ORIGINAL ARTICLE

Production of Bio-Coke from spent mushroom substrate for a sustainable solid fuel

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Abstract

Spent mushroom substrate (SMS), defined as the residual biomass after mushroom cultivation, has been known to cause serious pollution, especially river pollution, as it is produced in large quantities and has been disposed of without consideration of the environment. Thus, there is growing interest in converting this biomass waste into Bio-Coke as an alternative solid fuel to be used in a boiler to generate steam for mushroom substrate pasteurization. This study analyzes the physical characteristics of Bio-Coke conversion from SMS in Malaysia, and it was found to have better physical characteristics than other types of conventional biomass fuel. The results indicate that Bio-Coke from SMS at a formation temperature of 170 °C had an apparent density of 1.397 g/cm^3 and a combustion period of 1890 s. Its maximum compressive strength at room temperature (25 °C) and 700 °C was 105.2 and 5.302 MPa, respectively, which is ideal for a biomass solid fuel. Its high apparent density and mechanical strength provide evidence that SMS Bio-Coke is structurally robust and can remain intact when compressed at high pressure and burned at high temperature in a boiler. Thus, the use of SMS Bio-Coke presents itself as a potential strategy for biomass waste management in Southeast Asia, particularly Malaysia.
Trial registration number: Date of registration "retrospectively registered"

Abbreviations

SMS	Spent mushroom substrate
°C	Degree Celsius
g/cm^3	Gram per centimeter cubic
s	Second
MPa	Megapascal
kg	Kilogram
MJ/kg	Mega joule per kilogram
TGA	Thermogravimetric analysis
N	North
E	East
h	Hour
d	Day
mm	Millimeter
wt%	Weight percent
min	Minute
MCS	Maximum compressive strength
mm/min	Millimeter per minute
°C/min	Degree Celsius per minute
KPa	Kilopascal
L/min	Liter per minute
%/min	Percent per minute
EFB	Empty fruit bunch
$/kg	United States Dollar per kilogram

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$/ton   United States Dollar per ton
PBOT   Pruned branches of the olive tree

1 Introduction

Biomass has been commonly used as an energy source due to its high abundancy, low cost, and near carbon neutrality, as biomass is part of the carbon cycle. Malaysia is a tropical country situated near the equator, and its year-round hot and humid climate, which is suitable for agricultural activities, leads to a higher productivity of biomass than those of other temperate countries that can only seasonally produce biomass. A minimum of 168 million tons of biomass waste is annually produced in Malaysia [1]. Currently, some of this waste is used as fuel in boilers to generate steam in the oil palm industries and on oil palm farms, and some is used as fertilizer and animal feedstock, while most is disposed [2]. This shows that biomass waste has not been utilized economically because all the waste can be efficiently converted into value-added products.

Some of the other biomass waste has been converted into pellets to be used as heat source energy for the generation of electricity. A report from the Malaysian-German Chamber of Commerce and Industry stated that Malaysia produced approximately 1000 to 3000 tons of pellets in 2015 for export to European countries, China, Japan, and Korea [3]. However, this type of solid biomass fuel lacks mechanical strength, resulting in loss of revenue from fines, as the pellets are easily fragmented during transportation and storage [4]. The low mechanical strength of biomass pellets also causes problems when they are fed into the boiler, as it can increase the risk of dust emissions and explosions [5].

Mushroom cultivation, which is one of the contributors to agricultural feedstock in Malaysia, is in high demand due to interest in the nutritional and health benefits of mushrooms [6]. Among all the mushroom species, *Pleurotus* is one of the most highly valued and important species, occupying third place in the worldwide production of mushrooms with approximately 16.3% of the total production, and it shows good adaptability towards various changes in temperature; thus, it is possible to grow in temperate and tropical zones [7]. The mixing materials consist of several agricultural residues, such as rubber sawdust, rice bran, and other organic waste; these materials are used as substrates or cultivation media for mushrooms. Before cultivation, the mushroom substrate has to undergo a pasteurization and sterilization process to eliminate fungi and bacteria that might affect the quality of the mushroom produced [6]. The current system of steam pasteurization uses electricity [8] and encourages the cutting of trees for wood to be burned in the boiler; thus, it may cause sustainability issues [9] and may be expensive. This process is also energy intensive and consumes a large amount of wood [10].

Spent mushroom substrate (SMS) is defined as the residual biomass and leftover substrate after several flushes of mushroom are harvested, as it has low nutrient value, particularly low nitrogen content, that is not adequate for plant nutrition [11]. This residual biomass is produced in large quantities within a concentrated area every year, causing serious environmental problems, especially river pollution [12]. A previous study found that approximately 5 kg of SMS is produced for each kilogram of mushroom [13]. Currently, some SMS waste is used as fertilizer and animal feedstock, but the vast majority of SMS is discarded [2]. The current use of SMS and the methods for using this product do not represent the most economical solution; all SMS biomass may be utilized more efficiently to create value-added products. Therefore, alternative utilization methods for SMS are needed, which includes use as biomass fuels. Utilization of farm wastes could reduce operational costs and increase the value of the agricultural output [10].

Bio-Coke has been developed and manufactured under high pressure (~ 20 MPa) at moderate temperatures (120–200 °C) [14]. Bio-Coke exhibits unique features such as a high calorific range between 18 and 31 MJ/kg and a high density (1.4 g/cm^3) [15]. These features suggest that Bio-Coke may have a high heat of combustion and that Bio-Coke can be easily transported and stored at a relatively low cost. Bio-Coke also has a low moisture content and a relatively low tendency to retain water [15]. Bio-Coke has been found to have a high mechanical strength of approximately 38–149 MPa at room temperature and high temperature, demonstrating that it may be able to withstand high pressures during combustion at high temperature [15]. This new densified solid fuel can be used in many applications, including as a combustion and heat source for boilers in electricity generation. The transformation of biomass into Bio-Coke presents itself as a potential strategy for managing biomass waste due to its high retention of biomass energy and zero-weight loss during the production process. This means that 10 g of raw biomass can produce 10 g of Bio-Coke with no emissions of gases such as methane and carbon dioxide [15, 16]. Thus, this study aims to develop a method to fully utilize SMS and convert it into a value-added product, Bio-Coke. In addition to its abundance, it has been shown that SMS has better characteristics than other biomass waste as a raw material for Bio-Coke production due to its appearance and particle size. It was found that small particle size plays an important role in Bio-Coke production, as small particles better facilitate the lignin reaction due to their larger surface area; however, it was also confirmed that the maximum compressive strength is low at both room and high temperature when the particle size is too small [17]. In this study, this soil-like material does not need to be further ground before Bio-Coke conversion, as it has an ideal particle size, which could reduce the processing time, thereby reducing the operational cost. It has been reported that the total

grinding cost for other solid wastes such as wood is nearly 26.12 \$/ton (between 8.82 and 34.94 \$/ton) [18].

In this study, the production is performed at four different temperatures—130, 150, 170, and 190 °C—to identify the optimum temperature for Bio-Coke production from SMS. This study also analyzes the physical features of SMS Bio-Coke, including its apparent density and mechanical strength at room (25 °C) and high (700 °C) temperature. The combustion characteristics of the SMS Bio-Coke are determined using calorific value testing, combustion testing, and thermogravimetric analysis (TGA). Comparisons between SMS Bio-Coke with other biomass fuels such as firewood and pellet were also addressed.

2 Materials and methods

2.1 Preparation of sample

The SMS Bio-Coke production was sourced from the cultivation of *Pleurotus* sp. mushroom collected from Gray Oyster Mushroom Farm, Gombak, Selangor (3°16′ 25.3″ N 101° 43′ 43.7″ E). The SMS samples consisted of a mixture of wood sawdust, rice bran, and agricultural lime with a ratio of 100:10:1, and 70–75% water was added to the mixture. The mixture was then put inside a plastic bag, steamed for approximately 2 h, and cooled for 2 d. The samples collected were discarded from the site after several harvests due to their low nutrient value, which made them unsuitable for mushroom cultivation. The samples were further dried in an oven at 105 °C for 24 h and sieved to a particle size of less than 1 mm.

2.2 Production process of SMS Bio-Coke

A moisture content of 10 ± 0.25 wt%, an initial yield mass of 9 g, a molding size of 20 mm, and a holding time of 6.15 min were used in the SMS Bio-Coke production. The moisture content of the crushed raw materials was analyzed using a moisture analyzer (AND Company, MX-50). The value of the moisture content was adjusted and calculated using Eq. (1):

$$\frac{\text{Target value } [\%] - \text{Experimental value}[\%]}{100\% - \text{Target value } [\%]}$$
$$\times \text{ mass of sample } [g]$$
$$= \text{ value of water } [g] \quad (1)$$

The process was undertaken using a hydraulic press machine under a pressure of 21.7 MPa with simultaneous heating using an electric furnace (ARF-50M) until the temperature reached 130, 150, 170, and 190 °C, as previously described [19]. When the target temperature was achieved, the pressure

and temperature were retained for 6.15 min. The schematic diagram for the SMS Bio-Coke production process is given in Online Resource 1.

2.3 Compressive strength tests

Compressive strength tests were conducted at 25 and 700 °C using a compression press machine (SHIMADZU, AG-300 KNX). Trapezium × Material testing software was used to calculate the maximum compressive strength (MCS) at both temperatures.

The compressive strength test at 25 °C was conducted by placing the SMS Bio-Coke at the center of the machine and compressing the sample at a loading speed of 1.5 mm/min until it cracked. For the compressive strength test at 700 °C, the test was divided into two stages. In the first stage, the SMS Bio-Coke was simultaneously compressed under a constant pressure of 0.1 MPa and heated until it reached 700 °C. The second stage commenced when the temperature reached 700 °C, and the sample was compressed at a constant loading speed of 1.5 mm/min until it cracked.

2.4 Thermogravimetric analysis

The sliced SMS Bio-Coke at formation temperature 170 °C and the raw material were used for TGA. The SMS Bio-Coke at formation temperature 170 °C had a higher MCS value and a longer combustion duration. For the SMS raw material, a particle size below 1 mm and moisture content of 10 ± 0.25 wt% were used in this test. This test was conducted to measure the change in mass with heating at a constant rate using a Q50 thermogravimetric analyzer. Nitrogen gas was used as the purge gas alongside a heating rate of 10 °C/min and a temperature range between 0 and 900 °C for this test.

2.5 Calorific value tests

For this experiment, 0.5–1.0 g of either SMS Bio-Coke at formation temperature 170 °C or the raw material sample was measured and put into the vessel (CAL2K-ECO-4) of a bomb calorimeter (CAL2K-ECO). A pure cotton thread (CAL2K-4-FC) was tied to the firing wire of the vessel, touching the sample. Afterward, the vessel was filled with oxygen gas at a pressure of approximately 2000 KPa at the filling station (CAL2K-3). The calorimeter measured the increase in the temperature of the vessel, with constant mass, volume, and pressure in an isothermal environment.

2.6 Combustion analysis tests

The best SMS Bio-Coke samples were selected from the compressive strength tests at 25 and 700 °C. The SMS Bio-Coke at formation temperatures of 150 and 170 °C had the highest

MCS at 25 and 700 °C, respectively. To analyze the combustion period of Bio-Coke, a combustion analysis test was conducted using an electric heater (Toyo Technical Co., Ltd., NCH - IML 100 V/250 W) and an electrical tube furnace (ASAHI Rika Works ARF–50 M). The temperature inside the chamber of the electric tube furnace was set to 700 ± 5 °C, and the sample was inserted into the insertion port provided in the upper part of the combustion chamber. A compressor with air compressed to a flow rate of 10.0 L/min was used in this test.

3 Results and discussion

3.1 Production process of SMS Bio-Coke

Bio-Coke production from SMS was undertaken at four different formation temperatures—130, 150, 170, and 190 °C—as shown in Fig. 1. For the sample preparation, the moisture content of the raw material was set to 10 ± 0.25 wt%. A previous study reported that dried biomass with moisture contents ranging from 10 to 20 wt% may have higher calorific values, between 15 and 17 MJ/kg, than biomass with moisture contents between 50 and 60 wt%, which has calorific values ranging from 6 to 8 MJ/kg [20]. In this study, the raw material was crushed to particle sizes smaller than 1 mm. This was done because a previous study observed that the particle size of the raw material plays an important role in the apparent density of Bio-Coke; smaller sized particles are able to better facilitate lignin reactions due to their greater surface area [17]. However, when the particle size is too small, the material has weak maximum compressive strength at room and high temperatures [17]. A molding size of 20 mm, a pressure of 21.7 MPa, and a holding time of 6.15 mm were used during the Bio-Coke production process. Larger molding sizes may potentially cause permeation of heat through thermal conduction to the center of the Bio-Coke, producing less efficient Bio-Coke [16]. Generally, a higher loading pressure can improve biomass solidification, as it can promote the solid bridge bonding mechanism resulting from the diffusion of molecules. The holding time for Bio-Coke production is associated with

the density and mechanical strength of Bio-Coke, where a holding time greater than 3 min may increase the density of Bio-Coke [21].

Fig. 1 shows that SMS Bio-Coke could be produced at all four formation temperatures (i.e., 130, 150, 170, and 190 °C). It also shows that the color of the SMS Bio-Coke grew darker as the formation temperature increased. This is consistent with the results of a previous study that reported a darker coloration of Bio-Coke due to the reaction of lignin [17]. This result was also the same as that of Henan Kingman Mechanical & Electronic Complete Plant Co., Ltd. (KMEC) Engineering, where the color of biomass solid fuel became black due to carbonization. As some of the feedstock had been exposed to many years of wind and rain [22], enzymes had altered the raw material, and thus, it blackened when compressed. The moisture content of the raw material may also affect the color of Bio-Coke, as low moisture content results in a low-density Bio-Coke that can easily blacken [22].

Moreover, since the production process of SMS Bio-Coke only used heat (130–190 °C) and pressure (21.7 MPa), the treatment may not result in any differences between the elements and components in the raw SMS and those in the SMS Bio-Coke, but their chemical structures might be different. A previous study stated that during the densification process of biomass, one of the possible interactions among the surfaces of the polysaccharides is the interaction of hydroxyl groups, forming multiple hydrogen bonds [23]. Furthermore, during the heating process of Bio-Coke, dehydration reactions may occur that form covalent bonds that cross-link the surface [23], thus producing stronger binding mechanisms.

3.2 Degree of compactness using apparent density analysis

The apparent density of the SMS Bio-Coke was calculated using data collected following the completion of the production process prior to the recovery of the biomass elasticity, which is known as the "spring back effect" [24]. Bio-Coke has a relatively high apparent density and degree of compactness, which is conducive to its transportation and storage [25]. Mohd Isa (2019) stated that a higher apparent density of Bio-Coke indicated a high-quality biomass solid fuel as it implied

Fig. 1 Image of spent mushroom substrate (SMS) Bio-Coke in different formation temperature

Raw materials	Formation Temperature [°C]			
	130	150	170	190
Spent Mushroom Substrate (SMS)				
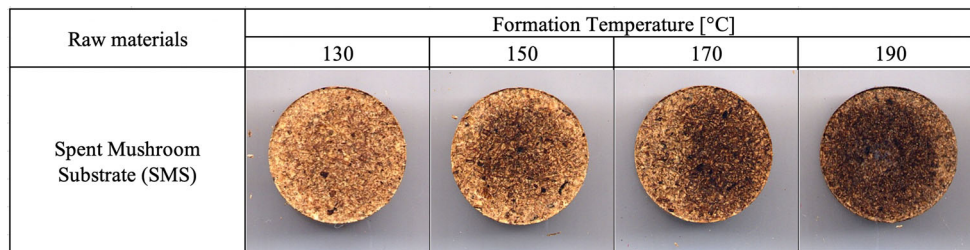
a high energy content per volume and slow-burning characteristics [16]. The formation conditions of Bio-Coke, such as the initial moisture content, particle size of the raw materials, and formation temperature, were also found to impact its apparent density.

Table 1 shows the apparent densities of the SMS Bio-Coke at the four formation temperatures: 130, 150, 170, and 190 °C. The SMS Bio-Coke at a formation temperature of 190 °C had the highest apparent density, at 1.435 g/cm^3, compared with those at the formation temperatures of 130, 150, and 170 °C, with apparent densities of 1.314, 1.357, and 1.397 g/cm^3, respectively. The apparent density of the SMS Bio-Coke increased with the formation temperature. Likewise, Sawai et al. [24] reported that the apparent density of Bio-Coke typically increases with increasing formation temperature [26]. As such, the formation temperature for Bio-Coke production has been known to influence its apparent density, as higher temperature facilitates plastic deformation between the biomass particles, enhancing the permanent bonding between particles [27]. The hemicellulose present in the biomass is hydrolyzed during heating in the Bio-Coke production and fills the voids between the particles; then, subcritical water destroys the micropore structures and reduces the volume of the Bio-Coke [19].

3.3 Compressive strength at room temperature (25 °C)

The results for the MCS value at room temperature (25 °C) for the SMS Bio-Coke are detailed in Table 1. It is critical to know the MCS value at room temperature, as it can determine the level of resistance to damage of Bio-Coke when it is stacked and thus the possibility of damage to the solid fuel during transportation and storage [28]. Damage to biomass solid fuel during the transportation process can result in lost revenue due to fines [4].

Table 1 shows that the SMS Bio-Coke with a formation temperature of 170 °C had the highest MCS value (105.2 MPa) at 25 °C compared with those of the SMS Bio-Coke at formation temperatures of 130 and 150 °C. This indicates that increasing the formation temperature of Bio-Coke can increase its hardness, making it difficult to break down

when compressed at high pressure [24]. Furthermore, a previous study reported that the low melting point of lignin, approximately 140 °C, could make it easier for lignin to penetrate the particles at higher Bio-Coke formation temperatures [29]. However, at a formation temperature of 190 °C, the MCS value at 25 °C was lower than that of the SMS Bio-Coke at a formation temperature of 170 °C. This suggests that at a certain point, the MCS value of Bio-Coke at room temperature (25 °C) decreases despite an increase in the formation temperature. This may be due to the loss of moisture content during heating at high temperature during Bio-Coke production, thereby increasing the glass transition temperature and potentially affecting the interdiffusion of the polymer through the particles in the Bio-Coke [16]. The initial moisture content may be an important factor affecting the mechanical strength of Bio-Coke, as it can soften cellulose, hemicellulose, and lignin during its densification process [30].

3.4 Compressive strength at high temperature (700 °C)

MCS tests of Bio-Coke at high temperatures are indicative of the permeability and aeration properties of Bio-Coke when it is heated in a furnace. Mizuno et al. [31] reported that a Bio-Coke with a higher MCS value at high temperature will remain solid and difficult to break down during flame combustion due to the extreme density of the structure. Thus, when the outer part is thermally decomposed, the interior part of the Bio-Coke has not yet decomposed, and oxygen can produce a longer combustion period [32]. Additionally, Hamidun [33] stated that this test was crucial in ensuring that Bio-Coke remains stable and intact during heating at high temperatures [31].

Table 1 shows the MCS values at 700 °C for the SMS Bio-Coke samples at the four formation temperatures. The results indicate that the SMS Bio-Coke at a formation temperature of 150 °C had the highest MCS value of 5.526 MPa at 700 °C. Although the apparent density of the SMS Bio-Coke increased when the formation temperature increased, as the biomass was densely compressed during the production process, the compressive strength of the SMS Bio-Coke decreased

Table 1 Average apparent density, maximum compressive strength in room temperature (25 °C) and 700 °C and combustion time of SMS Bio-Coke at several formation temperatures

Type of Bio-Coke	Formation temperature (°C)	Apparent density (g/cm3)	MSC in room temperature (MPa)	MSC in 700 °C (MPa)	Total combustion time (s)
Spent mushroom substrate (SMS)	130	1.314	87.744	3.735	NA
	150	1.357	97.412	5.526	1652
	170	1.397	105.200	5.302	1890
	190	1.435	92.392	4.141	NA

NA no data available

when the biomass was heated at temperatures higher than 150 °C. The structure of the SMS Bio-Coke at formation temperatures higher than 150 °C became brittle when compressed at 700 °C. This may be due to the loss of moisture content during Bio-Coke production when the biomass was heated at higher formation temperatures [16]. The initial moisture content is recognized as an important parameter for the production of Bio-Coke, as it functions to soften cellulose, hemicellulose, and lignin [30].

3.5 Combustion behavior under TGA

TGA was conducted to determine the temperature and decomposition reactions that occur when burning the SMS Bio-Coke. This test also shed light on the thermal behavior of the SMS Bio-Coke compared with that of the raw material. Additionally, this test was conducted to analyze the ignition and burnout temperature of the SMS Bio-Coke and the raw material. Figure 2 shows the TGA of the SMS Bio-Coke and the raw material. In this test, the temperature was increased from room temperature to 900 °C, resulting in three phases of weight loss in the samples. Figure 2 (a) and (b) show weight losses of 8.720 and 8.585% for the SMS Bio-Coke and raw SMS, respectively, in the first phase, which is associated with the water vaporization process [33]. Following the loss of moisture, the combustion process commenced, as indicated by the rapid decomposition rate, and the first dominant peak at approximately 320 °C was observed in the second phase for both samples. The second phase of weight loss is attributable to the degradation of hemicellulose and cellulose [33]; the SMS Bio-Coke and raw SMS experienced weight losses of 54.87 and 58.63%, respectively. Figure 2 (a) and (b) illustrate that the highest peaks for the degradation of cellulose and hemicellulose in the SMS Bio-Coke and raw SMS were 9.853 and 8.160%/min, respectively. This drastic weight reduction in the second phase is due to the degradation of hemicellulose, as hemicellulose is more easily oxidized due to its amorphous structure and relatively low molecular weight [34].

The third phase of weight loss represents the decomposition of lignin [34], showing that the raw empty fruit bunch (EFB) had a higher weight loss, at 29.98%, than the SMS Bio-Coke, at 18.56%. Ting Lee et al. [34] reported that char and lignin are decomposed at high temperature in the third phase [34], so the higher weight loss of the raw SMS compared with that of the SMS Bio-Coke may be due to the complete burning process and full decomposition of all chemical components into ash in the raw SMS, resulting in a decrease in the residue of 2.794%. Figure 2 (b) shows that the constant weight loss in the third phase indicates the completion of the combustion of the raw SMS. For the SMS Bio-Coke, as shown in Fig. 2(a), the percentage decrease in weight indicates that combustion is still possible, resulting in a longer combustion period than that of the raw SMS. The results of this study indicate that the

densification of Bio-Coke from the raw SMS produced a longer combustion period. A previous study reported a kinetic analysis that determined the activation energy using the Flynn-Wall-Ozawa method (FWO) for a corn residue pellet and wood chips, showing that the samples had activation energies of approximately 49–84 kJ/mol and 47–90 kJ/mol, respectively [35]. Jiang Longbo et al. [36] also examined the activation energy of a sludge-camphor pellet, which was approximately 50.64–144.99 kJ/mol using the same FWO method. Comparing the TGA graph of the SMS Bio-Coke with these two studies, it was estimated that the SMS Bio-Coke had an activation energy of approximately 50–120 kJ/mol, as there were no differences in the temperature ranges of the first and second phases, but the temperature range of the third phase of the SMS Bio-Coke was slightly lower than that of the sludge-camphor pellet [36] and higher than those of the corn residue and wood chips [35].

Next, the ignition and burnout temperatures of the SMS Bio-Coke and raw SMS were obtained from this test. Data on the ignition temperature of the biomass are necessary for understanding the possible risks, as this parameter is related to the safety of the fuel for storage and transportation purposes in industry [37]. The spontaneous ignition of the biomass might cause fire or an explosion [38]. The recognition of the burnout temperature of the biomass fuel is also important for providing insight into the mechanism of its combustion [37]. Moreover, both the ignition and burnout temperature are key parameters for evaluating the combustion design and its consumption [37, 39]. In this study, the ignition and burnout temperature of the SMS Bio-Coke and raw SMS were determined using the "Intersection Method" as previously described by Lu Jau Jang and Chen Wei Hsin [37]. Figure 2 (a) and (b) show the ignition temperature (T_i) and burnout temperature (T_b) of both the raw SMS and SMS Bio-Coke. As shown in Fig. 2(b), the ignition temperature of the raw SMS was between 250 and 260 °C, and the burnout temperature was approximately 535–545 °C. Next, according to the method, the ignition temperature of the SMS Bio-Coke was between 265 and 275 °C, while the burnout temperature was expected to be higher than 900 °C; as shown in Fig. 2 (a), the decreasing trend of the SMS Bio-Coke at the temperature of 700–900 °C showed that combustion was still possible after the temperature reached 900 °C. It has also been reported in a previous study that the combustion temperature range of Bio-Coke is approximately 1300–1500 °C [15]; thus, the results show that the Bio-Coke is suitable for use in combustion with higher temperature purposes.

3.6 Calorific value and combustion period

The calorific value is one way to measure the quality of solid fuel, as it can show the energy contained in and the total combustion heat of fuel. The calorific value of the SMS Bio-

Fig. 2 Thermogravimetric analysis of spent mushroom substrate (SMS). (a) SMS Bio-Coke. (b) Raw SMS
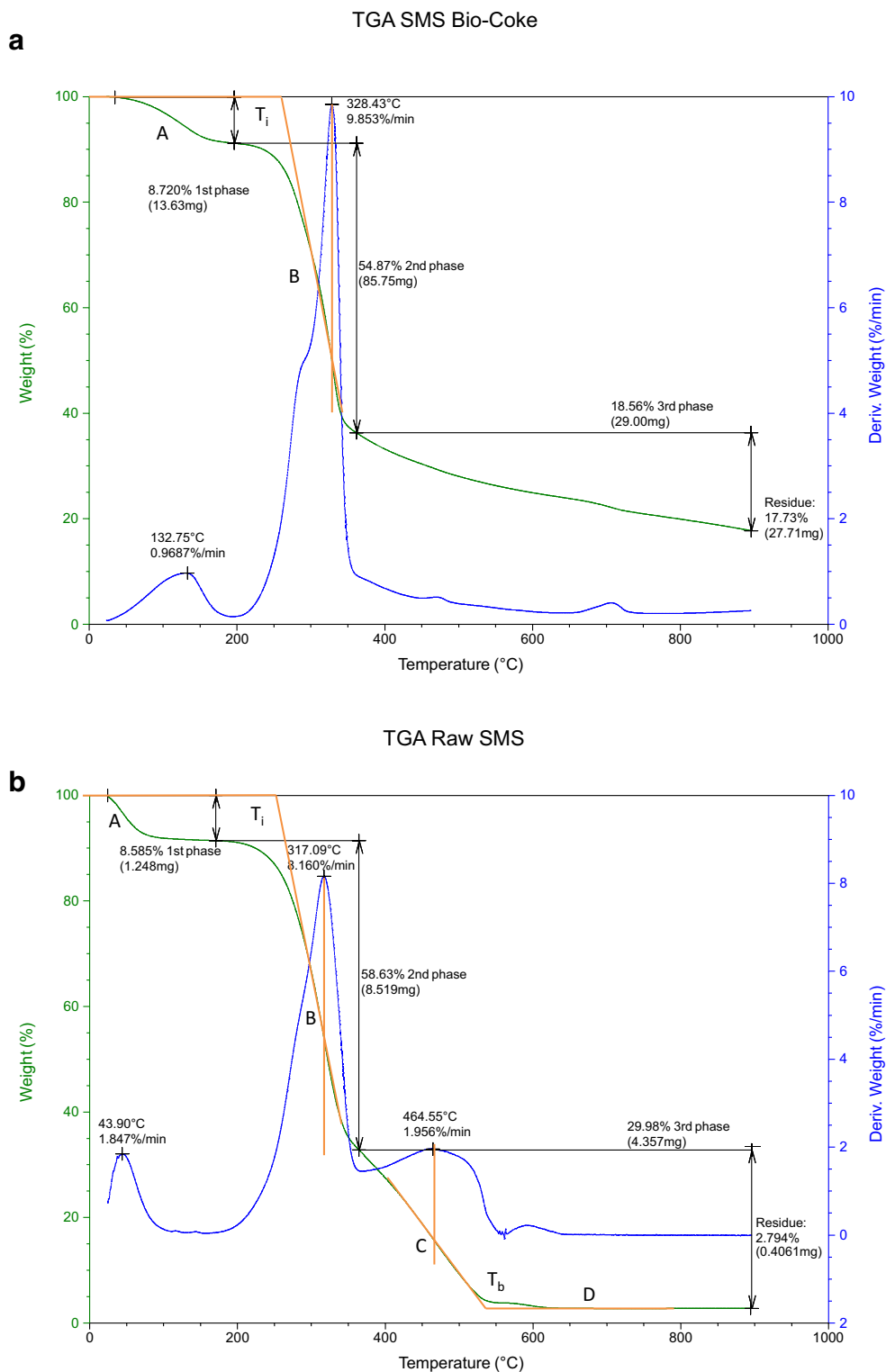
Coke was measured using a bomb calorimeter. The results showed that the calorific values of the raw material of SMS and the Bio-Coke were 17.4 and 17.47 MJ/kg, respectively. A previous study found that the calorific value of a biomass solid fuel is based on the raw material, as the fuel and raw material contain the same organic substances [40]. This study observed

that the calorific value of the SMS Bio-Coke was similar to that of the raw material.

A combustion test was conducted on the SMS Bio-Coke with the highest values at 25 and 700 °C to evaluate the combustion period. From Table 1, the SMS Bio-Coke at a formation temperature of 170 °C had a longer combustion

period (1890 s) than the SMS Bio-Coke at a formation temperature of 150 °C (1652 s). A previous study found that Bio-Coke with a higher MCS value has a longer combustion period due to its high density structure and its difficulty in breaking down during burning, thus producing longer combustion periods [32]. This indicates that the Bio-Coke, with its relatively high apparent density and MCS value, has ideal characteristics for a biomass solid fuel, as it can produce a long combustion period.

3.7 Comparison between characteristics of SMS Bio-Coke, wood pellets, fuel gas, firewood, and other kinds of Bio-Cokes

In this study, the characteristics of the SMS Bio-Coke were compared with those of other kinds of biomass fuel. The mechanical properties of the SMS Bio-Coke at the formation temperature of 170 °C with regard to the apparent density (1.397 g/cm^3) and the MCS value (105.2 MPa) showed that the SMS Bio-Coke had a stronger structure than the empty fruit bunch (EFB) pellets, with values of 1.185 g/cm^3 and 11.8 MPa, respectively [24]. Kang et al. [41] found that the total combustion time of a single pellet was approximately 150 s, with flame and char combustions of 50 and 100 s, respectively. This showed that the Bio-Coke had a longer combustion duration than the pellets, which might be due to its compact structure and high mechanical strength at room and high temperature. A lack of mechanical strength in biomass pellets has been found to cause problems during the transfer process into the boiler, as it can increase the risk of dust emissions and explosion [5]. The low mechanical strength of biomass fuel can also result in lost revenue due to fines, as the fuel is easily broken during transportation and storage [4]. It has also been reported that the cost for the production of Bio-Coke is 0.10 $/kg, which is lower than that of wood pellets (0.21 $/kg) [42], showing that the conversion of Bio-Coke is possibly more economical.

A previous study reported the application of a gasification process and the conversion of SMS to a fuel gas, which was expensive because of the investment in the gasifier system of approximately $3500 and an additional operating cost of approximately $10 a month [10]. The SMS Bio-Coke can potentially be used as a solid fuel in a boiler to generate steam for substrate pasteurization and heating for mushroom farms. With an estimated production cost of 0.10 $/kg [42], SMS Bio-Coke conversion technology is relatively economical, especially for use in small-scale industries and in rural areas [10]. Traditionally, wood is another source of energy that is used for boilers. However, this method can lead to overexploitation of forests, resulting in many environmental effects, such as deforestation, destruction of ecosystems, and soil erosion [43]. The price ranges of firewood (88–166 $/ton) and wood chips (66–100 $/ton) show that the utilization of mushroom

farm wastes such as the conversion of SMS Bio-Coke could reduce operational costs [10] and thus can maintain the sustainability of wood sources.

A comparison of the mechanical properties of the SMS Bio-Coke with those of other types of Bio-Coke in terms of apparent density highlights that the SMS Bio-Coke had a higher apparent density than coconut shell Bio-Coke at formation temperatures of 140, 160, and 180 °C, with apparent densities of 1.01, 1.06, and 1.12 g/cm^3, respectively [44]. Additionally, the results showed that the SMS Bio-Coke had a higher calorific value than that of the Bio-Coke of pruned branches of the olive tree (PBOT), with a calorific value of 16.10 MJ/kg [15].

4 Conclusions

The results of this study showed the conversion of SMS biomass to Bio-Coke, and based on its physical features, the Bio-Coke has potential as a solid fuel. The SMS Bio-Coke produced at formation temperature of 150 and 170 °C showed high potential due to its high apparent density, high mechanical strength at 25 and 700 °C, and long combustion period. Its high mechanical strength at 25 and 700 °C makes it an ideal biomass solid fuel, as it will not easily break down during transportation and storage and will be stable during combustion in a boiler at high temperature. The zero-weight loss characteristic, where 1 kg of SMS can be converted to 1 kg of Bio-Coke during production, is economically advantageous, as the fuel costs only 0.10 $/kg for production [42]. This technology also indicates that the conversion of SMS Bio-Coke is crucial for sustainable development because it reuses SMS and increases the efficiency of SMS biomass waste management.

Compliance with ethical standards

Conflict of interest   The authors declare that they have no conflict of interest.

References

1. Abd Aziz N, Dato' Leon KM (2012) Malaysia's biomass potential. BE-Sustainable Magazine. BiomassSP

2. Rinker D (2017) Spent mushroom substrate uses: technology and applications. In pp 427–454. doi:https://doi.org/10.1002/9781119149446.ch20

3. Oil Palm Biomass & BIogas in Malaysia 2017: Potential for European SMES (2017) EU-MalaysiaChamber of Omerce and Industry (EUMCCI). https://businessmalaysia.eu/admin/js/fileman/Uploads/BiomassBiogas2018_Final_20180508.pdf

4. Simple ways to check wood pellet quality (2007) COFORD. http://www.coford.ie/media/coford/content/publications/projectreports/cofordconnects/ccncheckpelletquality.pdf

5. Gil MV, Oulego P, Casal MD, Pevida C, Pis JJ, Rubiera F (2010) Mechanical durability and combustion characteristics of pellets from biomass blends. Bioresour Technol 101(22):8859–8867. https://doi.org/10.1016/j.biortech.2010.06.062

6. Sidik MAB, Buntat Z, Che Razali M, Buntat Y, Nawawi Z, Jambak MI, Smith IR (2015) A new method to sterilise mushroom substrate for oyster mushroom cultivation. Istanbul, Turkey

7. Phan C-W, Sabaratnam V (2012) Potential uses of spent mushroom substrate and its associatedlignocellulosic enzymes. Applied Microbiol Biotechnology 96:863–873. https://doi.org/10.1007/s00253-012-4446-9

8. Build a steaming vessel for mushrooms cultivation (2015) Funguys gourmet. https://funguys.co.za/mushroom-cultivation-tips/mushroom-news-myco-technology/build-a-steaming-vessel-for-mushrooms-cultivation/

9. Orge R, Leal LV (2018) Utilizing heat from rice hull biochar production for steam pasteurization of mushroom fruiting bags. Cogent Engineering 5 (1). :DOI: https://doi.org/10.1080/23311916.2018.1453972

10. Tippayawong N, Chaichana C, Promwungkwa A, Rerkkriangkrai P (2011) Clean energy from gasification of biomass for sterilization of mushroom growing substrates. International Journal of Energy 5 (4)

11. Sendi H, Mohamed MTM, Anwar MP, Saud HM (2013) Spent mushroom waste as a media replacement for peat moss in Kai-Lan (Brassica oleracea var. Alboglabra) production. The Scientific World Journal 2013. doi:https://doi.org/10.1155/2013/258562

12. Williams BC, McMullan JT, McCahey S (2001) An initial assessment of spent mushroom compost as a potential energy feedstock. Bioresour Technol 79(3):227–230. https://doi.org/10.1016/S0960-8524(01)00073-6

13. Lou Z, Sun Y, Zhou X, Baig SA, Hu B, Xu X (2017) Composition variability of spent mushroom substrates during continuous cultivation, composting process and their effects on mineral nitrogen transformation in soil. Geoderma 307:30–37. https://doi.org/10.1016/j.geoderma.2017.07.033

14. Mizuno S, Ida T, Fuchihata M, Namba K (2016) Effect of specimen size on ultimate compressive strength of bio-coke produced from green tea grounds. Mechanical Engineering Journal 3 (2016)

15. Mansor AM, Wai LT, Jeng SL, Ani FN, Hashim H, Wai SH (2018) Potential commercialisation of biocoke in Malaysia - a best evidence review. Renew Sust Energ Rev 90:636–649

16. Mohd Isa AA (2019) Influences of raw material characteristics on mechanical properties of blended biocoke. Kindai University, Japan

17. Mizuno S, Hamidun O, Ida T, Fuchihata M, Fumoto T, Namba K (2014) Effect of crushing particle size on cold/ hot compressive strength of high-density and high-hardness solid fuel produced from raw rice husk. Journal of Smart Processing 3(5):269–275. https://doi.org/10.7791/jspmee.3.269

18. Marrs G, Zamora-Cristales R, Sessions J (2016) Forest biomass feedstock cost sensitivity to grinding parameters for bio-jet fuel production. Renew Energy 99:1082–1091. https://doi.org/10.1016/j.renene.2016.07.071

19. Tagami N, Ida T (2018) Effect of moisture content, forming temperature and structural components on biocoke solidification from various biomass resources. Bulletin of the JSME 5(5):1–8. https://doi.org/10.1299/mej.18-00030

20. Szymajda A, Łaska G (2019) The effect of moisture and ash on the calorific value of cow dung Biomass. Proceedings 16:4. https://doi.org/10.3390/proceedings2019016004

21. Mohd Isa MAA (2016) Fundamental characteristic of mixed biocoke. Kindai University

22. Why the colors of pellet compressed by the wood pellet mill become black? (2020) http://www.biomasspelletplant.com/news/wood-pellet-mill-become-black.html

23. Frodeson S, Henriksson G, Berghel J (2018) Pelletizing pure biomass substances to investigate the mechanical properties and bonding mechanisms. BioResources 13:1202–1222. https://doi.org/10.15376/biores.13.1.1202-1222

24. Ruksathamcharoen S, Chuenyam T, Stratong-on P, Hosoda H, Ding L, Yoshikawa K (2019) Effects of hydrothermal treatment and pelletizing temperature on the mechanical properties of empty fruit bunch pellets. Appl Energy 251:113385. https://doi.org/10.1016/j.apenergy.2019.113385

25. Tumuluru JS (2018) Effect of pellet die diameter on density and durability of pellets made from high moisture woody and herbaceous biomass. Carbon Resources Conversion 1(1):44–54. https://doi.org/10.1016/j.crcon.2018.06.002

26. Sawai T, Ohmasa M, Kajimoto T, Ida T, Fuchihata M, Namba K (2010) Compressive strength properties of bio-solid fuel made from pruned branch. Journal of High Temperature Society 36(1):36–40. https://doi.org/10.7791/jhts.36.36

27. Zhang X, Cai Z, Chen L, Zhang D, Zhang Z (2016) Effects of moisture content and temperature on the quality of water hyacinth pellets. Bioresources 11:1407–1416. https://doi.org/10.15376/biores.11.1.1407-1416

28. Brunerova A, Muller M, Sleger V, Ambarita H, Valasek P (2018) Bio-pellet fuel from oil palm empty fruit bunches (EFB): using European standards for quality testing. Sustainability 10:doi: https://doi.org/10.3390/su10124443

29. Mani S, Tabil LG, Sokhansanj S (2006) Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses. Biomass Bioenergy 30(7):648–654. https://doi.org/10.1016/j.biombioe.2005.01.004

30. Amran MA (2019) An experimental study of the improvement of mechanical properties of blended bio-coke. Kindai University, Japan

31. Hamidun O (2016) An experimental study for densification mechanism based on initial physical properties of bio-coke and bio-charcoke. Kindai University

32. Mizuno S, Ida T, Fuchihata M, Namba K, Sawai T (2013) Scale effect of compressive strength properties under high temperature for green tea bio-coke (in Japanese). Journal of the Japanese Society for Experimental Mechanics 13(2):190–193. https://doi.org/10.11395/jjsem.13.190

33. Ríos-Badrán IM, Luzardo-Ocampo I, García-Trejo JF, Santos-Cruz J, Gutiérrez-Antonio C (2020) Production and characterization of fuel pellets from rice husk and wheat straw. Renew Energy 145:500–507. https://doi.org/10.1016/j.renene.2019.06.048

34. Lee T, Zubir ZA, Jamil FM, Matsumoto A, Yeoh F-Y (2014) Combustion and pyrolysis of activated carbon fibre from oil palm empty fruit bunch fibre assisted through chemical activation with acid treatment. J Anal Appl Pyrolysis 110:408–418. https://doi.org/10.1016/j.jaap.2014.10.010

35. Onsree T, Tippayawong N, Zheng A, Li H (2018) Pyrolysis behavior and kinetics of corn residue pellets and eucalyptus wood chips in a macro thermogravimetric analyzer. Case Studies in Thermal Engineering 12:546–556. https://doi.org/10.1016/j.csite.2018.07.011

36. Jiang L, Yuan X, Li H, Xiao Z, Liang J, Wang H, Wu Z, Chen X, Zeng G (2015) Pyrolysis and combustion kinetics of sludge–camphor pellet thermal decomposition using thermogravimetric

analysis. Energy Convers Manag 106:282–289. https://doi.org/10.1016/j.enconman.2015.09.046

37. Lu J-J, Chen W-H (2015) Investigation on the ignition and burnout temperatures of bamboo and sugarcane bagasse by thermogravimetric analysis. Appl Energy 160:49–57. https://doi.org/10.1016/j.apenergy.2015.09.026

38. Zheng S, Hu Y, Wang Z, Cheng X (2020) Experimental investigation on ignition and burnout characteristics of semi-coke and bituminous coal blends. J Energy Inst 93:1373–1381. https://doi.org/10.1016/j.joei.2019.12.007

39. Du S-W, Chen W-H, Lucas J (2007) Performances of pulverized coal injection in blowpipe and tuyere at various operational conditions. Energy Convers Manag 48:2069–2076. https://doi.org/10.1016/j.enconman.2007.01.013

40. Calorific value of different wood pellets (2019) http://www.pellet-making.com/blog/wood-pellets-calorific-value.html

41. Kang SB, Sim BS, Kim JJ (2017) Volume and mass measurement of a burning wood pellet by image processing. Energies 10 (603). doi:https://doi.org/10.3390/en10050603

42. Fuchigami Y, Hara K, Kita T, Uwasu M, Kurimoto S (2015) Analysis of effect on CO2 emission reduction and cost estimation for the use of bio-coke: a case study of Osaka, Japan. Journal Wood Science 62:93–100. https://doi.org/10.1007/s10086-015-1515-6

43. Advantages and disadvantages of wood as a source of energy (2020) Digital Frontline. https://revision.co.zw/advantages-disadvantages-wood-source-energy/

44. Sani AS (2018) Influence of a difference in thermal decomposition speed on the performance of torrefied biocoke. Kindai University