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Effect of microwave power level and processing time on the quality of palm shell charcoal (*Elaeis guineensis* Jacq.) briquettes

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Abstract: One of the developments in renewable energy sources is use of biomass. This research aims to analyze the effect of power (70, 150 and 230 W) and activation time of palm shell charcoal using microwave during different time intervals (360, 480 and 600 s) on the density, moisture, ash content and volatile matter of palm shell charcoal briquettes. Charcoal briquettes are obtained from the carbonization process at a temperature of 548.7°C for 6 h, grinding and sieving at 80–100 mesh, activation using a microwave at a fixed time of 480 s with variations in activation power of 70, 150 and 230 W and fixed 150 W with variations in activation time of 360, 480 and 600 s. The research results showed that the density of palm shell charcoal briquettes ranged from 0.51–0.54 g/cm^3, the water content ranged from 3.31–3.92 %, the ash content ranged from 7.13–7.86 % and the volatile matter ranged from 8.19–9.22 %. SEM characterization shows that microwave activation increases the number of pores evenly and enlarges the pores. From the research results, the power and activation time vastly improve the quality of palm shell charcoal briquettes.

Keywords: activation; carbonization; water content; ash content; volatile matter; pores.

INTRODUCTION

The use of fuel from fossil sources continue to increase even though the sources are decreasing. The development of renewable energy sources can replace fossil fuels to minimize the worst impacts.[1] The development of renewable energy sources, one of which is biomass energy, is very promising as an alternative energy.[2] The potential for biomass in Indonesia which can be used as an energy

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source is very abundant, the annual biomass potential is 146.7 million t, and in 2020, 53.7 million tons of biomass was produced from waste.[3] Oil palm (*Elaeis guineensis* Jacq.) is a promising plantation commodity in Indonesia, particularly in Southeast Sulawesi. The region's oil palm plantations cover an impressive 70000 ha, producing a total of 61300 t in 2022.[4] As these plantations expand, so does the potential for biomass waste, a key ingredient in the production of charcoal briquettes, a promising alternative energy source. Every processing of 1 t of palm oil produce waste of 6.5 % or 65 kg of shells with a calorific value of 20,093 kJ/kg in dry conditions.[5] Palm oil shells contain high carbon lignocellulose content and have a higher specific gravity than wood, reaching 1.4 g/cm^3. Shells from palm kernels were chosen as the primary raw material for their abundant and sustainable availability. Indonesia is the world's largest producer of palm oil, with a growing amount of plantation acres. Palm kernel shells contain a significant amount of lignocellulose (25.88 % cellulose, 12.18 % hemicellulose and 42.20 % lignin), thus they have a higher density and calorific value than some other biomass. They use less energy and burn more effectively as a result. Palm kernel shells high fixed carbon content (59.1 %) and low ash content (0.20 %), offer good combustion qualities. Additionally, it is expected that the briquettes' quality will be improved by the microwave activation process, increasing their competitiveness with conventional fuels. Using palm kernel shells as a renewable energy source can reduce waste from the palm oil industry that could pollute the environment, reduce dependency on fossil fuels, and increase energy efficiency by utilizing underutilized resources.[5]

The advantages of charcoal briquettes are that they are more economical (cheap), have a high calorific value with a more extended burning period, also are smokeless and environmentally friendly. The characteristics of briquettes are influenced by several factors, namely carbonization temperature and time, carbonized charcoal fineness, charcoal powder density, and pressure in the moulding process. Good-quality briquettes have a smooth texture, are not easily broken and have good burning properties.[6] The burning characteristics of good quality briquettes include a short ignition time, long burning time at maximum temperature, low burning rate, no soot and little smoke. One way to improve the burning characteristics of charcoal briquettes is by activating the charcoal to reduce volatile matter levels so that the combustion rate is low (economical) and produces little smoke.[7] The main volatile substances that need to be removed include carbon monoxide, a high content of volatile substances in charcoal briquettes that will cause more smoke when lit. The high smoke content is caused by the reaction between CO and alcohol derivatives.[8] Light hydrocarbon compounds (CHx) from decomposing organic compounds in charcoal raw materials can burn quickly and less efficiently.[9] Water vapour, the remaining bound water in charcoal, can increase volatility and deteriorate combustion.[10]

Activation is a complex process that involves altering the physical properties of charcoal to reduce the level of volatile matter, thereby lowering the briquette burning rate.[6] The activation process also aims to reduce the water content and increase the fixed carbon and calorific value of the charcoal.[11] Lestari[12] stated that the quality of charcoal briquettes can be improved through the activation process. Previous research conducted by Bonsu *et al.*[13] analysed the characteristics of charcoal made from palm oil shells, which was used as the primary raw material for briquettes. The study reported that the charcoal had a moisture content of 6.7 %, an ash content of 0.20 %, a volatile matter content of 34.09 % and a fixed carbon content of 59.1 %.

It is of interest to investigate the influence of power (70, 150 and 230 W) and activation time using microwave with activation time variations of 360, 480 and 600 s on: the density, moisture, ash content and volatile matter of palm shell charcoal briquettes. This research aims to determine the effect of microwave power and activation time on the density, moisture content, and ash content of palm shell charcoal briquettes, as well as to evaluate the overall quality of the briquettes produced through microwave activation. This research determines the best power and time to produce quality briquettes that meet Indonesian National Standard (SNI) briquette quality by utilizing microenergy in charcoal activation.

EXPERIMENTAL

Research procedure

*Making palm shell charcoal briquettes (*Elaeis guineensis *Jacq.)*. Palm shell biomass waste (*E. guineensis* Jacq.) was obtained from PT, Tani Prima Makmur, Lerehoma Village, Konawe, Southeast Sulawesi. The carbonization reactor used in this study was a self-designed and locally modified version of the conventional "kiln drum" type commonly utilized by local communities. The reactor's structural design and functional performance were systematically developed and scientifically validated in the prior work by Lestari *et al.* (2024).[25] The biomass was sun-dried for 2–3 days to reduce moisture content before carbonization. Sago, used as an adhesive, was also sun-dried and sieved using an 80-mesh screen. Wood twigs were prepared as ignition material. Carbonization was carried out in a limited-air reactor. A total of 45 kg of dried palm shell was loaded into the reactor up to 75 % of its volume. The reactor was sealed, and ignition was initiated using dried twigs. Reactor temperature was monitored every 2 min using an infrared thermometer. The carbonization process was considered complete when the smoke emitted from the chimney changed from thick/dark to thin and clear. The resulting charcoal was ground and sieved sequentially through 80- and 100-mesh screens; the fraction retained between these meshes was collected. Activation was conducted by weighing 5 g of the sieved charcoal into a porcelain crucible and subjecting it to microwave irradiation at 720 W for 6 min. Briquette formation involved mixing the activated charcoal with sago adhesive in a 9:1 ratio (by weight), using 4 ml of distilled water preheated to 100 °C. The mixture was moulded and compacted using a hydraulic press at 15 MPa for 3 min to ensure uniform density and structural integrity. Briquette compaction tool (0–200 kg/cm^2) and a cylindrical briquette mould (outer diameter: 4 cm, inner diameter: 0.8 cm, height: 8 cm) are used for shaping the briquettes.

Experimental parameters

Determination of density. This test is carried out by determining how dense the mass of the briquettes is by comparing the mass of the briquettes with the volume dimensions of the palm shell charcoal briquettes:[14]

$$\text{Briquette density } (\rho) = \frac{m}{V_{\text{tot}}} \tag{1}$$

$$\text{Briquette volume } (V_{\text{tot}}) = \pi(r_2^2 - r_1^2)t \tag{2}$$

Description: m = mass of briquettes (g); r_1 = inner radius of the briquette (cm); r_2 = outer radius of the briquette (cm); t = briquette height (cm)

Determination of water content (moisture). This procedure is in accordance with the American Society of Testing and Materials (ASTM) D 2866-70. Testing the moisture content of charcoal briquettes is carried out by comparing the water content in the material during the heating process using an oven at a temperature of 105 °C for 3 h with the mass of the material before heating:

$$\text{Water content } (\%) = 100\frac{MS - MC - SP(105\ ^\circ\text{C}) - MCK}{MS} \tag{3}$$

Description: MS = sample mass (g); MCK = mass of empty cup (g); $MC + SP$(105 °C) = mass of cup + sample after heating at 105 °C (g).

Determination of ash content. The steps in measuring ash content are based on American Society of Testing and Materials (ASTM) D 2866-70. Put the palm shell briquette sample into a porcelain cup whose empty weight has been calculated. Next, put the porcelain cup containing the sample into the furnace at 700 °C until it turns ash for 3 h. Remove and cool the sample in a desiccator for 15 min. Determine the ash content with the following equation:

$$\text{Ash content } (\%) = 100\frac{MS - MC - SP(700\ ^\circ\text{C}) - MCK}{MS} \tag{4}$$

Description: $MC + SP$(700 °C) = mass of cup + sample after heating at 700 °C (g).

Volatile matter

Based on Cheng *et al.*[15] determines volatile matter using the following stages: put a sample of charcoal briquettes with known water content into a porcelain cup, then cover with aluminium foil. Inserting the sample into the furnace carefully and heating the sample at 750 °C for 15 min; cool the sample in a desiccator; next, open the porcelain cover and weigh the cup containing the charcoal briquette sample; calculate the level of volatile matter contained in the sample using the following equation:

$$\text{Volatile matter } (\%) = KZH(750\ ^\circ\text{C}) - \text{Water content } (\%) \tag{5}$$

Description: KZH = level of substance lost (%).

Fixed carbon. The fixed carbon content test is determined by subtracting 100 % from the percentage of water content, ash content, and volatile matter content:

$$\text{Fixed carbon } (\%) = 100 - M - AC - VM \tag{6}$$

Description: M = moisture (%); AC = ash content (%); VM = volatile matter (%).

Activated charcoal surface morphology

Surface morphology and elemental composition of the charcoal were analyzed using scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS). The SEM instrument used was the COXEM EM-30AXN (COSDAQ Listed Company, Korea), operating under both high and low vacuum modes, with a magnification range of 20–150,000× and acceleration voltage between 1–20 kV. Samples were coated with gold prior analysis. Elemental analysis was conducted using an Oxford Instruments Ultim Max Infinity EDS (Oxford, United Kingdom) equipped with a 30 mm standard compact detector, operated *via* AZtecOne software. EDS measurements were performed at three points on each sample to obtain average elemental compositions and standard deviation values. Charcoal activation was carried out using a microwave furnace (Sharp R-21D0(S)-IN, China) with a chamber capacity of 23 L, five adjustable power levels, operating at 220 V and 50 Hz. The activation parameters used in this study were specific microwave power levels and durations.

Fourier transform infrared spectroscopy (FTIR)

FTIR measurements were carried out using a Shimadzu type IRPestige-21 FTIR. The spectral data were recorded in the range of 4000–400 cm^{-1}. The procedure was carried out, namely the charcoal powder was sieved with a 100-mesh sieve. Charcoal powder with a mass of 0.02 mg was mixed with 0.2 mg KBr and homogenized by stirring with a stainless spatula. Then, pellets were made by pressing into a thin cylinder.

RESULTS AND DISCUSSION

*Quality analysis of palm shell charcoal briquettes (*El. guineensis *Jacq.)*

The quality of palm shell charcoal briquettes was analyzed by testing density, water, ash content, volatile matter and fixed carbon. Microwaves are electromagnetic waves with super high frequency (super high frequency, SHF), which is above 3 GHz. Microwaves can theoretically be converted into heat through interaction with dielectric materials. Carbon materials are generally sound microwave absorbers and are quickly heated using microwave radiation. This characteristic allows carbon materials to transform due to microwave heating, producing new carbon with the desired properties. Microwave oven have the fastest heating capability of all ovens, and also heat distribution, because the material absorbs microwaves and converts them into heat. Palm oil shells are shown in Fig. 1.

Fig 1. Raw palm kernel shells prior to carbonization and microwave activation.

The interaction between microwaves and carbon materials mainly involves an efficient and unique heating mechanism. Carbon materials, such as activated carbon and carbon nanotubes, have dielectric properties that effectively absorb microwave energy. When microwaves interact with carbon materials, the oscillating electric field causes the molecular dipoles and ions to vibrate and move, generating internal friction converted into heat. This process is known as dielectric heating. In addition, carbon materials with porous structures, such as activated carbon, have high surface areas and good electrical conductivity, enhancing microwave absorption efficiency. This allows for rapid and uniform heating in processes such as pyrolysis or carbonization. In some cases, the interaction between microwaves and carbon materials can generate microplasma on the material's surface. This plasma consists of highly reactive charged particles and can enhance the rate of chemical reactions or enable the synthesis of new materials at lower temperatures than conventional methods. Overall, the ability of carbon materials to absorb and convert microwave energy into heat makes them ideal candidates for various applications, including heating, material synthesis and catalysis.[24]

Palm oil waste contains lignin, cellulose, and primary hemicellulose elements, which indicate long carbon chains and high carbon content in palm oil waste. The very high carbon content can be a potential green precursor in producing carbon-based nanomaterials that can be applied in various situations.[16] The lignocellulose content of palm kernel shells was determined using the gravimetric method. The levels of hemicellulose, cellulose and lignin were calculated from measurements of neutral detergent fiber (NDF), acid detergent fiber (ADF) and subsequent residue analysis (see Supplementary material to this paper for details). The detailed results are presented in Table I.

TABLE I. Results of hemicellulose, cellulose and lignin content tests; analysis method: gravimetry

Component	Content, mass %
Hemicellulose	12.18±0.06
Cellulose	25.88±0.05
Lignin	42.40±0.02

Based on the data in Table I, the pretreatment process produced hemicellulose with a content of 12.18 %, cellulose with 25.88 % and lignin with a content of 42.40 %. The charcoal activation process aims to reduce the volatile matter content so that the combustion rate is low, also the water content is reduced and the charcoal's fixed carbon and calorific value are increased.

Microwave activation of charcoal involves exposing it to a specific power level (*e.g.*, 70 W) for different time intervals (*e.g.*, 480 s), causing a temperature change that transforms it into activated charcoal. Palm shell charcoal was activated using microwave at three power levels (70, 150 and 230 W) and three activation

times, namely 360, 480 and 600 s. These parameters were selected based on preliminary observation from both heating and color change. Below 150 W or less than 360 s, no noticeably heating effect happened. It tells that activation was less sufficient but conversely beyond 600 s or at powers greater than 230 W leading to charring and ashes formation, indicating overheating. The selected ranges were aimed to produce optimally identified conditions without any degradation of the material. Table II shows the results of analysis of density, water content, ash content, volatile matter and fixed carbon of palm shell charcoal briquettes fixed time 480 s.

TABLE II. Results of analysis of density, water content and ash content of palm shell charcoal briquettes at fixed time of 480 s

Power, W	Density g/cm^3	Water content %	Ash content %	Volatile matter %	Fixed carbon %
No activation	0.49±0.01	4.36±0.02	6.94±0.01	10.10±0.02	78.60±0.01
70	0.51±0.01	3.92±0.01	7.13±0.01	9.22±0.01	79.73±0.01
150	0.52±0.01	3.52±0.01	7.54±0.01	8.79±0.02	80.15±0.02
230	0.54±0.01	3.31±0.01	7.86±0.01	8.19±0.02	80.64±0.02

The values presented in Tables II and III represent the mean ± standard deviation from three replicates (n = 3) for each treatment. The standard deviation (±0.01) indicates the variation observed in the repeated measurements. Although the standard deviation values appear identical, this is due to rounding to two decimal places. Actual raw data showed slight differences, but they were within a narrow range, indicating high precision. These results were obtained through gravimetric and volumetric methods following ASTM standards, as detailed in the experimental section.

TABLE III. Results of analysis of density, water content and ash content at 150 W fixed power palm shell charcoal briquettes

Time, s	Density g/cm^3	Water content %	Ash content %	Volatile matter %	Fixed carbon %
No activation	0.49±0.01	4.36±0.02	6.94±0.01	10.10±0.02	78.60±0.01
360	0.52±0.01	3.76±0.01	7.34±0.03	8.91±0.02	79.99±0.01
480	0.52±0.01	3.52±0.01	7.54±0.02	8.79±0.02	80.15±0.02
600	0.53±0.01	3.40±0.02	7.68±0.01	8.40±0.01	80.52±0.01

Density

The density of charcoal briquettes may be viewed as an index between mass and volume, since it evidently influences mechanical strength, combustibility, and calorific value.[17] Increasing density might enhance briquette firmness and burning efficiency, but may also, if too dense, affect ignition easiness. According to Indonesian National Standard (SNI), the optimal density must balance burning time and

permeability to air.[18] In this study, the density of briquette samples ranged from 0.49 to 0.54 g/cm^3 (Tables II and III), and higher values were generated at higher microwave power and activation time. Density is accordingly influenced by particle size, homogeneity of material and pressure applied during the molding process.

The test results in Table II show that the density, of the palm shell charcoal briquettes produced, is 0.49–0.54 g/cm^3. The highest density value of 0.54 g/cm^3 was obtained at an activation power of 230 W, while the lowest density value was 0.49 g/cm^3 or charcoal briquettes without activation. Fig. 2A shows the surface morphology of the briquettes as observed through SEM imaging. As the activation power increases, the SEM images indicate a more compact and uniform surface structure with fewer visible pores. While SEM images cannot directly quantify density, the observed morphological changes suggest improved particle bonding and reduced void spaces, which may correlate with the measured increase in density reported in Table II. This is because as the activation power increases, the temperature produced by the microwave will be higher, resulting in stronger bonds between charcoal molecules. After all, when pressure is applied, the charcoal particles will be forced to fill the empty cavities and allow the adhesive to flow across the surface of the charcoal. So, it can reduce cavities or gaps that water can fill.[6] The increase in density at higher activation power may be associated with enhanced thermal effects that promote partial softening or restructuring of the carbon surface, potentially improving particle packing and reducing internal voids. Similar effects of thermal activation on carbon structure compaction have been noted in the previous studies by Zhang *et al.* (2022).[29]

When charcoal particles are pressed, pressure compacts the material by forcing particles to fill voids, thereby increasing density and improving structural integrity.[19] This process also enhances adhesive distribution along particle surfaces, promoting stronger bonding due to increased contact area.[20] The adhesive fills micropores in the charcoal structure, providing additional mechanical interlocking.[21]

Table III shows that briquettes, made with charcoal activated using a microwave at a fixed power of 150 W, have values of 0.52–0.53 g/cm^3. The density value experienced an insignificant increase as the activation time increased. This is because the activation process can cause the surface area of the charcoal briquettes to become more prominent, which results in greater absorption capacity so that the briquettes can absorb the adhesive used ideally and can fill the voids between particles, which will then increase their density.[29,30] Palm shell charcoal briquettes made from charcoal that has been activated using a microwave at a fixed activation power of 150 W have the highest density value of 0.53 g/cm^3, which is activated for 600 s. The size and homogeneity of the adhesive and charcoal mixture also influence the high or low density of palm shell charcoal briquettes. The more homogeneous the mixture of charcoal and adhesive is, the stronger the briquettes produced will be, and the higher the size of the charcoal particles, the higher the

density the charcoal briquettes will produce. The density of charcoal briquettes is also influenced by the pressure applied during the briquette compaction process. The more significant the pressure applied, the more water content will decrease because more is wasted as the compaction pressure increases. According to SNI 01-6235-2000, a good density value is 0.5–0.6 g/cm^3 based on the briquette quality standards. The density test results show that all palm shell charcoal briquettes made through the activation process in this study meet SNI standards, except for palm shell charcoal briquettes, which were made without activation (0.49 g/cm^3). The best density value of palm shell charcoal briquettes was produced from charcoal activated at 230 W of power for 480 s.

Water content (moisture)

The moisture content of charcoal briquettes greatly influences the calorific value. The smaller the water content value of the charcoal briquette, the higher the calorific value produced by the charcoal briquette.[22] Tables II and III show that briquettes made from activated palm shell charcoal produce lower water content values than briquettes made from charcoal without activation. The test results in Table II show that the water content value of the palm shell charcoal briquettes produced ranges from 3.31–4.36 %.

Based on Table II, the water content of palm shell charcoal briquettes tends to decrease significantly along with increased activation power. The higher the activation power, the lower the water content of palm shell charcoal briquettes. The decrease in water content is due to microwave activation, where higher power increases heat energy, promoting greater evaporation of water molecules from the charcoal. The water content value in palm shell charcoal briquettes with the activation time parameter, in Table III above, shows that briquettes made with charcoal activated using a microwave at a fixed power of 150 W have a value in the range of 3.40–3.76 %. The water content value experienced a significant decrease as the activation time increased. This is because the higher the activation time, the greater the surface area of the briquettes produced, causing the water in the briquettes to evaporate quickly, resulting in lower water content in the briquettes. The lowest water content was produced from charcoal briquettes activated at 150 W power for 600 s, namely 3.40 %. According to SNI 01-6235-2000, a good water content value is less than 8 % based on the briquette quality standards. The results of the water content test show that all palm shell charcoal briquettes made through the activation and non-activation processes in this study meet SNI standards.

Ash content

Ash content is the residue remaining after combustion, which no longer contains carbon. Inorganic substances that are not burned will remain behind and

become ash. Briquette ash content is the remaining part of the briquette combustion. The ash content is silica, which influences the calorific value produced in the briquettes. The high or low ash content in briquettes is influenced by the high content of inorganic materials contained in biomass waste and the level of adhesive used in making briquettes. Low ash content will produce good-quality charcoal briquettes. The test results in Table II show that the ash content value of the palm shell charcoal briquettes produced ranges between 6.94–7.86 %. The treatment of variations in activation power on palm shell charcoal significantly influences the ash content of charcoal briquettes. Increasing the activation power will cause an increase in the ash content of palm shell charcoal briquettes. The increase in ash content is caused by microwave heating that causes decomposition of organic material, therefore lowering the content of organic compounds in charcoal and increasing the ash content after burning. The ash content value in charcoal briquettes is also influenced by the raw materials used in the briquette. Materials that contain high levels of silica can cause high ash content, resulting in lower briquette quality.[6] The presence of excessive ash can also cause a decrease in heating value. The ash content value in palm shell charcoal briquettes with the activation time parameter. Table III shows that briquettes made with charcoal activated using a microwave at a fixed power of 150 W, have a value range of between 7.34–7.68 %. The highest ash content value was 7.68 % in the activation treatment, with an activation power of 150 W for 600 s. Ash content value increases significantly as the activation time increases. According to SNI 01-6235-2000, a good ash content value is less than 8 % based on the briquette quality standards. The ash content test results show that all treatments in this study meet SNI standards.

Volatile matter

Volatile matter can evaporate due to the decomposition of compounds still present in charcoal other than water, ash, and bound carbon.[23] The volatile matter content of palm shell charcoal briquettes ranged from 8.19 to 10.10 % (Table II), decreasing with increased activation power due to the higher heat energy driving off volatile substances. Similarly, Table III shows that longer activation times at 150 W led to a slight decrease in volatile matter (8.91–8.40 %), attributed to decomposition of volatile compounds at higher temperatures. The lowest value (8.19 %) was obtained at 230 W for 480 s, indicating efficient activation. All values met the SNI 01-6235-2000 standard, which recommends volatile matter content below 15 %. Lower volatile content enhances combustion efficiency and reduces smoke.[18]

Fixed carbon

The fixed carbon is the carbon fraction bound in charcoal apart from the water, ash, and volatile matter fractions. The main content of fixed carbon is carbon. The

water content, ash content and volatile matter values influence fixed carbon. The test results in Table II show that the fixed carbon value, of the palm shell charcoal briquettes produced, ranges 78.60–80.64 %. Table II shows that increasing the activation power will cause the fixed carbon content of palm shell charcoal briquettes to increase slightly. This is due to the decreasing values of water, ash and volatile matter content, which will cause an increase in fixed carbon levels. The lower the moisture, ash and volatile matter, the higher the fixed carbon content will be. The process of activating palm shell charcoal briquettes using a microwave can produce increased ash content that can affect the fixed carbon content. The fixed carbon value in palm shell charcoal briquettes, with the activation time parameter in Table III, shows that briquettes made with charcoal activated using a microwave at a fixed power of 150 W have a value range of 79.99–80.52 %. The fixed carbon value tends to increase slightly as the activation time increases. This is caused by the long activation process, which causes the decomposition or breakdown of the compounds in the carbonized material, increasing the fixed carbon content of the charcoal briquettes. The results of testing the fixed carbon content of palm shell charcoal briquettes showed that all treatments in this study met the SNI 01-6235--2000 fixed carbon standard (>77 %) with the best-fixed carbon value found in the 230 W activation treatment for 480 s, namely 80.64 %.

Activated charcoal surface morphology

SEM-EDS to characterized activated charcoal surface morphology analysis. The following is a picture of the morphological changes in charcoal without activation and charcoal activated with variations in microwave power (Fig. 2).

Fig. 2 shows the surface morphology of activated palm shell charcoal, which has a rough and irregular pore surface. Fig. 2B, charcoal activated with 70 W power for 480 s has new pores that are smaller. Charcoal activated with 150 W power for 480 s has larger pores (Fig. 2C). Meanwhile, in Fig. 2D, activated charcoal with 230 W of power for 480 s causes several pores to merge so that the number seems to decrease.

Furthermore, the surface morphology of charcoal activated at 150 W for varying times is shown in Fig. 3. In comparison to non-activated charcoal, the surface looks smoother and has fewer, uniformly spaced pores at 360 s (Fig. 3A). The pores start to grow after 480 s (Fig. 3B), and some of them start to combine at 600 s (Fig. 3C). The emergence of new pores and changes in the number and average diameter due to activation plays an important role, where porous charcoal easily binds adhesives in making briquettes homogeneous. In addition, the presence of pores will also provide enough space to trap the oxygen needed in burning briquettes. Activated charcoal materials for making briquettes must be tested for their safety against their potential for air pollution during combustion. EDS characterization is carried out to check whether the charcoal contains sulfur as a pollutant.

In Fig. 3, the activation time dramatically affects the structure and size of the carbon pores. The longer the activation time, the better the carbon pores produced, but if the activation time is increased again, the pore size will be more prominent.

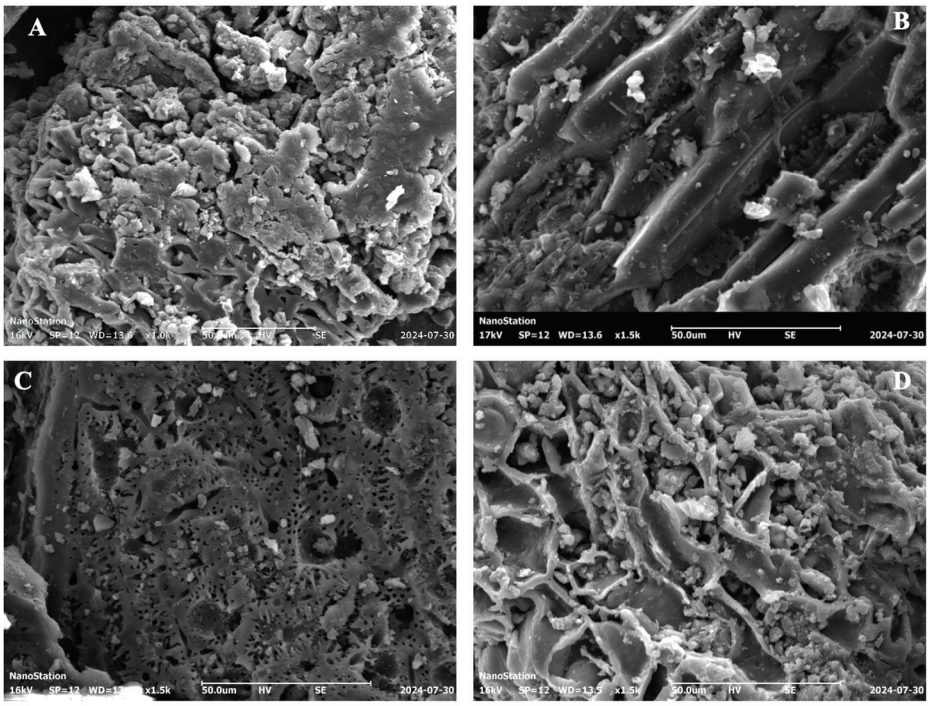

Fig. 2. Surface morphology of charcoal without activation (A) and charcoal activated by microwave for 480 s at: 70 (B), 150 (C) and 230 W (D).

Table IV shows that the weight composition of charcoal without activation. The predominant constituents are generally carbon and oxygen, though they can vary based on the activation circumstances. At lower power (*e.g.*, 70 W), microwave activation often increased carbon content; at higher power or longer exposure times; however, carbon content decreased, most likely as a result of structural oxidation. While activation at 150 W for 480 s revealed a lower carbon percentage (78.55 %) and higher oxygen content (showing more intensive oxidation), the sample activated at 70 W for 480 s had the highest carbon content (89.22 %), indicating negligible deterioration. Interestingly, no sulfur was found in any of the samples, indicating that burning the briquettes is safer for the environment. Furthermore, the increased ash content seen in proximate analysis is consistent with a slow rise in silicon and calcium in activated samples.

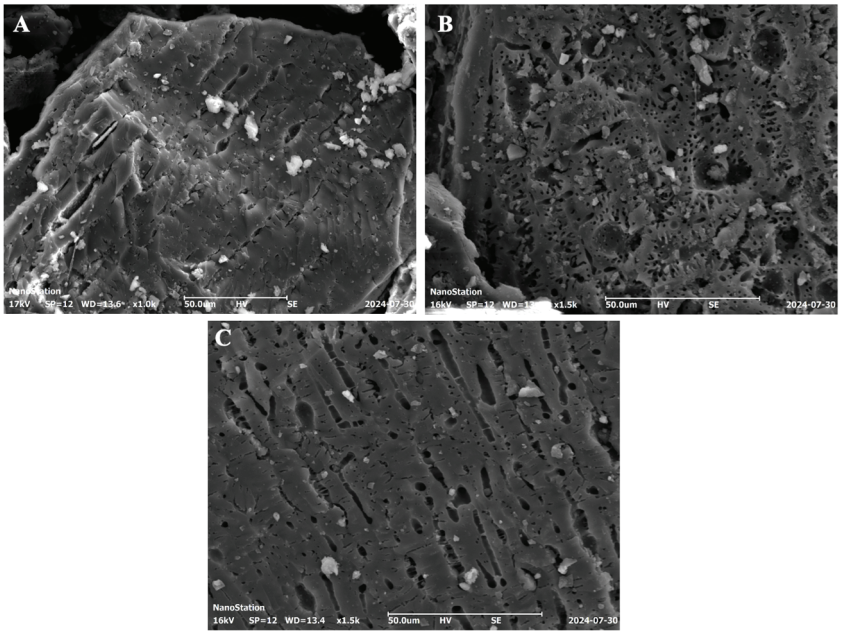

Fig. 3. Microwave at power activates the surface morphology of charcoal for 360 (A), 480 (B) and 600 s (C).

TABLE IV. Chemical composition of palm shell charcoal (*Elaeis guineensis* Jacq.)

Sample	Element	Amount, wt. %
Without activation	C	83.67±0.19
	O	15.62±0.12
	Ca	0.31±0.02
	K	0.29±0.02
	Si	0.09±0.00
	Al	0.01±0.06
Charcoal activated by microwave for 480 s at 70 W power	C	89.22±0.18
	O	8.88±0.09
	F	0.55±0.03
	K	0.42±0.05
	Ca	0.33±0.02
	Si	0.29±0.03
Charcoal activated by microwave for 480 s at 150 W power	C	78.55±0.13
	O	18.62±0.13
	Si	0.75±0.05
Charcoal activated by microwave for 480 s at 230 W power	C	83.19±0.22
	O	15.98±0.18
	F	0.37±0.02
	K	0.18±0.02
	Si	0.15±0.01

TABLE IV. Continued

Sample	Element	Amount, wt. %
Charcoal activated by microwave for 360 s at 150 W power	C	86.40±0.13
	O	10.80±0.20
	F	0.59±0.02
	K	0.46±0.03
	Si	0.36±0.03
Charcoal activated by microwave for 480 s at 150 W power	C	78.55±0.07
	O	18.62±0.07
	Si	0.75±0.03
	Ca	0.69±0.04
Charcoal activated by microwave for 600 s at 150 W power	C	81.03±0.13
	O	15.77±0.09
	Ca	1.56±0.06
	Si	0.51±0.05

EDS characterization shows that the absence of sulfur elements indicates that palm shell charcoal is safe to use during combustion without producing air pollutants. In addition, this characterization strengthens the proximate test of fixed carbon shown in Tables II and III. EDS characterization also shows an increase in Si content in activated carbon; this strengthens the proximate test of ash content, as shown in Table II and III.

Fourier transform infrared spectroscopy (FTIR)

The FTIR characterization results are shown in Fig. 4. The bands observed at approximately 3420 cm^{-1} are attributed to the hydroxyl group (O–H) vibration, consistent with the previous studies.[32] Absorption bands near 1035 cm^{-1} correspond to the C–O bond vibration, indicating the presence of alcohol groups.[33] A distinct double absorption band around 2920 cm^{-1} is associated with the Csp^3-H bond vibration (alkane), confirming the presence of alkane groups. Further, the methylene group (CH_2) vibration is evident around 1450 cm^{-1}, supporting the alkane presence. The carbonyl group (C=O) is identified by sharp absorption bands around 1735 cm^{-1}, and a band around 1600 cm^{-1} is consistent with C=C stretching in alkenes.[34] Additionally, the most intense absorption, between 570 and 600 cm^{-1}, likely corresponds to halogen compounds (C–X) or silicon oxide (Si–O) vibrations.[35]

FTIR results show that the activation process affects the functional groups present on the charcoal surface, especially in strengthening the presence of hydroxyl and alcohol groups, as well as increasing the complexity of inorganic groups. Microwave activation also has the potential to improve the chemical characteristics of charcoal for adsorption or energy applications, depending on the power and duration of treatment. The finding generated by O–H and C=O groups have indicated that there has been an increase in the oxygen-containing functional groups,

the existence of which affects the adsorption property through making such surfaces more polar. The indication concerning changes in peak intensity and existence of either Si–O bonds or C–X can also represent changes in pore structure and chemical composition upon activation. Such a relationship would suggest that microwave activation modifies not only the physical structure but also changes the chemical functionality of the material (as is shown by FTIR), which both complementarily influence the adsorption performance.

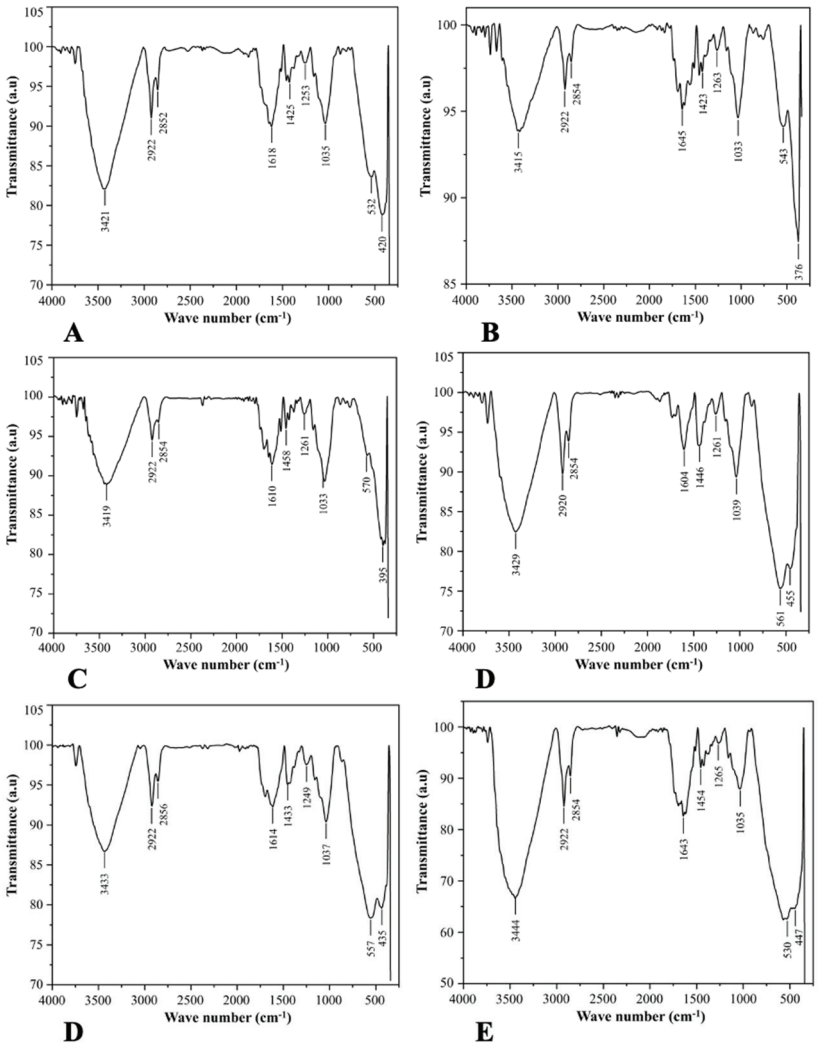

Fig. 4. FTIR spectra of palm shell charcoal (*Elaeis guineensis* Jacq.): sample 1 (without activation, A), charcoal activated by microwave: sample 2 (for 360 s at 150 W power, B), sample 3 (for 480 s at 70 W power, C), sample 4 (for 480 s at 150 W power, D), sample 5 (for 480 s at 230 W power, E) and sample 6 (for 600 s at 150 W power, F).

This study basically hinges around palm shell charcoal being the main precursor as it is plentiful and has a very low price coupled with very good adsorbing properties. The deciding factor for selecting this precursor was that it is high in carbon content and structurally compatible for activation. For example, coconut shell-based apparatus, wood-based biomass and agricultural residues. In addition to those, the FTIR spectrum from this work has revealed several functional groups such as O–H, C–O, Csp^3-H, CH_2, C=O, C=C and C–X or Si–O. Astuti (2020)[28] carried out research on palm kernel shell activated with $ZnCl_2$ and similarly found functional groups C–H, aliphatic C–O and aromatic C=C. The variation in FTIR was thus due to the activation methods, choice of activating agents, and precursor materials that have had significant influence on the physical and chemical property of activated carbon produced. Therefore, further optimization of method of activation is also necessary to improve the surface area of activated carbon and the adsorption characteristics of activated carbon produced in this study.

CONCLUSION

The study results indicate that an increase in microwave power and activation time play a significant role in affecting the physical and chemical properties of palm shell charcoal briquettes. Increased power and activation time increase the ash content, fixed carbon and density while diminishing both water content and volatile matter. Microwave activation increases pore formation, thus improving the properties and efficiency of combustion with an even more uniform and well-distributed porous structure, which allow better performance on adsorption properties. The absence of sulfur passes inspection through EDS characterization; hence the briquettes prove to be environmentally friendly and safe as they do not contribute to any air pollution caused by sulfur. Furthermore, there is an FTIR characterization to verify the presence of functional groups that include O–H, C–O, Csp^3-H, CH_2, (C–X) or silicon oxide (Si–O), C=O, as well as C=C that affect the chemical reactivity and potential adsorption of the material. It was observed that, upon the presence of oxygen-containing functional groups, activated palm shell charcoal can be used under high adsorption capacity applications, such as gaseous purification, effluent treatment, and industrial filtration. Besides combustion improvements, palm shell charcoal can also be considered an alternative fuel for household and industrial energy purposes with a reduced dependency on conventional fossil fuels. The developed porous structure generally is of high importance in increasing adsorption capacities, making the material suitable for removing contaminants, heavy metals or organic pollutants from water and air. Its functionalized surface chemistry also suggests future potential exploitation as a catalyst carrier in chemical processes, especially for biofuel production and environmental cleanup. In the agricultural sector, the material can serve as biochar in improving soil fertility and carbon sequestration. Microwave-activated palm shell charcoal indicates

great potential for variety applications in industries and environment, leaving room for more optimization and larger scale utilization. Future studies could focus on the long-term stability and economic feasibility of this material under practical conditions.

SUPPLEMENTARY MATERIAL

Additional data and information are available electronically at the pages of journal website: https://www.shd-pub.org.rs/index.php/JSCS/article/view/13028, or from the corresponding author on request.

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И З В О Д

УТИЦАЈ СНАГЕ МИКРОТАЛАСА И ВРЕМЕНА ОБРАДЕ НА КВАЛИТЕТ УГЉЕНИХ БРИКЕТА ОД ЉУСКИ ПАЛМЕ (*Elaeis guineensis* JACQ.)

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Један од праваца развоја обновљивих извора енергије је употреба биомасе. Циљ овог истраживања је да се анализира утицај снаге (70, 150 и 230 W) и времена активације угља од палминих љуски микроталасима током различитих временских интервала (360, 480 и 600 s) на густину, влагу, садржај пепела и испарљиве материје угљених брикета од љуски палме. Угљени брикети су добијени процесом карбонизације на температури од 548,7 °C током 6 h, млевењем и просејавањем на 80–100 mesh, активацијом помоћу микроталаса у фиксном временском интервалу од 480 s са варијацијама снаге активације од 70, 150 и 230 W, као и активацијом са фиксних 150 W уз варијације времена активације од 360, 480 и 600 s. Резултати истраживања су показали да се густина угљених брикета од палминих љуски кретала од 0,51–0,54 g/cm^3, садржај воде од 3,31–3,92 %, садржај пепела од 7,13––7,86 %, а испарљиве материје од 8,19–9,22 %. СЕМ карактеризација показује да микроталасна активација равномерно повећава број пора и увећава поре. Према резултатима истраживања, снага и време активације значајно побољшавају квалитет угљених брикета од љуски палме.

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