Assessment of spent coffee ground (SCG) and coffee silverskin (CS) as refuse derived fuel (RDF)

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Abstract. The implementation of waste into energy can be a solution for waste coffee handling. The mixture of spent coffee grounds (SCG) and coffee silverskin (CS) has the potential to produce better fuel. This study aims to determine the characteristics of SCG and CS and the effect of mixing SCG and CS on the quality of pellet fuel produced. Characteristics of SCG and CS as refuse derived fuel (RDF) include density, morphology, particle size distribution, parameters in biopolymer analysis, proximate and ultimate analysis. A densification method with a pressure of 195 MPa is used in the pellet-making process. Characteristics of pellet fuel analyzed include density, durability, proximate analysis, calorific value, and combustion testing. The results showed that the physical characteristics of CS were suitable for producing pellets with better density, durability, and combustion levels, but large amounts of CS in pellets potentially produce particulate and NOx emissions during combustion. Samples with a mixed composition of SCG, CS, and artificial adhesives are 75%, 20%, 5%, respectively, resulting in optimum quality pellets which conform to several parameters of the German pellet standard DIN 51731.

1. Introduction

Coffee is one of the major tropical commodities traded worldwide. Coffee production in the world increased by 1.99% from 1980 to 2013, and the generation of coffee waste is increasing along with the growth of coffee production. Organic materials with high levels of pollutants make this waste difficult to degrade [1]. The impact is declining soil and groundwater quality in coffee waste disposal areas. Coffee waste can also cause mutagenesis, which is responsible for DNA damage and toxicity to aquatic organisms [2].

Waste into energy can be implemented in the coffee waste treatment process. Coffee waste generated during brewing can be made into fuel and used as an alternative to coal [3]. In Adam's (1987) study, the calorific value of coffee powder was 6930 kcal / kg [4]. The high calorific value of spent coffee grounds (SCG) indicates its potential utilization as refuse derived fuel (RDF). However, the burning of pure SCG pellets can lead to low boiler efficiency resulting in increased particle emissions, thus additional material is required to produce good quality pellets. The addition of sawdust in SCG pellets can increase the burning and boiler efficiency from 86.3% to 91.9% and 64% to 83.5%, respectively [5].

In the coffee production process, the majority of solid waste generation is from spent coffee grounds (SCG) and coffee silverskin (CS) [6]. SCG is the residue of the brewing
process, which is the processing of coffee powder using hot water or steam to produce instant coffee. CS is a thin layer of the outer part of green coffee beans and a residue of the roasting process [7]. CS has a similar morphological structure to sawdust and its lignin content is higher than SCG [9]. Therefore, CS can be used in the mixture of SCG pellets.

The proportion of SCG and CS is important in the manufacture of pellets. The difference in quantity of the SCG and CS waste generated becomes the basis in determining the mixture proportions. This study aims to determine the characteristics of SCG and CS and the effect of mixing SCG and CS on the physical and chemical quality of the refuse derived fuel (RDF) produced. RDF is a solid waste processing technique that converts waste into fuel [9]. In this study RDF is produced in pellet form.

2. Research Method

2.1. Pellet Fuel Design

The composition of pellet fuel is as follows:

| Sample | SCG (%) | CS (%) |
|--------|---------|--------|
| 1      | 95      | 0      |
| 2      | 85      | 10     |
| 3      | 75      | 20     |
| 4      | 65      | 30     |
| 5      | 55      | 40     |

The adhesive in the pellets is made from a 5% starch composition with an 11% viscosity rate. Each pellet has a diameter of 8 mm with a length of 30–50 mm. The particle size is smaller than 0.85 mm. The water content is 10%–14%. The process used for making pellets is a densification technique (compaction). The pressure used is 195 MPa for 15 minutes.

2.2. Characteristics of Refuse Derived Fuel

RDF consists of physical and chemical characteristics. Physical characteristics include specific gravity, moisture content, particle size, and morphology. The chemical characteristics of solid waste include proximate analysis, ultimate analysis, and the resulting energy content [10]. Parameters in the proximate analysis consist of moisture, volatile content, ash, and fixed carbon. Parameters in the ultimate analysis consist of Carbon, Hydrogen, Oxygen, Nitrogen and Sulphur. The characteristics of biopolymers include cellulose, hemicellulose, and lignin content.

2.3 Characteristics of Pellet Fuel

Tests of pellet fuel characteristics include density, durability, parameters in the proximate analysis, calorific values, and combustion. Data obtained in the combustion process included the duration of fire time and temperature produced for 12 minutes. This data was compared with the German pellet literature and standard DIN 51731. DIN 51731 is the standard issued in 1996 for briquettes and pellets usually applied to small-scale pellet burning processes.
3. Results

3.1 Pretreatment

The pretreatment process consists of drying, grinding, and the sample storage process. The raw materials used are SCG and CS. SCG and CS have a moisture content of 67% and 1%, respectively. The high water content of the sample affects the quality of RDF, thus a drying process is needed. The process used is an open drying method which reduces water content by utilizing radiant heat emitted by sunlight for 2–3 days, decreasing water content from 67% to 10%.

Below is the distribution of particle size of the SCG and CS raw materials.

![Size distribution of SCG (left) and CS (right) samples](image1)

**Figure 1.** Size distribution of SCG (left) and CS (right) samples

The particle size of SCG is homogeneous where 52% of SCG particle size is smaller than 0.85 mm, but different CS sizes require a process to obtain a size smaller than 0.85 mm.

3.2 Refuse Derived Fuel Characteristics

3.2.1 Morphology

![Scanning Electron Microscopy(SEM) test results from SCG (left) and CS (right) samples](image2)

**Figure 2.** Scanning Electron Microscopy(SEM) test results from SCG (left) and CS (right) samples

CS particles have a denser fiber structure compared to SCG, meaning that CS particles have a lower porosity than SCG. The porosity of raw materials affects utilization processes, one of which is the densification process [8]. The high porosity of SCG results in low-density raw material as there are many voids between the particles. On the contrary, the low porosity of
the particles in CS causes high-density samples during the compaction or densification process.

Table 2. Characteristics of SCG and CS as RDF

| Parameter        | SCG  | CS  |
|------------------|------|-----|
| Moisture (%)     | 67   | 1   |
| Volatile (%)     | 32   | 91  |
| Ash (%)          | 0.30 | 1.30|
| Carbon (%)       | 43   | 49  |
| Hydrogen (%)     | 8.65 | 6.46|
| Oxygen (%)       | 45.44| 38.83|
| Nitrogen (%)     | 1.41 | 3.21|
| Sulphur (%)      | 1.60 | 2.80|
| Hemicellulose (%)| 30.49| 33.04|
| Cellulose (%)    | 8.71 | 5.46|
| Lignin (%)       | 21.37| 27.08|

3.2.2 Proximate analysis

The optimal water content for the densification process is approximately 8–23% [15]. The water content of the sample will affect the calorific value. High water content results in a low calorific value because water (H₂O) has no calorific value. The volatile content in the raw materials indicates the ability of the sample to burn. The high volatile content of CS is expected to speed up the ignition time of the burning pellets. Volatile substances can shorten the time to reach combustion temperatures, but an excessive number of volatiles in a sample can cause fuel to burn faster. The ash content indicates the emission of ash and particulate matter that will be generated by the combustion process [12].

3.2.3 Ultimate analysis

Carbon and oxygen are the main elements that contribute to the combustion process. Carbon and oxygen content are the most abundant raw materials, i.e. ± 40%. It is high carbon and oxygen content that provides SCG and CS the potential to be utilized as RDF [11]. The nitrogen content in SCG is 1.41%, lower than the N content in coal (about 3%), but the N content in CS is quite high at 3.21%. However, high nitrogen content can cause NOₓ pollutants [12].

3.2.4 Biopolymer analysis

The random hemicellulose structure simplifies the hydrolysis process or dissolution in an alkaline solution. The high hemicellulose content of both feedstocks support the densification process. Cellulose is a polysaccharide consisting of hundreds, to hundreds of thousands of glucose bonds. Cellulose is also considered an abundant source of carbon in biomass. The hydrogen bonds present in cellulose can be formed by the increase in temperature that makes cellulose more flexible. Lignin content is a component that has a major influence on the densification process, as it allows adhesion in wood structures and acts as a reinforcing and bulking agent. Lignin is also a content fuel because it produces more energy than cellulose when combusted. The presence of lignin in plant material allows pelletization without adding
an adhesion [13]. Lignin content in SCG and CS is fairly high, above 20%. The greater lignin content in CS helps the densification process by forming a natural adhesion in the pellet.

3.3 Pellet Fuel Characteristics

3.3.1 Pellet fuel results

![Figure 3. Pellet samples](image)

Each pellet has a diameter of 8 mm with different lengths. Pellets of good quality tend to be intact, but poor quality pellets will be easily cracked and broken. In sample 1, the resulting pellets were cracked and broken and adding CS to samples 2–5 increased the durability of the pellet, whereby the resulting pellets were more intact.

| Parameter               | DIN 51731        | Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 |
|-------------------------|------------------|----------|----------|----------|----------|----------|
| Diameter (mm)           | 4–10             | 8        | 8        | 8        | 8        | 8        |
| Length (mm)             | <5D              | 15–20    | 30–50    | 30–50    | 30–50    | 30–50    |
| Density (kg/dm$^3$)     | <1,2             | 0.806    | 1.026    | 1.051    | 1.154    | 1.167    |
| Durability (%)          | -                | 84.7     | 95       | 99       | 91.2     | 95.9     |
| Moisture (%)            | <12              | 13.9     | 13       | 12       | 11.2     | 10.3     |
| Volatile (%)            | -                | 85.5     | 85.7     | 86       | 86.1     | 86.8     |
| Ash (%)                 | <1.5             | 0.1      | 0.5      | 0.5      | 0.6      | 0.6      |
| Fixed Carbon (%)        | -                | 0.5      | 0.8      | 1.5      | 2.1      | 2.4      |
| Calorific value (cal/g) | 3,707–4,661      | 4,710    | 4,681    | 4,618    | 4,331    | 4,248    |
| Calorific value (cal/m$^3$) | -                 | 4,018    | 4,803    | 4,855    | 5,001    | 4,957    |
| Additives (%)           | -                | 5        | 5        | 5        | 5        | 5        |

3.3.2 Proximate analysis
Mixing SCG with CS decreases moisture content and increases volatile content in the sample, thus improving the sample quality. High moisture and low volatile content inhibit the combustion process and thus it takes a longer time to ignite the sample [14]. However, the addition of CS in large quantities can increase the ash content, adding to the waste volume to be processed before disposal in the landfill. Moisture content in pellets according to the German DIN 51731 standard is <12% and ash content is <1.5%. The samples that meet the water content standards are 1, 2, and 3. The ash content produced by all samples meets the German DIN 51731 standard.

3.3.3. Energy density
Densification increases the density of raw materials 2–4 times (Figure 4). An increase in density reduces the volume of raw materials thereby increasing the efficiency of storage, delivery, and lowering the risk of damage. Bulk density is influenced by moisture content, particle size, natural adhesive content, and raw material morphology. The optimal moisture content and particle size improve lignin function during the densification process. High lignin content in CS results in better compaction rates. The morphology of CS raw materials has a lower porosity, i.e. smaller pore space, than SCG raw materials, providing favorable results in the densification process. The resulting pellet density range is 800–1200 kg/m$^3$. In the German DIN 51731 pellet standard pellet density value is 1000–1400 kg/m$^3$. In this study pellets that meet these standards are samples 2–5.

![Figure 4. Energy density](image)

Since the carbon and oxygen content of the CS raw material is lower than SCG raw material, the addition of CS decreases the calorific value (cal/g) in the pellet. Based on the German DIN 51731 pellet standard, the pellet heating value at 3705–4661 still meets these standards. The calorific value generated from the test uses an energy unit per mass unit. The density and calorific value obtained are used to determine the energy content in the volume unit.

High-density pellets will produce greater energy than low-density pellets. The increase in heating value due to the densification process is approximately 1–4 times. Increasing pellet density by the addition of CS to the pellets also has an impact on the energy produced. Increasing the amount of energy in volume units will also improve the efficiency of pellet storage.

3.3.4. Durability
Durability affects the storage and delivery process of pellets. Figure 5 shows the abrasion rate of the pellet and shows the percentage of the final mass divided by the initial mass when the durability test is performed. The addition of CS to SCG increases the durability of pellets 1.1–1.3 times.

![Figure 5. Durability](image)

One of the factors affecting durability is the density of pellets—the higher the pellet density, the higher the durability. Other factors affecting durability are the lignin and water content of the sample. Low moisture content inhibits the activation of lignin content in the raw material. Sample 3 has the highest durability, where the optimum moisture content is obtained and activates lignin contained in the raw material. The durability of the pellets on day 7 increases 5–10% from day 1 due to the stronger bond between particles in the pellet fuel.

3.3.5. Combustion process
In the pellet combustion test a 10 gram sample was applied to the furnace, then burned for 3 minutes to fire the pellets. The temperature was measured for 12 minutes. Below are the observed results of the combustion process for each sample.

| Sample | Duration of flame | Explanation |
|--------|------------------|-------------|
| 1      | No flame         | The sample did not produce a flame, but a coal |
| 2      | 30 seconds       | The flame is small and does not last long |
| 3      | 90 seconds       | Constant flame |
| 4      | 22 seconds       | The flame is large but burns quickly |
| 5      | 30 seconds       | The flame is large but burns quickly |
In this research, it was determined the peak combustion temperature of SCG and CS is 500–600°C. The peak temperature is the temperature achieved during stoichiometry. In the graph of the effect of temperature with time (Figure 6-right), the addition of CS to SCG results in a slow decrease in temperature and tends to be constant. In Figure 6-left, the resulting temperature tends to be constant for a few minutes then drops dramatically in the seventh minute, while in Figure 6-right the decrease in temperature is relatively constant. One factor that affects the resulting temperature is pellet density, which affects combustion efficiency [12]. Temperature stability is an important factor in the fuel supply of a boiler or furnace. Irregular temperature changes can decrease heating efficiency, while the expected temperature in a boiler is relatively constant.

### 3.3.6. SCG and CS mixture

Based on the German pellet standard DIN 51731, sample 3 is the best pellet, with 75% SCG, 20% CS, and 5% artificial adhesive. Sample 3 has the highest durability and optimum water content. In the combustion process, sample 3 had a constant flame and decrease in temperature.

### 4. Conclusion

Based on testing the characteristics of CS, SCG, and pellets, the CS morphological structure has a lower porosity than SCG, so a mixture of both feedstocks can increase the density of the pellets. Higher volatile content in CS than SCG improves the combustion quality of the pellets, but the addition of large amounts of CS results in reduced flame duration. The ash content in CS is higher than in SCG. Mixing CS with SCG results in an increase in the ash content in the pellets. The nitrogen content in CS is higher than in SCG, thus mixing CS with SCG may result in increased NO\textsubscript{x} emissions in the air. The addition of CS in large quantities is not recommended. The lignin content in CS is higher than in SCG, and mixing CS with SCG improves the density and durability of the pellets. The mixing of CS and SCG does not significantly affect the energy value and is still within the standard range of pellets. But in the energy calculation per unit volume, the addition of CS can increase the energy produced due to the increase in pellet density. The decrease in temperature caused by mixing CS with SCG is relatively constant because the pellet density affects combustion efficiency.

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