

RESEARCH ARTICLE

Microwave torrefaction of sawdust as biomass energy source

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Abstract - Sawdust is a lignocellulosic waste generated from timber-processing activities and has potential as a renewable solid fuel. However, its direct use is limited by high moisture content and volatile matter, which reduce its fuel quality. This study aimed to enhance the chemical characteristics and fuel properties of sawdust through microwave-assisted torrefaction. Torrefaction was carried out under an oxygen-free nitrogen atmosphere at a microwave power of 1000 W. The effects of residence time, varied at 5, 10, 20, and 30 min, and nitrogen flow rate, varied at 30, 60, and 90 mL/min, were investigated. The torrefied sawdust was evaluated based on physical appearance, proximate properties, carbon content, and higher heating value (HHV), which refers to the total heat released during complete combustion of a fuel, including the latent heat recovered from water vapour condensation. The results showed that microwave torrefaction changed the colour of sawdust from light brown to nearly black, indicating carbon enrichment and volatile matter removal. The process reduced moisture content by 28%, increased HHV by 50%, and enhanced carbon content by 60%. These improvements were attributed to the thermal decomposition of biomass constituents and the release of volatile compounds during torrefaction. In conclusion, microwave-assisted torrefaction effectively improved the fuel quality of sawdust, suggesting that torrefied sawdust has strong potential as a renewable solid fuel for energy applications.

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1. Introduction

Malaysia is rich in biomass resources, primarily due to its tropical climate and extensive agricultural activities. The primary sources of biomass in Malaysia include oil palm, rice, forestry and other agricultural biomass. Oil palm biomass is the dominant source of biomass in Malaysia, followed by rice residues and forestry waste [1]–[2]. It is estimated that Malaysia generates approximately 9.83 million m³ of wood residues annually, including sawdust, slabs, wood chips, bark, and wood fragments from activities such as logging, primary processing, plywood production, and other related operations [3]. Wood waste generation can reach up to 45% when the furniture industry processes 1 ton of wood [4]. This wood waste can be recycled into a beneficial product that can help the future of the world, rather than being burned directly. It helps reduce environmental pollution and hazardous gas emissions that contribute to climate change. Sawdust can be converted to alternative energy sources that can replace fossil fuel and charcoal via the torrefaction process [5]–[7]. It can be an environmentally friendly fuel. However, sawdust cannot be used directly as fuel because it contains higher moisture content, lower energy and heating values, and other factors [8]–[9]. Therefore, sawdust needs to undergo torrefaction to improve its properties before it can be used as fuel. Torrefaction aims to enhance the energy yield produced after the process by reducing the relative amounts of oxygen and hydrogen compared with carbon [10]. Torrefaction involves a heating process of raw material at a temperature range between 200–300 °C and employs a low heating rate process (<50 °C/min) with the presence of nitrogen in an inert atmosphere [11]–[12]. This process shows significant improvement in sawdust properties, including good hydrophobicity, as it will not readily absorb water and can be kept in the long term [13]. It also helps increase the heating values, carbon content and energy density as the volume of sawdust decreases [10].

A recent study has focused on microwave torrefaction, which offers advantages over conventional heating, such as rapid, uniform heating that can reduce residence time by approximately 60–80% and promote faster chemical reactions [14]. Microwave heating enables volumetric heating by penetrating the material and distributing energy more evenly throughout the sample [15]. In this study, microwave torrefaction was used to improve the chemical composition and energy potential of sawdust for use as an energy source. Further analysis, including higher heating value (HHV), mass yield, energy yield and proximate analysis, was investigated on the torrefied sawdust by studying the effect of microwave torrefaction parameters, which are residence times and flow rate of nitrogen gas at the microwave power of 1000 W. This study aims to upgrade the quality of torrefied sawdust to become one of the potential alternatives of energy source.

2. Materials and Methods

2.1 Materials and Sample Preparation

Sawdust was collected at Seng Peng Sawmill Sdn. Bhd., Gambang, Pahang, Malaysia. The sample was dried overnight at 105 °C in the oven to remove moisture. The dried sawdust was ground using a mechanical grinder and sieved using a laboratory sieve shaker fitted with a 0.5 mm mesh sieve to obtain a uniform particle size.

2.2 Experimental Method

A 1 g portion of sawdust was placed in the reactor, which was subsequently inserted into the microwave oven (Samsung 28 L MS28J5255GB). The system was purged with nitrogen (99.9% purity) at 30 mL/min for 5 min to remove residual impurities. Microwave torrefaction was then carried out at a constant power of 1000 W for residence times of 5, 10, 20, and 30 min. The torrefied sawdust was collected after the reactor reached ambient temperature. A separate experiment was also conducted by varying the nitrogen flow rate from 30 to 90 mL/min while maintaining the microwave power at 1000 W and the treatment time at 20 min. The torrefied samples were evaluated for mass change and colour variation. Further analyses, including mass and energy yield, higher heating value, and proximate analysis, were performed on the final products. Figure 1 shows the apparatus arrangement employed in this work.

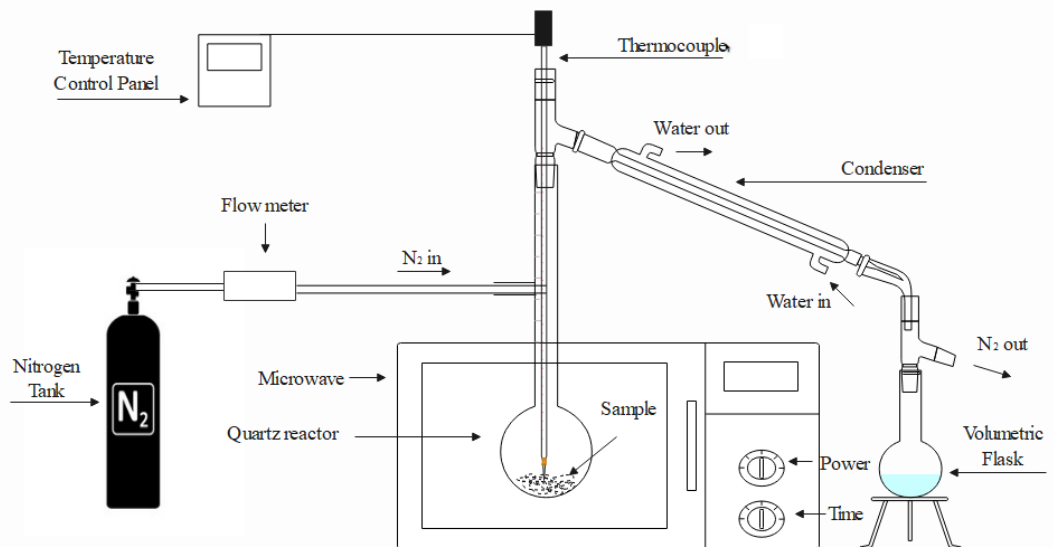


Figure 1. Schematic diagram of microwave torrefaction

2.3 Torrefied Sawdust Characterisation

Both raw and torrefied sawdust were evaluated for HHV, proximate properties, and mass and energy yields. The HHV was measured using a bomb calorimeter to assess the energy content and overall fuel quality of the torrefied material. Proximate analysis was conducted using a thermogravimetric analyser (TGA) (Q500-0617). For each analysis, approximately 10 mg of the sample was heated in nitrogen from ambient temperature to 900 °C at a constant heating rate of 10 °C/min. The proximate components were determined from the corresponding weight-loss regions and the residual mass obtained from the TGA profile. Mass and energy yield were then calculated using Eqs. (1) and (2), respectively [16].

$$\text{Mass Yield } (Y_M) = \frac{\text{Mass torrefied}}{\text{Mass before torrefied (raw)}} \times 100\% \quad (1)$$

$$\text{Energy yield } (Y_E) = Y_M \times \frac{\text{HHV torrefied sample}}{\text{HHV before torrefied (raw)}} \times 100\% \quad (2)$$

3. Results and Discussion

3.1 Effect of Residence Time on Torrefaction of Sawdust

Figure 2 shows the appearance of raw and torrefied sawdust after the experiment with different residence times at a constant power of 1000 W. The colours of the raw and torrefied sawdust changed from light brown to slightly brown after 5 min of torrefaction. The colours of the raw and torrefied sawdust changed from light brown to slightly brown after 5 min of torrefaction, and then from 10 min to 20 min before becoming slightly black at 30 min of torrefaction. The temperature increased to 130 °C, 174 °C, 196 °C and 215 °C at 5, 10, 20 and 30 min, respectively, under a fixed microwave power of 1000 W. The rise in temperature with increasing residence time promoted thermal decomposition of the more reactive biomass fractions, particularly hemicellulose, as indicated by the reduction in volatile matter content in Figure 4. Correspondingly, the fixed carbon content increased with torrefaction time, reaching its highest value at 30 min (as shown in Figure 4), which is consistent with the darker appearance of the torrefied sawdust. The observed colour changes agree well with earlier findings [17].

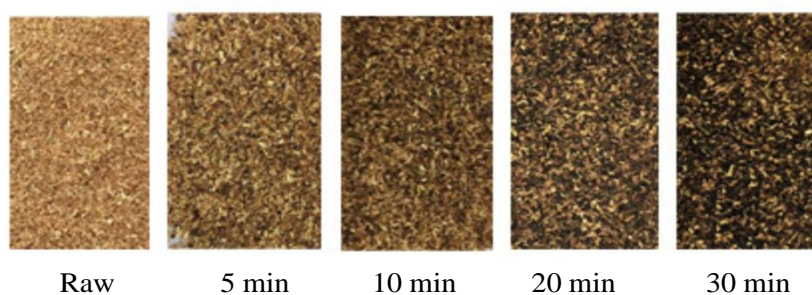


Figure 2. Appearance of raw and torrefied sawdust at different residence times

3.2 Mass Yield, Energy Yield and Higher Heating Value

Figure 3 shows a clear decline in solid product recovery as torrefaction duration increases. The mass yield decreased from 99.10% at 5 min to 77.20% at 30 min, indicating that prolonged microwave treatment led to greater loss of solid material. A similar pattern has been reported for other lignocellulosic feedstocks; for instance, oat hulls showed a mass yield of only 60.77% at extended residence time during microwave torrefaction [18]. This behaviour is primarily due to the breakdown of thermally unstable biomass fractions, particularly hemicellulose and cellulose [19]. Their decomposition releases water vapour and gaseous products, such as CO and CO₂, thereby reducing the remaining char mass [13]. A comparable trend was observed for energy retention. The energy yield, which describes how much of the initial energy in the raw sawdust is retained in the torrefied product, decreased from 99.04% to 96.38% as the residence time increased from 5 to 30 min. This reduction is associated with the progressive degradation of hemicellulose during torrefaction [20]. In contrast, the fuel quality of the solid product improved as treatment time increased. More severe torrefaction conditions promoted the removal of volatile compounds, leading to a material with lower oxygen and hydrogen contents and a relatively higher carbon fraction [21]–[23]. As a result, the higher heating value increased from 20.21 MJ/kg for the untreated material to 25.24 MJ/kg after 30 min of torrefaction, as presented in Table 1.

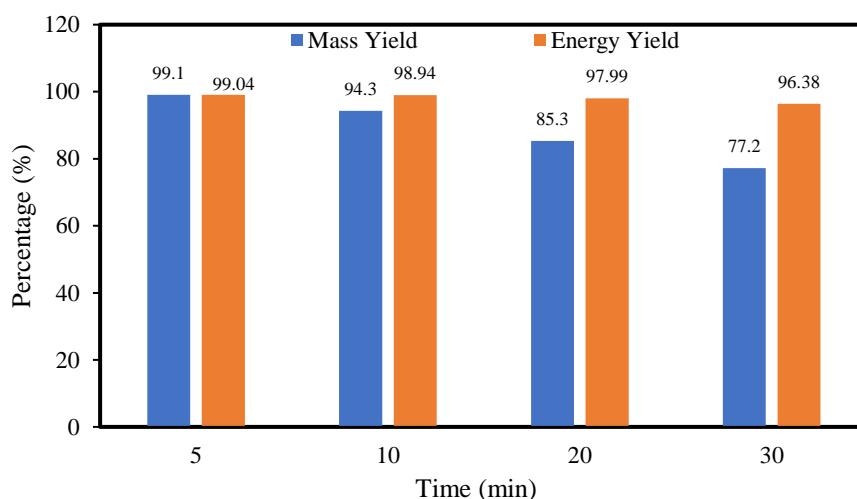


Figure 3. Mass and energy yield (%) of sawdust at different residence times

Table 1. HHV at different residence times

Residence Time (min)	Temperature (°C)	HHV (MJ/kg)
Raw	-	20.21
5	130	20.20
10	174	21.21
20	196	23.22
30	215	25.24

3.3 Proximate Analysis

Figure 4 presents the proximate characteristics of raw and torrefied sawdust at different residence times. Compared with the raw material, the torrefied sawdust showed a reduction in moisture content and volatile matter from 6.92% and 70.00% to 5.02% and 64.75%, respectively. In contrast, the fixed carbon and ash content increased from 6.81% and 16.27% in raw sawdust to 10.87% and 19.36%, respectively, as the residence time increased. The decrease in moisture content was mainly attributed to the removal of residual water that remained after oven drying prior to torrefaction. This reduction is beneficial because it reduces the risk of biological degradation and improves the hydrophobicity of the torrefied material

[19,24]. In addition to moisture reduction, volatile matter declined as torrefaction severity increased, with higher temperatures and longer residence times. Previous studies have shown that volatile loss is strongly influenced by biomass composition [12,25]. Biomass containing a higher proportion of hemicellulose generally experiences greater volatile release because hemicellulose is the most thermally reactive component during torrefaction [12,26]. Volatile matter refers to compounds that release gas readily when heated under oxygen-free conditions, whereas fixed carbon is the carbon-rich solid remaining after devolatilization [13,27]. As moisture and volatile matter were progressively removed during torrefaction, the fixed carbon content of the sawdust increased. This trend can be associated with the longer treatment time and higher torrefaction temperature. A higher fixed carbon fraction indicates better fuel quality and a greater potential heat of combustion [12,28]. Under favourable torrefaction conditions, torrefied sawdust may achieve HHV values in the range of 22 to 25 MJ/kg, which are comparable to those of coal [6,29]. Therefore, torrefied sawdust has strong potential as an alternative solid fuel for energy applications. The ash content also increased after torrefaction. This was mainly due to changes in biomass composition during thermal treatment. As the organic fraction decomposed and mass was lost, the inorganic components remained in the solid residue, leading to a higher ash concentration in the torrefied product [30]–[31].

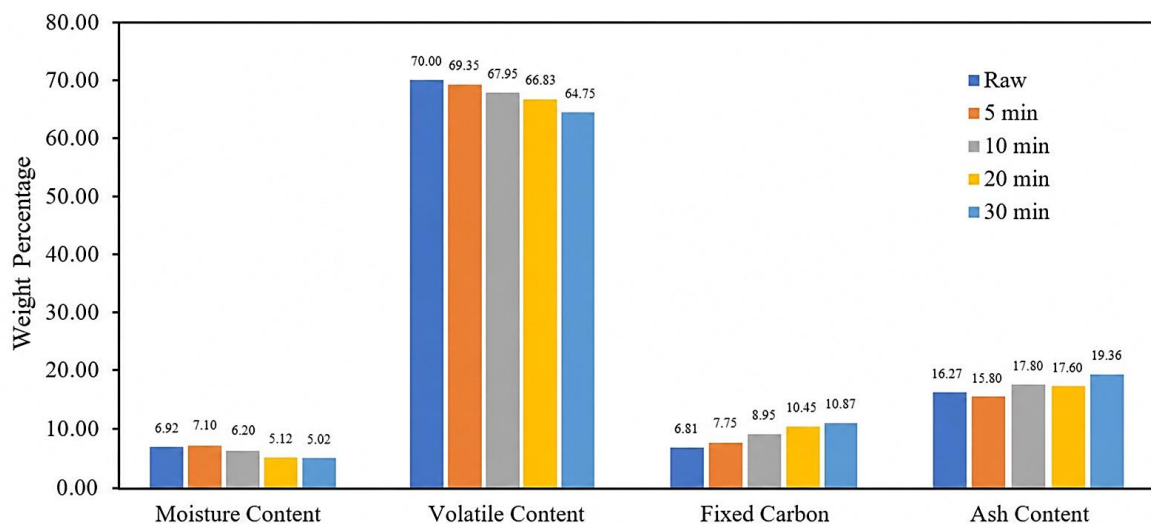


Figure 4. Proximate analysis at a different residence time

3.4 Effect of Nitrogen Flow Rate

Figure 5 shows that increasing the nitrogen flow rate from 30 mL/min to 90 mL/min increased the carbon content of the torrefied sawdust, as indicated by a colour change from slightly brown to darker black at a constant residence time of 20 min. The mass yield of torrefied sawdust under various nitrogen flow rates of nitrogen is tabulated in Table 2. It was found that the mass yield of torrefied sawdust decreased from 85.30% to 75% as the flow rate increased from 30 mL/min to 90 mL/min. Increasing the gas flow rate agitates and evenly distributes the sample; thus, the torrefaction process occurs throughout the sample rather than at a single spot. As part of the mass yield, Table 2 indicates the HHV of torrefied sawdust under various nitrogen flow rates. It was observed that the HHV increased from 23.22 MJ/kg to 30.29 MJ/kg as the nitrogen flow rate increased from 30 mL/min to 90 mL/min. This increase may be attributed to the higher fixed-carbon content of the torrefied sawdust produced at 90 mL/min. The higher HHV at increased nitrogen flow rates may also be associated with the enhanced degradation of hemicellulose components during torrefaction [32].

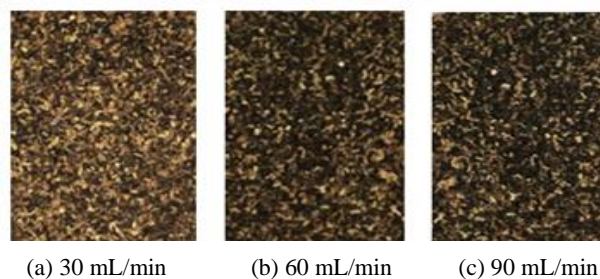


Figure 5. Appearance of the torrefied sawdust sample at a different flow rate of nitrogen (a) 30 mL/min, (b) 60 mL/min and (c) 90 mL/min

Table 2. Mass yield and HHV at different nitrogen flow rates

Nitrogen flow rate (mL/min)	Temperature (°C)	Mass yield (%)	HHV (MJ/kg)
30	196	85.30	23.22
60	201	79.00	27.26
90	210	75.00	30.29

4. Conclusions

This work successfully assessed the chemical and energy-related improvements in microwave-heated sawdust torrefied at 1000 W across a range of residence times and nitrogen flow rates. Increasing the residence time in the torrefaction process from 5 to 30 min can improve the quality of torrefied sawdust. The fixed carbon content increased from 7.75 to 10.87%, thereby increasing the HHV with increasing residence time. It was observed that the HHV increased from 23.22 MJ/kg to 30.29 MJ/kg as the nitrogen flow rate increased from 30 mL/min to 90 mL/min. The increase in flow rate improved agitation and evenly heated the samples during torrefaction. In conclusion, microwave torrefaction improved the quality of sawdust at 20 min and 1000 W of microwave power, with a nitrogen flow rate of 90 mL/min, resulting in a 50% increase in HHV.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRedit Authorship Contribution Statement

F. A. Abd Rahim and N. D. Faridon contributed to the conceptualisation, methodology, investigation, formal analysis, and writing of the original draft.

M. Ismail and R. Abdul Rasid contributed to the conceptualisation, supervision, review, and editing of the manuscript. A. Kadri and N. S. Engliman contributed to the review and editing of the manuscript.

Availability of Data and Materials

The data and materials used in this study are available from the corresponding author upon reasonable request. No source code was generated or used in this research.

Ethics Statement

This study did not involve any human participants, animal subjects, or sensitive data. Therefore, ethical approval and informed consent were not applicable.

Generative Artificial Intelligence Declarations

The authors used OpenAI ChatGPT and Scopus AI for language editing and literature support. All scientific interpretations, results, and conclusions remain the responsibility of the authors.

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