 2022). In addition to scarcity issues, the use of fossil fuels contributes significantly to global climate change. Burning fossil fuels releases greenhouse gases, mainly carbon dioxide (CO_2), which causes global warming. Two-thirds of the increase in global energy demand in 2023 is met by fossil fuels, which drives increased CO_2 emissions (IEA, 2024). The Intergovernmental Panel on Climate Change (IPCC) reports that CO_2 emissions from fossil fuel combustion and industrial processes accounted for about 78% of the total increase in greenhouse gas emissions from 1970 to 2010 (Hood, 2005). To address this, one of the most promising potential renewable energy sources is biomass. Biomass can be sourced from forestry, agriculture, and water as feedstock for energy production (Radhiana et al., 2023).

The abundant availability of biomass worldwide and its easy availability from agricultural by-products and industrial processes

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make it a high potential renewable energy source (Perea-Moreno et al., 2019). The constraint in utilizing biomass waste as an energy source lies in the nature of raw (untreated) biomass, which generally has a low energy density value, high moisture content, and a high content of fly ash compared to fossil fuels such as coal (Mamvura & Danha, 2020). A promising approach is the utilization of biomass for bio-char production through pyrolysis, which has potential as a renewable energy source (Lehmann & Joseph, 2024). Bio-char is one of the main products of pyrolysis, in addition to bio-oil and gas, which can also be utilized as a sustainable alternative energy source (Powar & Gangil, 2013).

The advantages of using energy from biomass include providing an environmentally friendly source of energy and increasing the efficiency of agricultural resource utilization (Haryanti et al., 2018). One biomass that is suitable for conversion to bio-char is Moringa oleifera seeds. Previous research results show that Moringa oleifera seeds contain relatively high carbon (>77.6%) and moderate oxygen (<19.7%) on average, resulting in an O/C ratio of 0.25, which is comparable to lignite coal at 0.21. Therefore, Moringa oleifera seeds have the potential to be converted into char (bio-char) and liquid (bio-oil) products through pyrolysis (Sukarni et al., 2024). Pyrolysis, a thermal decomposition of organic materials in low oxygen conditions, is used to convert biomass into bio-char. This process produces a solid product with low moisture content and higher energy compared to the initial biomass. The properties of bio-char are influenced by various technological parameters, especially pyrolysis temperature and feedstock type. Differences in these parameters can result in products with varying pH values, specific surface area, pore volume, volatile matter, ash content, and carbon content (Tomczyk et al., 2020).

From a molecular perspective, bio-char exhibits a more stable structure than the original carbon present in its raw biomass feedstock. This stability suggests that bio-char is more resistant to degradation back into CO_2 (Asmunandar et al., 2023). Bio-char has potential applications in soil quality improvement while simultaneously acting as a carbon sink, whereas the oil and gas products from the pyrolysis process can be utilized as sources of energy and heat (Dolah et al., 2021). Additionally, bio-char derived from biomass pyrolysis has potential as an alternative fuel with high calorific value, which can positively influence combustion temperature, duration, and overall efficiency (Iskandar et al., 2021).

The research conducted by Aini et al., (2023) using waste materials such as twigs, leaves, and tea fluff with pyrolysis temperature variations between 300-500°C, showed that bio-char from tea twigs better meets the criteria for high-quality bio-char according to SNI 1683:2021. This is due to the high carbon content in tea twigs, which is more than 40%. Thus, it can be concluded that carbon content and pyrolysis temperature affect the quality of the resulting bio-char. The use of Moringa oleifera seeds, which have high carbon content (>77.6%), is expected to produce bio-char with better characteristics.

Although various studies have shown the potential of biomass as a renewable energy source, research on the utilization of Moringa oleifera seeds specifically as a raw material for bio-char is still limited, especially in the context of optimizing pyrolysis parameters and comprehensive characterization of its physical and chemical properties. Most previous studies have focused on agricultural waste such as twigs, leaves, and other organic residues, which generally have lower carbon content. Meanwhile, Moringa oleifera seeds have high fixed carbon content and an O/C ratio comparable to lignite coal, indicating great potential as an alternative solid fuel. Additionally, there is a lack of research that comprehensively examines the relationship between pyrolysis temperature and important parameters such as density, calorific value, ash content, and stability of bio-char from Moringa oleifera seeds. Therefore, this research is important to enrich scientific information on the utilization of Moringa oleifera seeds as a raw material for high-quality bio-char. The findings of this study are expected to contribute scientifically to the development of more efficient and sustainable biomass energy, while expanding the potential applications of bio-char in the energy and environmental sectors.

MATERIALS AND METHOD

This research uses Moringa oleifera (Moringa) seed powder as raw material. Before being pyrolyzed, Moringa oleifera seed powder was dried at 60°C for 24 hours and sieved using a mesh size of 20. The Moringa oleifera seed powder is shown in Figure 1.

Figure 1. Moringa oleifera seed powder.

The raw materials are then pyrolyzed using a microwave reactor as the heating media. Microwaves are electromagnetic waves with a very high frequency, generally 2450 MHz with a wavelength of 12.24 cm (Anis et al., 2020). Microwave assisted pyrolysis is faster and more efficient in producing products compared to conventional heating. Microwave heating can accelerate the pyrolysis process where heat arises from within the material, allowing more homogeneous heating and the heating rate can be faster (Anis et al., 2018). A schematic of the pyrolysis process using a microwave reactor can be seen in Figure 2.

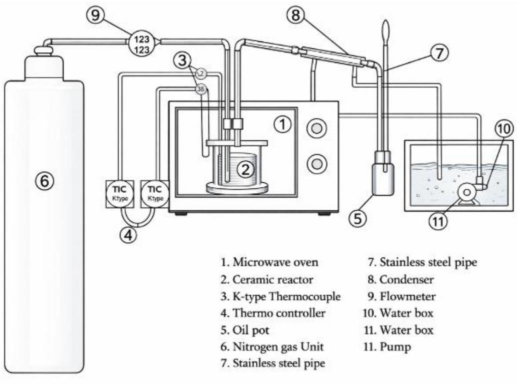

Figure 2. Schematic diagram of pyrolysis using microwave technology (Anis et al., 2020).

The microwave-based pyrolysis process in this study utilized a 1-liter ceramic vessel as the external reactor and a 250 mL Pyrex beaker as the internal reactor. The external reactor contained a microwave absorber to convert microwave energy into thermal energy, while the internal reactor held the biomass feedstock for pyrolysis. The use of these two reactor types was intended to facilitate the separation of the absorber and the resulting bio-char, enabling accurate measurement of the bio-char yield. The external reactor was connected to a stainless steel pipe serving as the vapor outlet. The temperature inside both the internal reactor and the microwave oven chamber was monitored using K-type thermocouples. These thermocouples were connected to a thermocontroller to regulate the pyrolysis process temperature. Prior to and during the pyrolysis process, nitrogen gas was introduced into the reactor at a flow rate of 0.15 NL/min.

The vapor exiting the pipe was condensed using a Leibig condenser or double-tube condenser (300 mm long) and cooled with water. The bio-oil resulting from condensation was collected in a 500 ml container. This pyrolysis process used 100 g of raw material inserted into the internal reactor, and 100 g of granular activated carbon inserted into the external reactor as a microwave energy absorber. The pyrolysis experiment was conducted at a temperature of 400°C. After reaching the target temperature, the pyrolysis temperature was maintained for 120 minutes.

Collection of pyrolysis products was done after the bio-oil stopped flowing from the condenser, and then the bio-char could be taken after the reactor cooled down. The yield of bio-char product was weighed using a balance. Further characterization of the physical and chemical properties of the pyrolysis bio-char product was conducted, including calorific value (ASTM D-240), density (ASTM B-311-17), and proximate analysis including ash content (Ash) using ASTM D-3174-12, moisture content (MC) using ASTM D-3173-17, volatile matter (VM) using ASTM D-3175-17, and fixed carbon (FC) using ASTM D 3172-13.

RESULTS AND DISCUSSION

Figure 3 shows the results of proximate analysis (moisture content, volatile matter, ash content, and fixed carbon) of bio-char from pyrolysis of Moringa oleifera seeds at a temperature of 400°C.

Based on Figure 3, the Moringa oleifera seed bio-char has a low volatile matter (VM) content of 5.09%, a very high fixed carbon (FC)

Table 1. Comparison of VM, FC, and Ash composition of Moringa oleifera seed bio-char with bio-char from other biomass.

Bio-char	VM (wt.%)	FC (wt.%)	Ash (wt.%)	Reference
Moringa oleifera seeds	5.09	79.13	15.78	This research
Pine nut shells	41.08	57.38	1.54	(Qin et al., 2020)
Soybean straw	25.93	54.14	19.93	(Xu et al., 2021)
Coffee husks	41.8	41.9	16.29	(Del Pozo et al., 2022)
Olive mill waste	33.55	61.7	4.8	(Del Pozo et al., 2022)
Durian peels	33.48	55.09	11.43	(Manmeen et al., 2023)

content of 79.13%, and an ash content of 15.78%. The exceptionally high FC content is a key indicator that this bio-char contains a substantial amount of stable carbon, which burns slowly while releasing maximum energi (Chandrasekaran et al., 2024). This makes Moringa oleifera seed bio-char a highly promising candidate for high-quality solid fuels, such as carbon briquettes, pellets, or blends for biomass power generation.

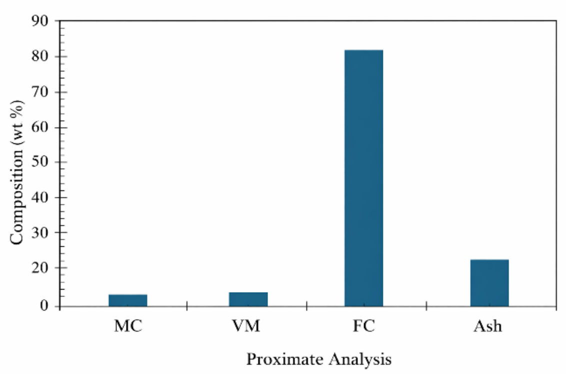

Figure 3. Composition of MC, VM, FC, and Ash in bio-char produced from the pyrolysis of Moringa oleifera seeds.

The FC value of Moringa oleifera seeds is higher compared to other materials, as shown in Table 1, including olive mill waste (61.7%), pine nut shells (57.38%), and durian shells (55.09%). On the other hand, the low VM content (5.09%) indicates high chemical and thermal stability. Bio-char with low VM is more resistant to biological decomposition and does not easily ignite spontaneously, making it suitable for long-term storage and carbon sequestration applications (Rodrigues et al., 2023). In comparison, bio-char from coffee husk and pine nut shells has very high VM content, 41.8% and 41.08% respectively, which means it is more reactive to rapid combustion but less stable for long-term storage or use.

However, the ash content of Moringa oleifera seed bio-char is quite high (15.78%), indicating that the solid residue after combustion is more than other materials such as pine nut shells (1.54%) and olive mill waste (4.8%). This can be a constraint in combustion systems that require high efficiency or require regular cleaning. Nevertheless, the ash content can be a added value if the bio-char is used as a soil ameliorant, because the ash contains minerals that can increase soil fertility, depending on its composition (Asirifi et al., 2025)

Overall, the proximate profile of Moringa oleifera seed bio-char shows an optimal balance for energy and environmental applications, namely high FC for efficient and long-lasting combustion, low VM for stability and storage safety, and ash that can be utilized in agricultural applications. This combination makes Moringa oleifera seed bio-char a superior material in the development of renewable bioenergy, as well as a biomass-based solution for carbon management and soil improvement.

Calorific value can be defined as the heat released from the combustion of a certain quantity of fuel (mass). Table 2 shows the calorific value of Moringa oleifera seed bio-char and its comparison with bio-char from other biomass. Based on the data, Moringa oleifera seed bio-char produced by pyrolysis at 400°C has a high calorific value of 25.04 MJ/kg, surpassing all other types of raw materials in the table, including coffee husk (24.18 MJ/kg), durian husk (24.49 MJ/kg), mixed wood waste (24.65 MJ/kg), and even olive mill waste (23.0 MJ/kg). Meanwhile, bio-char from bagasse recorded the lowest calorific value, only 11.29 MJ/kg, indicating relatively low energy quality.

The high calorific value of Moringa oleifera seed bio-char indicates a high fixed carbon (FC) content and relatively low volatile matter (VM) content, making it highly suitable for use as a solid fuel in the form of briquettes, pellets, or blends in biomass combustion systems for both household and industrial scales. This energy content >25 MJ/kg approaches the calorific value of low-grade coal, making it a potential substitute for fossil fuels in certain applications. Additionally, the high calorific value indicates good combustion efficiency and can reduce the amount of residue (ash) after the combustion process, which is highly beneficial from an operational standpoint (Anis et al., 2021; Venkatesh et al., 2022).

Table 2. Comparison of the calorific value of Moringa oleifera seed bio-char with bio-char from other biomass sources.

Bio-char	Calorific Value (MJ/kg)	Reference
Moringa oleifera seeds	25.04	This research
Sugarcane bagasse	11.29	(Stegen, 2018)
Olive mill waste	23.0	(Del Pozo et al., 2022)
Coffee husks	24.18	(Del Pozo et al., 2022)
Durian peels	24.49	(Manmeen et al., 2023)
Mixed wood waste	24.65	(Suresh Babu et al., 2024)

Compared to bio-char from other raw materials such as agricultural waste or fruit peels, Moringa oleifera seed bio-char not only excels thermally but also has a more stable structure. The combination of high calorific value and dense structure reinforces its position as a multifunctional bio-char, not only as a fuel but also as a long-term carbon storage, filler material in composite materials, or slow-decomposing growing medium.

In contrast, bio-char from bagasse with a calorific value of only around 11.29 MJ/kg is less ideal for energy applications but can still be utilized for other applications such as improving soil cation exchange capacity, heavy metal adsorption, or organic waste management, where calorific value is not the primary parameter (Zafeer et al., 2024). Thus, bio-char from Moringa oleifera seeds shows overall superiority for renewable energy applications and can be a strategic alternative in the development of bioenergy based on tropical biomass waste.

Table 3 shows the density of Moringa oleifera seed bio-char and its comparison with bio-char from other biomass. Density is a measurement of mass per unit volume of a substance. The greater the density of a substance, the greater the mass per unit volume. Density serves to determine the density of a substance, as each substance has a different density.

Table 3. Comparison of the density of Moringa oleifera seed bio-char with bio-char from other biomass sources.

Bio-char	Density (g/cm^3)	Reference
Moringa oleifera seeds	0.905	This research
Sugarcane bagasse	0.47	(Singh et al., 2019)
Rice husk	0.60	(Singh et al., 2019)
Olive mill waste	0.39	(Del Pozo et al., 2022)

The density of bio-char is an important indicator that reflects the level of density of carbon material produced by pyrolysis, and has direct implications for the performance of bio-char in various applications, including as a solid fuel, adsorbent, and soil ameliorant (Li et al., 2023). Based on data from pyrolysis at 400°C, bio-char from Moringa oleifera seeds has the highest density, which is 0.905 g/cm^3, far exceeding the density of bio-char from rice husk (0.60 g/cm^3), bagasse (0.47 g/cm^3), and olive mill waste (0.39 g/cm^3). High density indicates that the structure of bio-char from Moringa oleifera seeds is very dense and compact, with a low level of porosity. This characteristic makes it very stable and durable against decomposition, making it ideal for long-term applications such as carbon sequestration in soil and as a soil filler or stabilizer.

In the context of energy, high density contributes to a high volumetric calorific value, meaning more energy can be generated per unit volume of material (Santos et al., 2024). This makes Moringa oleifera seed bio-char highly potential as an alternative solid fuel, especially in the form of briquettes or pellets. Bio-char with high density will produce longer and more stable combustion, and is easy to package and store due to its smaller volume per unit mass. However, low porosity also means limited surface area, which may limit the effectiveness of this bio-char in applications that require high adsorption capacity, such as wastewater treatment or as a growing medium (Haris et al., 2024).

Conversely, bio-char from raw materials such as olive waste and bagasse, which have lower density, are lighter and more porous, tend to be more suitable for adsorption applications or improving water and nutrient retention in soil. Thus, the density characteristics of bio-char need to be carefully considered based on its intended use. Bio-char from Moringa oleifera seeds, with its high density, is well-suited for applications as a solid fuel, long-term carbon storage, and solid structure material in construction or environmental fields, but is less ideal for applications that require high porosity. The choice of bio-char raw material should be tailored to the physical properties required by its end-use application.

CONCLUSION

The biochar produced from pyrolysis of Moringa oleifera seeds at a temperature of 400°C exhibits superior properties as a solid fuel. The very high fixed carbon content (79.13%) accompanied by low volatile matter (5.09%) reflects efficient combustion and good thermal stability, making it suitable for use in energy systems such as briquettes, pellets, and biomass power plants. Although the ash content is relatively high (15.78%), this characteristic provides an opportunity for utilizing bio-char as a soil ameliorant, making it also relevant for environmental applications. With a calorific value reaching 25.04 MJ/kg, this bio-char surpasses most other biomass and approaches the calorific value of low-grade coal. This indicates the potential of Moringa oleifera seed bio-char as a high-energy source that can be a viable alternative to fossil fuels in the development of renewable energy. Physically, this bio-char has a high density (0.905 g/cm^3), indicating a dense structure that is resistant to decomposition, thereby supporting its use for long-term carbon storage or as a structural filler material.

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