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Engineering char production from mushroom bag log waste

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Abstract

Oyster mushrooms are one of Indonesia's most widely consumed horticultural commodities, which consequently generates large quantities of spent mushroom substrate (baglog waste) that may cause environmental pollution if not properly managed. One promising utilisation pathway is carbonisation into char, which offers added value as both an energy source and a substrate for mushroom cultivation. This study aimed to produce char from oyster mushroom baglog waste and to evaluate its characteristics. The waste was collected from mushroom farmers in Indralaya Utara, Ogan Ilir, and sun-dried for one to three days. Carbonisation was carried out in a drum kiln at 300–350 °C for two hours. The resulting char was assessed for quality parameters, including moisture content, ash content, volatile matter, fixed carbon, and calorific value. The results indicated that three days of drying (T3) produced the lowest moisture content (20.5%), although with less consistent yield. Post-carbonisation, moisture content decreased significantly to 2.05–2.64% (adb) compared to the raw substrate (50.84%). Ash content increased to approximately 48.10% (adb), with T2 recording the lowest value (45.34%) and T3 the highest (50.80%). Volatile matter remained relatively high, yet T2 exhibited the lowest level (27.10% adb) and the highest fixed carbon content (25.51%). The calorific value ranged between 1960 and 2645 kcal/kg; T2 achieved the highest value (2645 kcal/kg), exceeding that of the raw substrate (2009 kcal/kg). Overall, oyster mushroom baglog waste demonstrates considerable potential to be converted into high-quality char, with T2 showing the most favourable performance as an alternative solid fuel.

Keywords: Carbonisation; Calorific value; Cultivation; Oyster mushrooms; Ulitisation

1. Introduction

Oyster mushrooms (*Pleurotus ostreatus*) have become one of the commodities that many Indonesians favour to meet their dietary needs. According to data from the Central Statistics Agency (BPS) in 2020, mushroom consumption in Indonesia reached 48 thousand tonnes and is projected to continue increasing [1]. However, this growing demand is accompanied by an expansion in mushroom production, which, if not properly managed, may give rise to environmental problems such as water and soil pollution. Moreover, the uncontrolled burning of spent baglog waste can cause air pollution and pose risks to human respiratory health.

Mushroom baglogs consist of agricultural and forestry residues such as sawdust, bran, and other materials with a high polysaccharide and lignin content, in addition to macromolecular organic compounds and mineral nutrients that can be recycled [2, 3, 4]. The oyster mushroom cultivation centre in Payakabung Village, Ogan Ilir Regency, is managed by the

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Payakabung Oyster Mushroom Farmers' Group under the guidance of PT PLN Indonesia Power UBP Keramasan UP Indralaya. Its farming activities generate considerable quantities of organic waste in the form of spent baglogs, which are currently underutilised and often discarded around the production site. These residues, however, are rich in lignocellulosic content and have strong potential to be converted into char through carbonisation.

The valorisation of mushroom baglog waste has been explored in various ways, including its conversion into organic fertiliser [5], char [6], fuel [7], biogas digester feedstock [8], and animal feed [9]. Among these, char stands out as a multifunctional material with excellent prospects for the utilisation of mushroom baglog residues [6, 10]. Compared with conventional substrates, char contains more carbon, exhibits a porous structure, and possesses greater cation exchange capacity, making it particularly suitable for supporting mushroom cultivation [11]. Furthermore, employing char as a substrate has been shown to optimise mushroom yields while offering greater economic value than the application of fertiliser [6, 12]. Thus, processing mushroom baglog waste into renewable char is seen as a more prospective recycling method. Research related to char has reduced potential environmental pollution while improving the efficiency of char recycling and the production value of mushrooms. This research aims to produce char from oyster mushroom baglog waste.

2. Material and Method

2.1. Materials

Oyster mushroom baglog waste was selected as the raw material for carbonisation and collected from mushroom farmers in Payakabung Oyster Mushroom Farmers Groups, Ogan Ilir Regency.

2.2. Collection and Pre-treatment of Oyster Mushroom Baglog Waste

Before the carbonisation process, oyster mushroom baglog waste was subjected to sun-drying treatments with varying durations of 1, 2, and 3 days. The waste was first sorted to remove impurities and coarsely broken down to ensure uniform exposure during drying. Each treatment utilised approximately 500 g of material per replicate, with three replicates conducted for each drying duration. The samples were spread evenly on a clean drying platform with a 2–3 cm thickness, placed in an open area with good air circulation, and exposed to sunlight between 08:30 and 15:30 local time. To maintain consistency, the materials were turned every 60–90 minutes to prevent clumping and ensure even evaporation. During the night or in the event of rain, the materials were covered with a tarpaulin to avoid reabsorption of moisture.

2.3. Char Production from Oyster Mushroom Baglog Waste

3 kg of dried baglog waste was placed into a carbonisation drum and heated at ±300 °C for 2 hours. The carbonisation process produced black char in granular powder form. The resulting samples were then cooled and subjected to parameter characterisation.

2.4. Characterisation Parameters

The parameters of char and baglog waste were determined according to ASTM D3173 (Moisture), ASTM D3174 (Ash), ASTM D3175 (Volatile Matter), Fixed Carbon calculated in accordance with ASTM D3172, and ASTM D5865 for Calorific Value (bomb calorimeter).

3. Results and discussions

3.1. Moisture Content after Drying

Activated char derived from post-harvest oyster mushroom baglog waste exhibited a moisture content of 62.5%, and the drying process was carried out in two replications, namely for 1 day [T1], 2 days [T2], and 3 days [T3]. The results indicated the best outcome after 3 days of drying. The test results of the moisture content of char from baglog waste samples are presented in Figure 1.

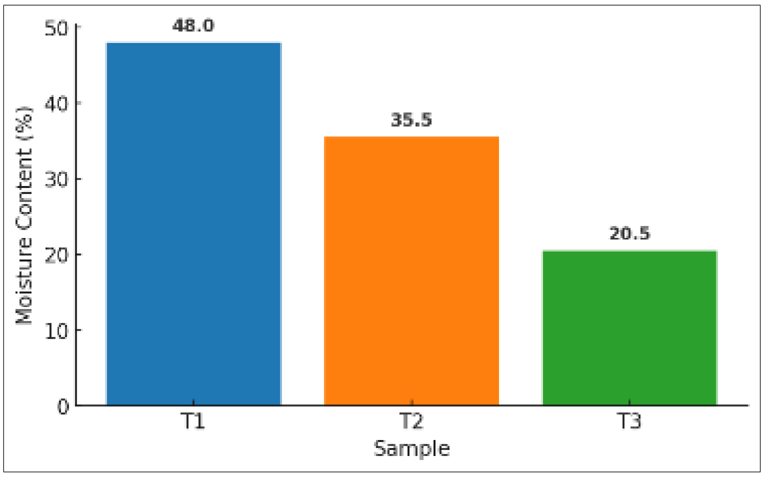

Figure 1 Average moisture content of mushroom baglog waste char

The activated char produced exhibited a deep black colour, a granular texture, and a low bulk density. Surface analysis using an optical microscope revealed good porosity, with the adsorptive surface area estimated to exceed 500 m^2/g. Treatment T3 yielded the lowest moisture content, namely 20.5% with a standard deviation of 0.14, making it the most consistent among the three treatments. Sunlight heating played a crucial role in reducing the moisture content of oyster mushroom baglog waste, both before and after the carbonisation process. The intensity of solar heat accelerated water evaporation from the activated carbon pores, although the outcome remained dependent on drying duration, material thickness, and weather conditions [13]. In T1 and T2, the moisture content remained high, likely due to the shorter drying duration or the stacking of materials during sun-drying, resulting in uneven evaporation [14]. T3 demonstrated a significantly lower moisture content, indicating that sun-drying in this treatment was more effective due to the longer duration or the thinner spread of materials, allowing for more uniform exposure to sunlight [15].

3.2. Char Yield from Carbonisation

Char Yield represents the ratio between the amount of char produced and the initial quantity of raw material. This value serves as an indicator of the efficiency of the carbonisation process. The higher the yield, the more optimal the conversion of biomass into char [16]. A high yield directly impacts productivity and profitability [17]. The average yield of char from oyster mushroom baglog waste is presented in Figure 2.

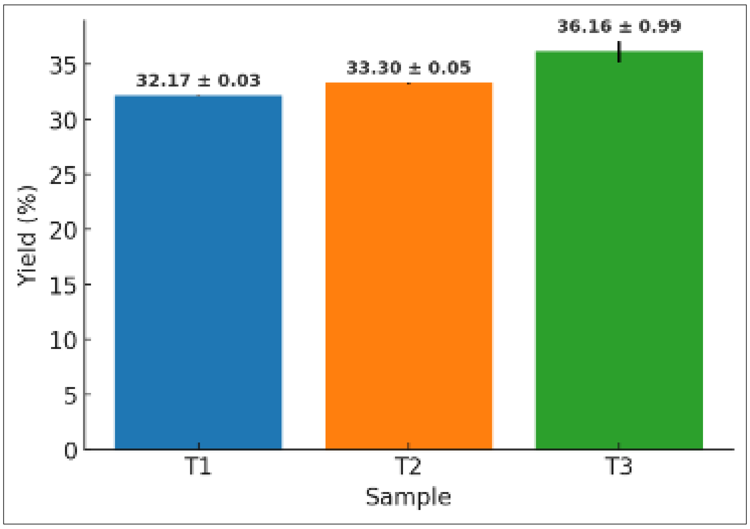

Figure 2 Average yield of char from mushroom baglog waste

Figure 2 illustrates that treatment T3 produced the highest yield, 36.16, compared with treatments T1 and T2. The higher yield in T3 may be attributed to the more optimal solar-heating treatment, which facilitated the release of volatile compounds while retaining the carbon fraction [18]. However, the considerable fluctuations among replications should be noted, as they may affect production consistency [19]. Treatments T1 and T2 demonstrated better stability, although their yields were lower than T3, making them suitable options when the production objective is to maintain uniform quality. Oyster mushroom baglog waste shows considerable potential as a raw material for activated carbon, as it can yield more than 30%. This indicates that the lignocellulosic residues in the baglog remain abundant and can be effectively utilised.

3.3. Moisture Content after Carbonisation

Figure 3 shows that the moisture content of the carbonised samples ranged from 2.05–2.64% (adb), with T1 recording 2.20%, T2 at 2.05%, and T3 at 2.64%. All of these values are considered low and are consistent with the characteristics of solid fuels, such as briquettes or coal, produced through an effective carbonisation process [20]. The slight variation among samples (±0.6%) is likely related to operational factors, including differences in temperature and carbonisation duration, the heterogeneity of raw material composition, and cooling conditions following the process [21]. Compared with the pre-carbonisation wet samples, which exhibited a moisture content of 50.84% (adb), it is evident that carbonisation significantly reduced the moisture level. This reduction is significant, as high moisture content is known to lower the calorific value, increase smoke production during combustion, and decrease the energy efficiency of solid fuels [22]. The average water content of char from carbonization is presented in Figure 3.

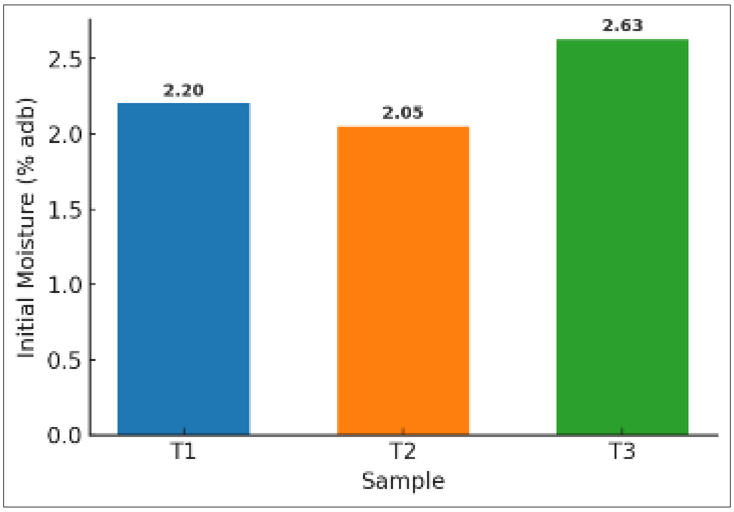

Figure 3 Average Water Content of Char from Carbonization

3.4. Ash Content

The analysis of ash content showed that the average ash content of the carbonised baglog waste samples reached approximately 48.10% (adb). Among the treatments, T1 exhibited the highest ash content (50.80%), followed by T2 (48.17%), while T3 recorded the lowest value (45.34%). This pattern indicates that the carbonisation process influenced the concentration of mineral fractions differently depending on the treatment applied [23]. The relatively high ash content is attributed to the concentration of inorganic minerals during carbonisation, as both moisture (IM) and volatile matter (VM) are significantly reduced, leaving ash as a concentrated fraction on an air-dried basis [24]. The reduction observed in T3 suggests that the longer or more uniform carbonisation conditions in this treatment may have enhanced the release of volatile matter while maintaining lower mineral retention, thus producing char with lower ash content [25].

From an energy perspective, ash is a non-combustible component that reduces fuel quality. High ash content can decrease the calorific value, impair combustion efficiency, and increase the risk of slagging and fouling in thermal systems [26]. Consequently, T3, with the lowest ash content, is likely to have better fixed carbon (FC) content and calorific value (CV) than T1, which showed the highest ash fraction. Therefore, although all treatments produced char with relatively high ash levels, T3 offers the most favourable balance for energy applications. The average ash content of the carbonization results is presented in Figure 4.

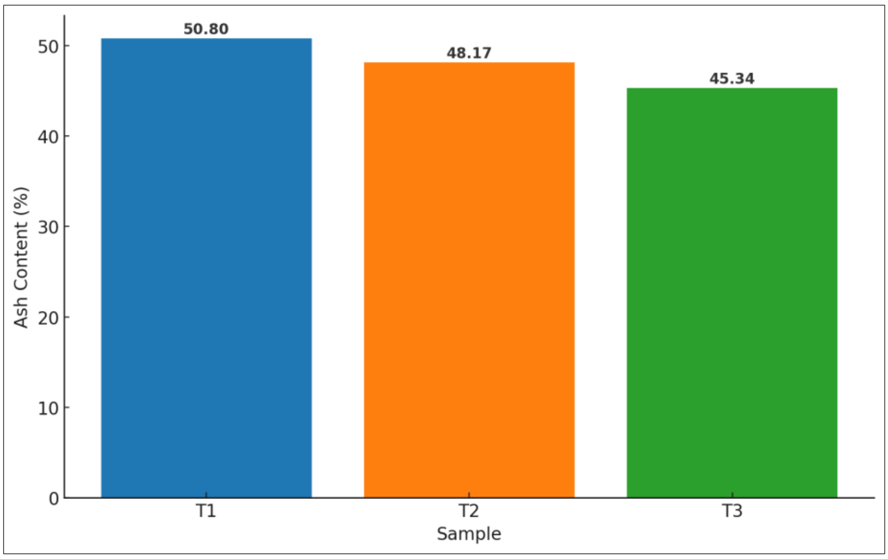

Figure 4 Average ash content of the carbonization results

3.5. Volatile Matter

The relatively high volatile matter (VM) content observed in samples T1, T2, and T3 indicates that the carbonisation process was carried out at sub-optimal temperatures and for a relatively short duration, resulting in a portion of volatile compounds such as tar, waxes, and light gases remaining trapped within the char. Carbonisation at higher temperatures generally reduces VM levels while increasing the fixed carbon (FC) fraction 27]. Among the three samples, T3 exhibited the lowest VM content at 27.10% (adb), suggesting a more effective degree of carbonisation compared with T1 (28.61%) and T2 (27.53%). Following carbonisation, both moisture and a proportion of volatile components were reduced. However, because the mineral fraction (ash) becomes concentrated and the processing conditions were insufficient to release all volatile compounds, the percentage of VM on an air-dried basis may appear higher than in the pre-carbonised wet samples [28]. This phenomenon is consistent with the characteristics of low-temperature carbonisation 15].

High VM levels generally produce a rapid flame but are accompanied by greater smoke and tar formation and lower combustion stability [29]. Conversely, lower VM content (as in T3) reflects cleaner and more stable combustion, a more efficient calorific value, and a reduced tendency for smoke and deposit formation [30]. Thus, optimising carbonisation temperature and duration is crucial to lowering VM content, enhancing FC and calorific value (CV), and ultimately improving combustion performance and the char quality [31].

3.6. Fixed Carbon (FC, % adb)

The fixed carbon (FC) content in the carbonised samples (T1–T3) showed a significant increase compared with the raw wet sample, rising from 7.76% to 19–25%. This increase indicates that the carbonisation process effectively decomposes moisture and reduces the volatile matter (VM) fraction, thereby making the fixed carbon proportion more dominant [32]. FC is a crucial parameter as it is directly associated with calorific value and the material's capacity to generate energy during combustion [33]. Average fixed carbon resulting from carbonization is presented in Figure 5.

Among the three samples, T3 exhibited the highest FC value at 25.51%, indicating the effectiveness of the carbonisation conditions in reducing volatile content and enriching the fixed carbon fraction. The higher the FC value, the better the char quality as a fuel, as it contributes to more stable combustion, longer burning duration, and greater energy availability. Thus, an increase in FC can be regarded as a key indicator of the success of the carbonisation process in producing high-quality solid fuel [34].

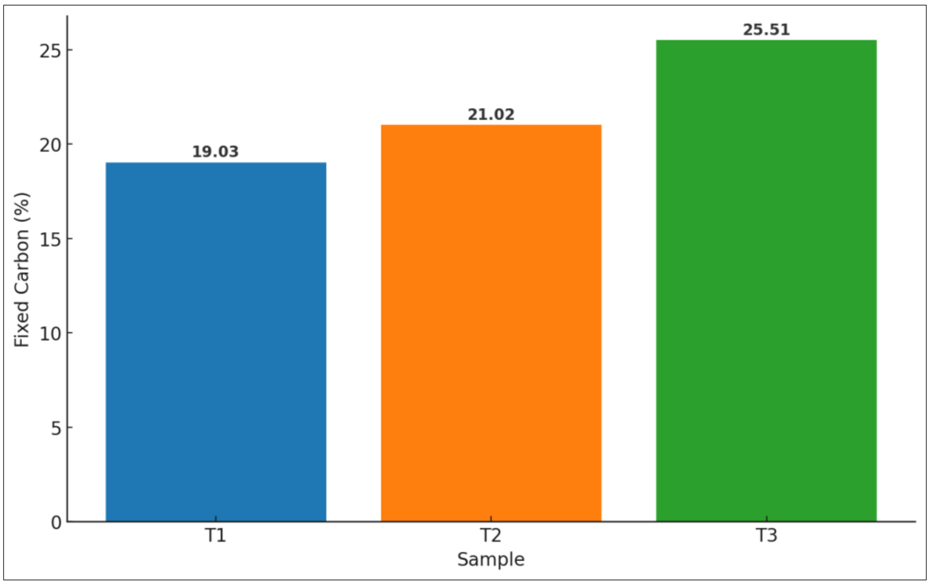

Figure 5 Average fixed carbon resulting from carbonization

3.7. Calorific Value (CV, kcal/kg; % adb)

In general, the carbonisation process enhances the calorific value (CV) as it reduces the initial moisture (IM) and volatile matter (VM) fractions, while simultaneously increasing the proportion of fixed carbon (FC). The test results indicated that the CV of the carbonised samples varied; some were higher than that of the raw sample, while others were lower. Sample T2 (2307 kcal/kg) and T3 (2645 kcal/kg) showed an increase compared with the raw sample (1960 kcal/kg), whereas T1 exhibited a decrease to 2009 kcal/kg. This condition suggests that the carbonisation of T3 was less optimal, possibly due to relatively low temperature, short heating duration, or uneven heat distribution, which prevented maximum energy conversion [35]. Calorific Value of Treatments is presented in Figure 6.

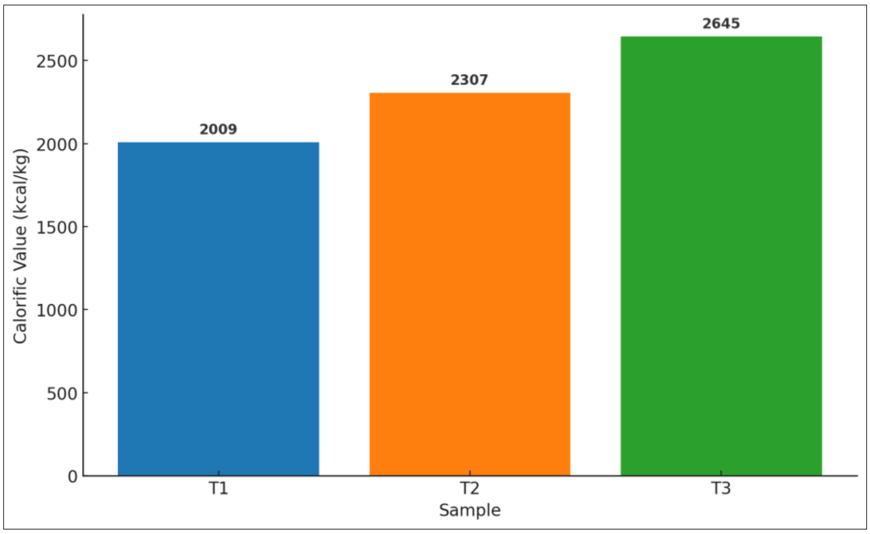

Figure 6 Calorific Value of Treatments

Figure 6 illustrates the average calorific value for each treatment. The fixed carbon (FC) increase correlated positively with calorific value, as observed in T2, which exhibited the highest FC (25.51%) alongside the highest CV. Conversely, high ash content tended to lower the calorific value, which is evident in T3, which recorded an ash content of 50.80% and the lowest CV. Low moisture content also contributed to improved CV, as demonstrated by T2, which had an IM of only 2.05%.

From the perspective of alternative energy, carbonised oyster mushroom baglog waste shows promising potential as a solid fuel. Sample T2 can be categorised as highly feasible as an alternative fuel, as its calorific value (>2600 kcal/kg) approaches that of certain types of low-rank coal. Sample T1 also demonstrated reasonably good quality, while T3 requires further optimisation of carbonisation conditions to enhance its energy performance.

4. Conclusion

This study demonstrates that oyster mushroom baglog waste holds considerable potential as a raw material for char production through a simple carbonisation process. The characterisation results revealed that pre-carbonisation drying treatments significantly affected the energy quality of the resulting char. Treatment T1 produced a calorific value of 2009 kcal/kg with the highest ash content (50.80%) and fixed carbon of 19.03%, yielding relatively low energy quality. Treatment T2 showed improved energy quality, with a calorific value of 2307 kcal/kg, ash content of 48.17%, and fixed carbon of 21.02%. Meanwhile, Treatment T3 exhibited the best performance, achieving the highest calorific value of 2645 kcal/kg, the highest fixed carbon content (25.51%), and the lowest ash content (45.34%). These findings confirm that an increase in fixed carbon correlates positively with calorific value, whereas higher ash content reduces the energy quality of the char. Thus, oyster mushroom baglog waste can be categorised as a promising lignocellulosic biomass resource for developing renewable solid fuels, while offering an environmentally friendly and circular-economy-based waste management solution.

Compliance with ethical standards

Acknowledgment

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Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest regarding the publication of this article.

Human and Animal Rights

This research did not involve human participants or animals, and therefore ethical approval was not required.

Statement of Informed Consent

This study does not involve human participants, thus informed consent was not applicable.

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