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CARBONIZATION OF SPENT COFFEE GROUNDS: A PATHWAY TO HIGH-ENERGY BIOMASS PELLETS

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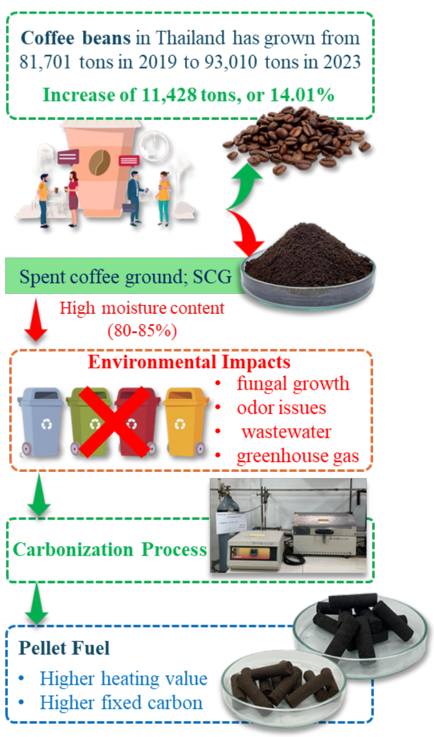
Graphical abstract



Abstract

This research investigates the use of spent coffee grounds (SCG) for producing pellet fuel (PF), with a focus on enhancing their energy properties through carbonization. Thermogravimetric analysis (TGA) was employed to determine the optimal carbonization temperatures. Three types of SCG samples were prepared for pelletization: (1) Dry spent coffee grounds (DSCG), (2) Carbonized spent coffee grounds at 250 °C (CSCG250), and (3) Carbonized spent coffee grounds at 350 °C (CSCG350). The pellets were formed using a custom-built single pellet press, utilizing a cold pressing technique with tapioca starch as a binder. The physical properties (length, diameter, durability index, bulk density, and weight) and fuel properties (moisture content, ash content, volatile matter, fixed carbon, and heating value) were analyzed in accordance with ASTM (American Society for Testing and Materials) standards. The analysis showed that the length, diameter, durability index, bulk density, and ash content of all three pellet types met established biomass pellet standards. However, moisture content analysis revealed that DSCG-PF and CSCG250-PF exceeded the standard threshold, likely due to the cold pressing technique, which does not reduce moisture content. Although sun-drying was employed post-production, the resulting moisture levels were inconsistent. Nonetheless, the residual moisture did not significantly impact fuel quality. The heating value analysis revealed a substantial increase from 21.9 MJ/kg in DSCG-PF to 30.9 MJ/kg in CSCG350-PF, representing a 40.1% improvement. All pellet types met the standard heating value criteria, with CSCG350 displaying the most favorable energy properties. The production of pellet fuel from SCG presents an effective solution for coffee waste management. Furthermore, the carbonization process substantially enhances the fuel properties and heating value of the resulting pellets, with the CSCG350 sample showing the most promising results. Therefore, producing SCG into pellet fuel is another good way to solve the problem of SCG waste. The carbonization process is a way to make the fuel properties and heating value of the pellets more efficient. This research contributes to the development of sustainable, high-efficiency biomass fuels from SCG, while addressing the issue of coffee waste disposal.

Keywords: Solid fuel, Biomass pellet fuel, Energy properties, Heating value

1.0 INTRODUCTION

Coffee has become an extremely popular beverage in recent years, with both roasted and instant coffee gaining widespread popularity among Thai consumers. Statistical data indicates that coffee consumption in Thailand has increased by an average of 15% annually. Over the past five years (2019-2023), the demand for coffee beans in Thailand has grown from 81,701 tons in 2019 to 93,010 tons in 2023, representing an increase of 11,428 tons, or 14.01% [1]. This increasing trend in coffee consumption and demand for coffee beans has generated a significant amount of organic waste known as spent coffee grounds (SCGs). These are the residues left after the coffee extraction process. Based on coffee consumption in Thailand, more than 290,000 tons per year of SCG were discarded in 2022 [2]. Currently, over 6 million tons of SCG worldwide are disposed of through landfilling. SCG has a high moisture content, and if not managed properly, they can lead to environmental impacts such as fungal growth, odor issues, wastewater, and greenhouse gas emissions resulting from the decomposition of accumulated SCG.

Environmental concerns are currently receiving significant attention, leading to campaigns focused on reducing waste by reusing or repurposing it into other raw materials. This approach focuses on maximizing resource efficiency in the concept of a circular economy [3]. Concurrently, Thailand's energy consumption rate has been continuously increasing, but the domestic energy production rate is insufficient to meet the consumption rate [4]. Utilizing agricultural residues such as giant mimosa plants [5], durian peels [6], coconut leaves [7], and corn cobs and husks [8] to produce biomass fuel for household use presents a viable alternative renewable energy source. Thailand has the potential to efficiently produce biomass fuel from these agricultural residues, contributing to renewable energy development [9].

SCG is considered another useful biomass waste, rich in various important compounds such as fatty acids, caffeine, proteins, phenol, polysaccharides, and various minerals [10-12]. Due to its fuel properties, SCG has a high heating value of approximately 19.3 MJ/kg, making it suitable for use as fuel. Additionally, SCG has a high fixed carbon content of about 19.83%, which contributes to high-heat combustion and longer combustion times, along with a low ash content of around 2.2% [13-15]. An analysis of the fuel properties of SCG indicates that it meets the standard requirements of biomass pellet fuel.

Therefore, SCG is well-suited for producing solid fuel or fuel pellets. Pellet fuel is created by compressing biomass into cylindrical shapes with high density, which reduces volume and increases heat content. This process enhances the convenience of storage, transportation, and use as an efficient alternative biomass energy source [16].

However, SCG has a volatile matter content exceeding 70% [13,17,18], which is considered very high and can lead to increased smoke and soot during combustion. To mitigate this, SCG can be subjected to a carbonization process, which reduces the volatile matter content and increases to fixed carbon content. Carbonization involves heating materials in a low-oxygen environment while controlling the temperature and pressure inside the furnace. This process decomposes organic matter and releases various volatile matter [19]. The reduction in volatile matter decreases the amount of smoke and soot produced during combustion, while the increased fixed carbon content enhances the fuel's combustion and extends combustion time.

Currently, numerous studies have been conducted to explore, research, and develop processes for utilizing waste materials, such as SCG, for various beneficial purposes. The collected data reveals significant progress in converting SCG into fuel products, offering an alternative method to reduce the large volume of waste. Relevant research related to the production of fuel from SCG includes the following research:

Chanathaworn and Phumivanichakit (2019) studied the effects of coffee husk and spent coffee grounds on the properties of biomass pellet fuel. They examined different concentrations of cassava starch as a binder at 5%, 10%, 15%, and 20% by weight and studied the ratio of coffee husk to spent coffee grounds affecting the properties of pellet fuels, examining 5 ratios (100:0, 75:25, 50:50, 25:75, and 0:100). The results indicated that using 20% cassava starch and a ratio of 0:100 coffee husk to spent coffee grounds ratio produced the best pellet fuel properties. Biomass pellet fuel made from spent coffee grounds exhibited higher quality than that made from coffee husk alone, with the highest measured properties being: a density of 0.9699±0.0045 g/cm^3, durability of 92.6510±0.2102%, heating value of 17.2772±0.0319 MJ/kg, and fuel utilization efficiency of 16.59±0.02%. In conclusion, spent coffee grounds demonstrated physical and fuel properties that meet the standards for pellet fuel products [20].

Lapunt and Lapunt (2024) studied the production of fuel briquettes from spent coffee grounds, aiming to examine the effectiveness of using spent coffee ground with wet starch as a binder at a ratio of 8:2 (spent coffee grounds to cassava starch). The study found that spent coffee grounds had a heating value of 5,262.97 cal/g, while the briquettes had a heating value of 5,033.92 cal/g. The fixed carbon content was 0.07 g/100 g, and the briquette density was 0.48 g/cm^3. Thermal efficiency testing by boiling water showed a maximum water temperature of 101.2 °C, a combustion duration of 100 minutes, a combustion rate of 5.03 g/minute, and an actual utilization efficiency of 21.90%. The spent coffee grounds briquettes ignited well, exhibited high combustion rates and produced smoke. Consequently, spent coffee grounds can be considered a viable alternative for producing fuel briquettes [21].

Tangmankongworakoon and Preedasuriyachai (2015) investigated the use of coffee and tea residues in the production of fuel briquettes. They produced two types of briquettes: (1) dried coffee and tea residues, and (2) carbonized coffee and tea residues at 500 °C, with a heating rate of 10 °C/min for 2 hours. The raw materials were mixed with wet starch glue at a 9:1 ratio and then cold-pressed into briquettes. The result showed that the heating value of carbonized coffee residue briquettes increased from 5,517 cal/g to 7,460 cal/g, while carbonized tea residue briquettes increased from 4,482 cal/g to 5,600 cal/g. Analysis of moisture content, ash content, and elemental composition indicated that the briquettes met biomass standards. Combustion tests showed the coffee residue briquettes ignited easily, burned without smoke, and did not spark or pop. The tea residue briquettes also ignited well but produced smoke due to their higher volatile matter content compared to coffee residues [17].

Thongchuchuay et al. (2022) studied the properties of briquette fuel made from spent coffee grounds and coconut husk. The research aimed to determine the optimal ratio between spent coffee grounds and coconut husk for forming compressed fuel briquettes and to examine their physical properties. The study found that fuel briquettes made from a mixture of spent coffee grounds and coconut husk, using cassava starch and rice flour as binder, could be successfully compressed at ratios of 2.5:7.5:2.6, 5.0:5.0:2.6, 7.5:2.5:2.6, and 10.0:0.0:2.6. However, the ratio of 0.0:10.0:2.6 could not be compressed into briquettes. In the testing of the fuel properties, the 10.0:0.0:2.6 ratio with cassava starch as a binder produced the highest density at 0.815 g/cm^3. The same ratio (10.0:0.0:2.6) with rice flour as a binder achieved the highest shatter index at 0.998. Additionally, the 10.0:0.0:2.6 ratio with cassava starch as a binder demonstrated the highest compressive strength at 265 kg/cm^2. The study concluded that using cassava starch and rice flour as binders resulted in fuels with slightly different physical properties [22].

Therefore, this research aims to explore the utilization of spent coffee grounds as an energy fuel by compressing them into pellet fuel, without requiring prior extraction or pre-treatment. The objective is to address the challenge of managing excessive coffee waste generated by coffee shops. The research will subject spent coffee grounds to various processes to enhance the fuel properties of resulting pellets and compare these properties with those of carbonized spent coffee ground pellet fuel. The ultimate goal is to develop more efficient pellet fuel that can serve as an alternative solid fuel for household use, with potential expansion into other industries in the future. The production process for these pellet fuels is straightforward, using easily accessible equipment that can be operated by households. In addition to repurposing waste, this initiative aims to reduce environmental impacts associated with improper waste management.

2.0 METHODOLOGY

2.1 Materials

2.1.1 Preparing Spent Coffee Grounds

Wet spent coffee grounds (WSCG) (Figure 1a) were subjected to a drying process to reduce moisture content using a hot air oven at 105 °C for 12 hours or until the moisture content was reduced to below 10%. The dry spent coffee grounds (DSCG) (Figure 1b) had a friable texture, did not clump together, and did not stick to hands when touched. The DSCG was then subjected to proximate analysis and heating values assessments in accordance with ASTM standards.

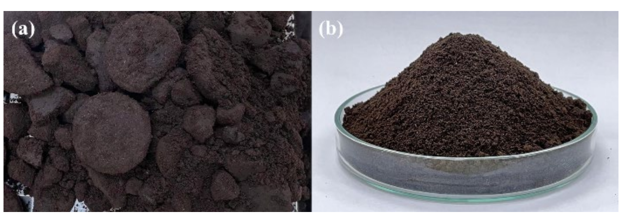


Figure 1 (a) Wet spent coffee grounds (WSCG); (b) Dry spent coffee grounds (DSCG)

2.1.2 Determining the Temperature Conditions for Carbonization Temperature

The SCG was subjected to thermal analysis using the thermogravimetric analysis (TGA) method. This analysis was conducted within a temperature range from 25 to 1,000 °C at a heating rate of 5 °C/min under a nitrogen atmosphere combustion. The results, as shown in the graph, show the relationship between weight loss (TG/%) and temperature (Figure 2). This data was used to determine the optimal temperature range for the carbonization process of the SCG.

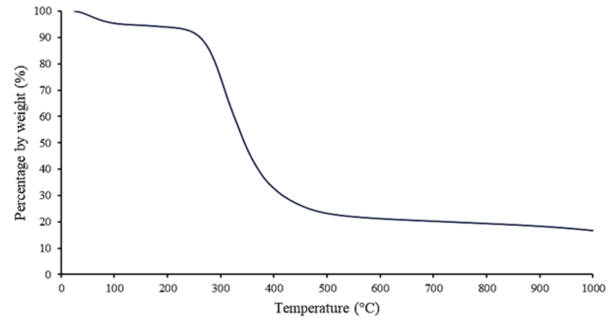


Figure 2 The relationship between temperature (°C) and the percentage weight change (%) of SCG

The TGA thermogram (Figure 2) reveals that moisture was removed from the SCG at a temperature between 25 and 250 °C. Rapid decomposition of volatile matter occurred between 250 and 500 °C, the weight loss was minimal, indicating an increase in the approximate percentage of fixed carbon. Therefore, the optimal temperature range of carbonizing SCG is between 250 and 500°C. In this research, two temperature conditions were selected for the carbonization of SCG: 250 °C and 350 °C, underwent carbonization in a tube furnace (Figure 3) with a heating rate of 5 °C/min under nitrogen gas atmosphere and a holding time of 2 hours. The carbonized SCG had mass yields of 97.7607% at 250°C and 47.6034% at 350°C.

Figure 3 Tube furnace for the carbonization process

2.2 Methods

2.2.1 Preparation of Pellet Fuel

The SCG used for pellet fuel production was prepared in three conditions: (1) dry spent coffee grounds (DSCG), (2) spent coffee grounds carbonized at 250 °C (CSCG250), and (3) spent coffee grounds carbonized at 350 °C (CSCG350). The pellet fuel was produced using the cold press technique with a binder, employing a custom-made single pellet press with a mold diameter of 10 mm and a length of 50 mm (Figure 4) to produce cylindrical pellets. Tapioca starch was used as a binder at 10% by weight (ratio of material to binder of 9:1) for all conditions. The pellet fuel was formed using a compression force of 799 Pascal (Pa). This identical compression force was applied 10 times under consistent material conditions. The pellets were pressed without initially reducing their moisture content. Subsequently, the wet pellets were dried either by sun-drying or in a hot air oven at 105 °C to reduce the moisture content to below 10% and prevent mold growth. This process resulted in dry pellet fuel ready for use.

Figure 4 Mold for pressing pellet fuel

2.3 Fuel Property Analysis

The testing of biomass fuel properties involves analyzing both physical and proximate properties to evaluate its suitability as an alternative energy source or for other applications. This assessment is conducted according to ASTM standards to ensure reliable and consistent test results. The findings are then compared with results from other sources to validate the effectiveness and quality of the biomass fuel.

2.3.1 Physical Analysis

This analysis involves evaluating observable external characteristics and using instruments to measure parameters such as weight, length, diameter, and properties related to the volume and density of the pellet.

(1) Size

This involves measuring the length and diameter of the pellet fuel using Vernier calipers.

(2) Bulk Density, ASTM E 873

The bulk density of pellet fuel is the density that accounts for the void spaces between the particles. It is calculated by dividing the total mass of the sample by the volume of the container holding the sample. Bulk density can be calculated using the equation (1).

$$\rho b = M / V \tag{1}$$

Where ρb = Bulk Density, kg/m^3
M = Mass of sample, kg
V = Volume of a container, m^3

(3) Durability Index, ASTM D3038

The durability index is a physical property of pellet fuel that reflects its practicality for real-world use, including its resistance to breakage during transport. To determine this, the sample is placed in a container and subjected to simulated transportation conditions. The fuel was tested by placing it in a closed container, dropping the container from a height of 2 meters, then sifting the fuel to remove any spent coffee grounds that had come loose. The weight of the fuel was compared before and after the test. The durability index can be calculated using the equation (2).

$$R = w / w_f \tag{2}$$

Where R = Durability index, %
w = Weight of the simple before testing, g
w_f = Weight of the sample after testing, g

2.3.2 Proximate Analysis

Proximate analysis of fuel properties is a method used to determine the combustible and non-combustible components of pellet fuel. This analysis measures the moisture content, ash content, volatile matter, and fixed carbon. It provides insight into the fuel's composition by evaluating the ratio of combustible to non-combustible components. The details of the of the testing procedure are as follows:

(1) Moisture Content, ASTM D 7852-10

This analysis determines the water content in the pellet fuel by drying the sample at 105 °C for 1 hour. The percentage of moisture content is calculated using equation (3).

$$M (\%) = [(B - C) / (B - A)] \times 100 \tag{3}$$

When A = Weight of the cup, g
B = Weight of cup and sample before testing, g
C = Weight of cup and sample after testing, g

(2) Ash Content, ASTM D 5373-08

This analysis measures the non-combustible component, or the inorganic matter, that remains after the sample has been completely burned at 650 °C for 3 hours. The percentage of ash content is calculated using equation (4).

$$\text{Ash Content } (\%) = [(C - A) / (B - A)] \times 100 \tag{4}$$

Where A = Weight of the cup, g
B = Weight of cup and sample before testing, g
C = Weight of cup and sample after testing, g

(3) Volatile Matters, ASTM D 5832-98

This analysis evaluates the volatile components of biomass fuel, which are gaseous and can vaporize when heated. Materials with high volatile matter content typically exhibit higher heating values. The released volatiles consist of both organic and inorganic substances [23]. After combustion, the primary volatiles released are carbon dioxide and hydrogen gas. The sample is burned at 950 °C for 7-10 mins. The percentage of weight loss is calculated using equation (5), and the percentage of volatile matter is calculated using equation (6), respectively.

$$\text{Weight loss } (\%) = [(B - C) / (B - A)] \times 100 \tag{5}$$

When A = Weight of the cup, g
B = Weight of cup and sample before testing, g
C = Weight of cup and sample after testing, g

$$\text{Volatile Matter } (\%) = D - M \tag{6}$$

Where D = Weight loss, %
M = Moisture content, %

(4) Fixed Carbon, ASTM D 3177-02

This analysis measures the fixed carbon content remaining after combustion. Fixed carbon represents the remaining combustible portion of biomass fuel after accounting for moisture content, ash content, and volatile matter. Fuels with high fixed carbon content are considered high quality, as they burn for a longer time. The percentage of fixed carbon is calculated using equation (7).

$$\text{Fixed carbon (\%)} = 100 - (M + V + A) \tag{7}$$

Where M = Moisture content, %
V = Volatile matters, %
A = Ash content, %

2.3.3 Heating Value Analysis, ASTM E 711

Heating value is the amount of heat generated when fuel is completely combusted. It is a crucial indicator of the energy content of the fuel. There are two key types of heating values: the higher heating value (HHV) and the lower heating value (LHV). Bomb calorimetry is a technique used to determine the heating value by combusting a fuel sample in a closed system. The energy released during this process is referred to as the calorific value or heating value.

The heating value of the fuel was determined using a Parr Oxygen Bomb Calorimeter (Figure 5). The pellet fuel was placed in a specialized metal cup and positioned on the support base. A 10 cm nickel wire was attached to both terminals of the bomb in a U-shape configuration. The Oxygen Bomb cylinder was sealed and pressurized with oxygen at approximately 30 atmospheres. The Oxygen Bomb was then submerged in a vessel containing 2 liters of distilled water. The vessel and Oxygen Bomb were placed in the calorimeter tank. After connecting the electrical wires to the bomb, inserting the thermometer, and adjusting the water stirrer, the stirring mechanism was activated. After 5 minutes, the bomb was detonated to ignite the fuel, and temperature and time data were recorded until the experiment's completion. The remaining nickel wire length was measured to determine the amount consumed. The temperature data and wire length measurements were then used to calculate the calorific value.

When reporting the calorific value of a sample, it is essential to provide results that accurately reflect the true energy content. The calorific value should be expressed in terms of the lower heating value (LHV) or net calorific value (NCV), which represents the practical energy available [24].

Figure 5 Bomb Calorimeter

3.0 RESULTS AND DISCUSSION

3.1 Proximate Analysis of Dry Spent Coffee Grounds

The sieving technique is widely utilized in powder technology to determine particle size distribution. This method has been employed by numerous researchers to analyze the particle size of SCG. Findings from these studies indicate that the majority of SCG particles ranged from 250-500 µm [25-27]. The collected SCG were analyzed for their fuel properties and heating value to determine their suitability for pelletization and use as a fuel. The results are presented in Table 1.

Table 1 The proximate analysis of dry spent coffee grounds

Proximate Analysis and Heating Value	Dry Spent Coffee Grounds (DSCG)			
	[A]	[B]	[C]	[D]
1. Proximate analysis				
Moisture content (wt.%)	11.69	6.64	8.38	6.32
Ash content (wt.%)	3.88	1.78	5.77	1.43
Volatile matters (wt.%)	70.03	72.15	75.98	77.46
Fixed carbon (wt.%)	16.22	19.43	18.25	14.79
2. LHV (MJ/kg)	-	23.1	18.5	16.8

Where [A] is Kang et al. [13]
[B] is Tangmankongworakoon and Preedasuriyachai [17]
[C] is Usapein and Tuntiwiwattanapun [18]
[D]* is DSCG used in this research

As shown in Table 1, the moisture content of the DSCG used in this research was 6.32% by weight. This is consistent with the low moisture content reported by Kang et al. [13], Tangmankongworakoon and Preedasuriyachai [19] and Usapein and Tuntiwiwattanapun [18]. The ash content of the DSCG was 1.43% by weight, indicating a very low amount of residual waste from combustion, like the finding of Tangmankongworakoon and Preedasuriyachai [17]. The volatile matter content was 77.46% by weight. While this is higher compared to the results reported by Kang et al. [13], Tangmankongworakoon and Preedasuriyachai [17] and Usapein and Tuntiwiwattanapun [18], it remains within a similar range. The fixed carbon content was 17.61% by weight, aligning with the results of the studies. The heating value of the DSCG was 16.8 MJ/kg. Although lower than the values reported by Tangmankongworakoon and Preedasuriyachai [17] and Usapein and Tuntiwiwattanapun [18], they still fall within the standard range for biomass pellet fuel.

The analysis of DSCG's fuel properties and heating value shows that SCG, when combusted, has a high heating value, low ash content, and long combustion time. These characteristics make SCG a viable biomass for fuel production. To enhance the value of SCG and improve fuel efficiency, a carbonization process is required to reduce the highly volatile matter and increase fixed carbon, thereby optimizing the fuel properties.

3.2 Properties of Spent Coffee Grounds Pellet Fuel

The physical analysis of spent coffee grounds pellet fuel includes measuring the length, diameter, durability index, bulk density, and weight of the pellets. The produced fuel pellets are solid, cylindrical in shape, and range in color from dark brown to black, depending on the conditions of the SCG used during the pelletization process, as shown in Figure 6.

Figure 6 Spent coffee grounds pellet fuel: (a) DSCG-PF; (b) CSCG250-PF; (c) CSCG350-PF

The physical analysis for spent coffee grounds pellet fuel under three conditions was conducted according to ASTM standards. The average values, obtained from ten replicate samples, are presented in Table 2 and Figure 7.

Table 2 The physical properties of spent coffee grounds pellet fuel

Physical Properties	Spent Coffee Grounds Pellet Fuel			STD
	DSCG-PF	CSCG250-PF	CSCG350-PF	
Length (mm)	32.6±2.0	33.9±2.0	31.5±2.3	3.15–40
Diameter (mm)	9.0±0.0	9.0±0.0	9.0±0.0	6–12
Durability index (wt.%)	98.0±1.0	98.0±1.0	99.0±1.3	≥95
Bulk density (kg/m^3)	783±11.5	698±13.9	603±14.4	≥600
Weight (g)	1.67±0.04	1.58±0.01	1.33±0.05	-

Remark: STD refers to the standards for biomass pellet fuel [28]

3.2.1 Size of Pellet fuel

The spent coffee grounds pellet fuel was found to have a length ranging from 28 to 40 mm and a diameter of 9 mm. Table 2 shows that the average lengths of the pellet fuel made from DSCG, CSCG250, and CSCG350 were 32.6, 33.9, and 31.5 mm, respectively. The diameter of the pellet fuel remained consistently 9 mm across all conditions.

The difference in diameter between the pellet fuel mold (10 mm) and the final dried pellet fuel (9 mm) is attributed to the cold pressing technique used in the pelletization process, which does not involve heat or moisture reduction. As a result, the pellets do not expand. The moisture content in these pellets was over 20%, necessitating further drying through hot air or sun drying to reduce the moisture content. During the drying process, the loss of moisture caused the pellets to shrink, affecting both their length and diameter. Consequently, the diameter of the dried pellet decreased from the initial 10 mm (mold size) to 9 mm (final product size).

However, when comparing the length and diameter of the pellet fuel to the standards for biomass pellet fuel, it was found that the spent coffee grounds pellet fuel from all three conditions meets the specified standards, which require a length of 3.15-45.0 mm and a diameter of 6.0-12.0 mm.

3.2.2 Bulk Density

The bulk density of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 783, 698, and 603 kg/m^3, respectively. Analysis indicates that the moisture content of SCG affects the bulk density, with lower moisture content leading to a decrease in bulk density. Despite this, all three conditions of spent coffee grounds pellet fuel meet the standard criteria for biomass pellet fuels, which require a minimum bulk density of 600 kg/m^3. This confirms that these spent coffee grounds pellet fuel are suitable for use, as shown in Table 2.

3.2.3 Durability Index

The durability index of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 98, 98, and 99% by weight, respectively. Analysis of these findings reveals that all three conditions of spent coffee grounds pellet fuel have very similar durability indices, ranging from 98 to 99% by weight. These values are well within the standard for biomass pellet fuels, which range from 50 to 100% by weight. Based on these results, it can be concluded that the different processing conditions of SCG do not significantly affect the durability index of the resulting fuel pellets. As shown in Table 2, spent coffee grounds pellet fuel maintains a high durability index regardless of the specific processing conditions used in their production. This high durability index is crucial for the practical use and transportation of the fuel.

3.2.4 Weight

The average weights of pellet fuel from DSCG, CSCG250, and CSCG350 were found to be 1.67, 1.58, and 1.33 g, respectively. Analysis shows that CSCG350-PF has the lowest average weight per pellet, which is attributed to its lower moisture content. The carbonization process effectively reduced both the moisture content and volatile matter in the SCG. As the moisture content and volatile matter decreased, the weight of the resulting fuel pellets also decreased. These findings, presented in Table 2, highlight the intricate relationship between processing conditions, moisture content, and the physical properties of spent coffee grounds pellet fuel.

Based on the findings from sections *3.2.2* and *3.2.4*, it can be concluded that there is a significant relationship between moisture content, pellet weight, and bulk density of the spent coffee grounds pellet fuel. The reduction in moisture content of the SCG led to a decrease in the weight of the pellets, which subsequently resulted in a decrease in their bulk density.

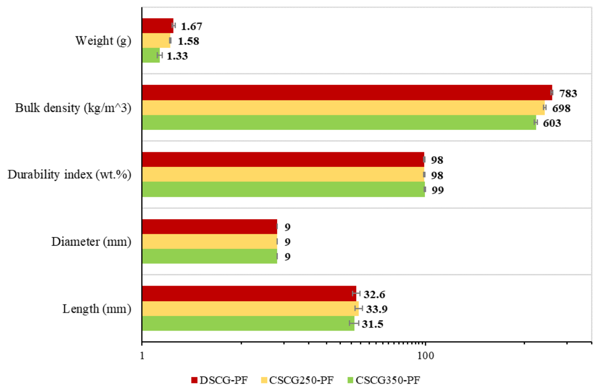


Figure 7 The physical analysis of spent coffee grounds pellet fuel

3.3 Proximate Analysis and Heating Value of Spent Coffee Grounds Pellet Fuel

The proximate analysis of spent coffee grounds pellet fuel involves determining the proportions of combustible and non-combustible components in the pellets. These components include moisture content, ash, volatile matter, and fixed carbon. The ratio of combustible to non-combustible components is then calculated. The results of this analysis are summarized in Table 3 and Figure 8.

Table 3 The proximate analysis and heating value of spent coffee grounds pellets fuel

Proximate Analysis and Heating Value	Spent Coffee Grounds Pellet Fuel			STD
	DSCG-PF	CSCG250-PF	CSCG350-PF	
1. Proximate analysis				
Moisture content (wt.%)	11.52±0.04	12.38±0.01	4.82±0.06	≤10.0
Ash content (wt.%)	0.94±0.01	1.25±0.02	2.05±0.13	≤20.0
Volatile matters (wt.%)	74.10±0.40	72.01±0.12	17.02±2.06	-
Fixed carbon (wt.%)	13.44±0.34	14.36±0.07	76.11±2.36	-
2. LHV (MJ/kg)	21.9	21.8	30.9	≥16.7

Remark: STD refers to the standards for biomass pellet fuel [25]

3.3.1 Moisture Content

The moisture content of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 11.52, 12.38, and 4.82% by weight, respectively, as shown in Table 3. The CSCG350-PF exhibited significantly lower moisture content compared to DSCG-PF and CSCG250-PF, likely due to the carbonization process, which reduced both the moisture content and volatile matter in the SCG, resulting in lower overall moisture in the final fuel product.

The CSCG250-PF showed slightly higher moisture content than the DSCG-PF. This minor difference may be attributed to the drying process used to reduce moisture content and solidify the pellets. During this step, the pellets were sun-dried until they appeared solid, with the drying process deemed complete when the pellets could be handled without breaking or sticking to fingers. After drying, the pellets were stored in moisture-resistant containers to prevent damage from ambient humidity.

3.3.2 Ash Content

The ash content of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 0.94, 1.25, and 2.05% by weight, respectively, as shown in Table 3. DSCG-PF exhibited the lowest ash content, followed by CSCG250-PF and CSCG350-PF. This trend is attributed to the carbonization process, which increased the percentage of fixed carbon, consequently leading to a higher ash content in the pellet fuel. Therefore, it can be concluded that the processing conditions of SCG significantly influence the ash content of the resulting fuel. Notably, the ash content of all three conditions of spent coffee ground pellet fuel falls within the standard for biomass pellet fuels.

3.3.3 Volatile Matters

The volatile matter content of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 74.10, 72.01, and 17.02% by weight, respectively, as shown in Table 3. The significantly lower volatile matter content in CSCG350-PF compared to DSCG-PF can be attributed to the carbonization process at 350 °C, which led to the decomposition of volatile matter in the SCG.

3.3.4 Fixed Carbon

The fixed carbon content of pellet fuel from DSCG, CSCG250, and CSCG350 was found to be 13.44, 14.36, and 76.11% by weight, respectively, as shown in Table 3. DSCG-PF and CSCG250-PF had similar fixed carbon content, while CSCG350-PF had the highest. This is due to the carbonization process, which reduced the volatile matter content and consequently increased the fixed carbon content. The higher fixed carbon content contributes to a longer burning time of the fuel.

3.3.5 Heating Value

The heating values of pellet fuel from DSCG, CSCG250, and CSCG350 were found to be 21.9, 21.8, and 30.9 MJ/kg, respectively, as shown in Table 3. DSCG-PF and CSCG250-PF exhibited similar heating values, while CSCG350-PF had the highest. This increase in heating value for CSCG350-PF is attributed to the carbonization process, which reduced the volatile matter content and consequently increased the fixed carbon content in the SCG. The higher fixed carbon content resulted in a longer combustion time and increased heating value of the pellet fuel. Therefore, CSCG350-PF, with the highest fixed carbon content, also had the highest heating value.

As shown in Sections *3.3.2, 3.3.3, 3.3.4,* and *3.3.5*, there is a correction between the percentage by weight of volatile matter, fixed carbon, and ash content. A decrease in volatile matter leads to an increase in fixed carbon, which subsequently results in a higher ash content. However, the increase in fixed carbon also contributes to a higher heating value of the fuel.

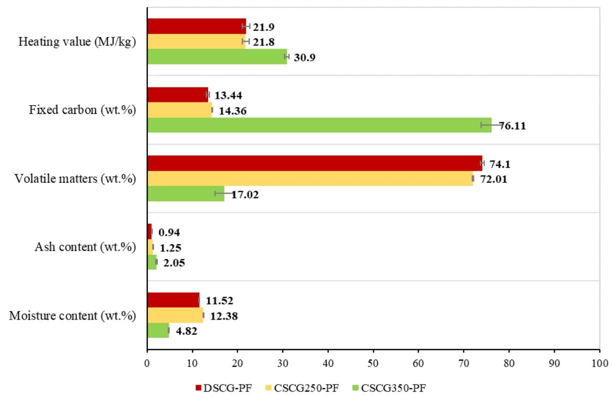


Figure 8 The proximate analysis and heating value of spent coffee grounds pellet fuel

4.0 CONCLUSION

The development of fuel properties in spent coffee grounds pellet fuel through the carbonization process revealed that CSCG350-PF exhibited the highest heating value of 30.9 MJ/kg, surpassing DSCG-PF at 21.9 MJ/kg and CSCG250-PF at 21.8 MJ/kg. CSCG350-PF showed a 40.1% increase in heating value compared to the DSCG-PF. All three conditions of spent coffee grounds pellet fuel exceeded the standard for biomass pellet fuels, set at 16.7 MJ/kg. Therefore, converting spent coffee grounds into pellet fuel presents a viable solution for coffee waste disposal, offering an effective alternative to other types of pellet fuels and being particularly suitable for household use.

The enhancement of energy properties in spent coffee grounds pellet fuel through the carbonization process provides an effective method for improving its fuel properties and significantly boosting its heat efficiency. Carbonization increases the efficiency of spent coffee grounds pellet fuel, maximizing resource utilization. This approach not only addresses the issue of coffee waste and reduces environmental impacts from improper disposal but also adds value to spent coffee grounds. Additionally, the pelletization process is straightforward and can be achieved with household materials. Besides reducing waste volume, this method helps minimize environmental impacts associated with improper waste management practices. It exemplifies a practical way to repurpose waste materials for beneficial use, contributing to both waste reduction and environmental conservation.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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