Material flow analysis for energy potential in coffee production

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Abstract. Agricultural waste has the potential of biomass as a raw material for producing renewable energy. The primary processing of coffee produces waste from pulping and hulling activities. Waste can be processed further through composting, anaerobic water waste treatment and burning to be converted into electrical energy. Therefore, the calculation is needed that estimates the amount of potential biomass that is converted. Then, the purpose of the paper is to analyze each stage in the life cycle of Gayo Arabica coffee and calculate the potential amount of electrical energy produced. The life cycle assessment method uses material and energy analysis intending to explain the flow of inputs and outputs within the system boundary and analyze the movement and transformation of materials, energy, waste, and emissions. In the context of the paper, the study uses material flow analysis to estimate the biomass potential from solid and water waste treatment. The study uses interviews, observations and a cooperative report located in Central Aceh district as an Arabica coffee producer area in Indonesia. Production of Arabica coffee is managed by cooperatives involving small farmers and collectors from cultivation, primary processing, packaging, and delivery. Cultivation uses the agroforestry system with a shade tree of the type of lamtoro (\textit{Leucaena leucocephala}). Packing with a pack of burlap is done by the cooperative. Activities undertaken cooperatives include the acceptance of coffee beans from the collector. Since 2016 cooperatives implemented a policy of processing coffee beans at the collector level. The estimation of the study shows that waste treatment through anaerobic water waste treatment, composting and combustion from 1 ton of cherry coffee (primary processing) has an energy potential of 34 kwh.

Keywords: Arabica Coffee, By Product, Energy Potential, Material Flow Analysis, Waste Treatment

1. Introduction
Coffee production produces commercial coffee beans and potential by-products with high added value [1]. The by-products usually generated from linear and open production systems [2] that produce solid and liquid pollutants that have the potential to contaminate land and water [3]. Pollution from untreated organic matter will affect the environment, causing global warming [4], eutrophication and acidification [5].

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Sustainable coffee agroindustry can be achieved by implementing closed and cycle production models in the entire production process. By-products optimization and reuse of resources are needed [6]. The model is known as the application of industrial symbiosis in the study of industrial ecology at the regional scale [7]. The model has been applied in the development of the Rubber City area in Malaysia [8] and in the utilization of cassava by-products in Thailand [9]. Both studies use the management of mass and energy flow in the entire process and evaluate the potential utilization of by-products and their impact on the environment.

In coffee production, the by-product is the pollution source, and when waste management technology is applied, by-products become a source of renewable energy (biogas or bioethanol) and organic matter (compost). The potential can be estimated using mass flow analysis or MFA (Material Flow Analysis). MFA can be used to calculate various streams in the process, including broader studies, environmental calculations, and as a basis for system analysis [10].

Gayo Plateau is one of the largest Arabica coffee producer, located in Aceh Province with the administrative regions of Central Aceh and Bener Meriah. The coffee plantation area, which is planted together with the lamtoro (Leucaena leucocephala) shade tree [11] is known as a coffee agroforestry model [12]. Fertilizers are derived from water and solid waste of the pulping and hulling process [11], pruning from the branch of lamtoro tree, weeds, and sometimes lemongrass [13].

Primary processing starts with harvesting the cherry coffee and ends at the delivery of the beans. Generally, organic material waste is dumped on land or waterbody without further handling. A common practice is by storing organic material into the soil for six months and use it as fertilizer.

Farmers sell the coffee beans to collectors after the pulping process. Collectors dry the beans and grind using hullers that have been certified by organic processing machines. The beans then sold to the cooperatives. Cooperative further process the beans through sorting, grading, and packing. Generally, the primary processors of Gayo Arabica coffee are involved in exporters’ cooperative.

Optimizing the utilization of organic materials is expected to benefit all actors. Hence, it is necessary to analyze the raw materials flow and estimate the potential by-products from each actor.

This study formulated a coffee production model and used raw material flow analysis to estimate the production of energy and organic fertilizer. The energy was expected to be utilized for electricity generation. The primary data used came from the parties involved in the production. They were farmers, collectors, huller owners, and cooperative management. Mass flow analysis was limited to data available in 2016.

2. Methodology

2.1. The Analysis of Mass and Energy Balance

2.1.1. Mass and Energy Balance in Pulping, Hulling, and Drying. The calculation of mass and energy balance was based on the law of conservation of mass and energy, which states that mass and energy cannot be created or destroyed, but they can be transformed into another form. The mass and energy balance did not involve a chemical reaction because the green beans coffee was generated through drying and physical separation.

In the calculation, the basic mass balance employed was 100 kg of cherry coffee. Based on the proximate analysis of processed cherry in the cooperative, the composition was dominated by dry pulp (24%), dry parchment (3%), dry green bean (21%), and water (52%).

The mass balance was calculated based on the law of mass balance [14] with the formula in equation (1):

\[ m_{\text{input}} = m_{\text{output}} \]  

Where:
- \( m_{\text{input}} \) = input mass (kg)
- \( m_{\text{output}} \) = output mass (kg)
In some production processes, production costs can be estimated based on the number of energy needs. The basic concept of energy balance is defined in equation (2):

\[ E_{\text{input}} + E_{\text{output}} \pm Q = 0 \]  

Where:
- \( E_{\text{input}} \) = energy input (MJ)
- \( E_{\text{output}} \) = energy output (MJ)
- \( Q \) = heat (MJ)

The assumptions used in the calculation of the energy balance were:
- the energy enters the process as electrical and fuel energy and exit as carbon emissions
- one-dimensional flow at both the entrance and the exit process
- kinetic energy and potential energy were ignored

The mass and energy balance analysis were performed in all processes (pulping, hulling, and drying).

2.1.2. Energy Balance in Land Transportation. Energy balance inland transportation was calculated based on the total fuel used during transportation and exit as carbon emissions.

2.2. The Analysis of Energy Potential from By-product
Conversion of wastewater, pulp, and parchment to energy was calculated based on the generated methane (CH\(_4\)).

2.2.1. \( \text{CH}_4 \) Generated from Wastewater. The energy potential from wastewater was calculated based on anaerobic wastewater treatment. Wastewater from the coffee processing contains BOD around 3,800 – 4,780 mg/L (average 4,290 mg/L) [15]. The wastewater must be treated to reduce the BOD level to a maximum value of 90 mg/L before discharged into the waterbody. It is based on the Regulation of the Minister of Environment of the Republic of Indonesia Number 5 of 2014 concerning Wastewater Quality Standards for Businesses and/or Coffee Processing Industry Activities. Based on observations, there was a BOD value of 4,200 mg/L (0.0042 kg/L), which must be removed before the wastewater can be discharged safely. According to [16], the maximum methane (CH\(_4\)) production per kg of BOD removed is 0.6 kg CH\(_4\)/g BOD. Methane gas generated from the wastewater was estimated using equation (3):

\[ CH_{4\text{ww}} = \frac{BOD_{\text{in}} - BOD_{\text{out}}}{1000} \times Q \times 0.6 \]  

Where:
- \( CH_{4\text{ww}} \) = methane gas generated from the wastewater (m\(^3\)/yr)
- \( BOD_{\text{in}} \) = BOD concentration in the inlet of biogas reactor (mg/L)
- \( BOD_{\text{out}} \) = BOD concentration in the outlet of the biogas reactor (mg/L)
- \( Q \) = flow rate of wastewater (m\(^3\)/yr)
- 0.6 = potential of methane generated (m\(^3\)/kg BOD removal) [16]

2.2.2. \( \text{CH}_4 \) Generated from Pulp. The energy potential from the pulp was calculated based on the composting method. Methane gas generated from the parchment was estimated using equation (4):

\[ CH_{4\text{ww}} = \frac{\pi p x 0.004}{15} \times 22.42 \]  

Where:
\[ \text{CH}_4 = \text{methane gas generated from the pulp (m}^3/\text{yr)} \]
\[ \Sigma p = \text{activity data from emission source are using mass (kg)} \]
\[ 0.004 = \text{CH}_4 \text{ factor (kg/kg wet waste)} \][16]
\[ 16 = \text{molecular Weight of CH}_4 (\text{kg/kg mol}) \]
\[ 22.42 = \text{specific volume of ideal gas (m}^3/\text{kg mol CH}_4) \]

2.2.3. **CH}_4 Generated from Parchment.** The energy potential from parchment was calculated based on the burning treatment. Methane gas generated from the parchment was estimated using equation (5) and equation (6):

\[ C = \frac{\Sigma p \times HC}{16} \times 22.42 \quad (5) \]

Where:
- \( C \) = consumption (TJ)
- \( \Sigma p \) = activity data from emission source are using mass (kg)
- \( HC \) = heat content per unit (TJ/kg)
- 16 = molecular Weight of CH\(_4\) (kg/kg mol)
- 22.42 = specific volume of an ideal gas (m\(^3\)/kg mol CH\(_4\))

\[ \text{CH}_4_{\text{wvw}} = C \times 42.5 \times 0.98 \quad (6) \]

Where:
- \( \text{CH}_4_{\text{wvw}} \) = methane gas generated from the wastewater (m\(^3\)/yr)
- \( C \) = consumption (TJ)
- 42.5 = emission factor of CH\(_4\) (m\(^3\) CH\(_4\)/TJ) [16]
- 0.98 = efficiency factor

2.2.4. **Energy Potential from Wastewater, Pulp, and Parchment.** By using the equation, the potential of methane generated per year in the observed coffee green bean production can be estimated. Energy can be estimated based on the potential of methane generated from the wastewater, pulp, and parchment. The heating value of methane was used to calculate the energy generation from the wastewater using equation (7):

\[ P = [\text{CH}_4_{\text{wvw}} \times 1.17] \times LH_v \times 0.35 \quad (7) \]

Where:
- \( P \) = power generation (MJ)
- \( \text{CH}_4_{\text{wvw}} \) = methane gas generated from the wastewater (m\(^3\)/yr)
- 1.17 = conversion value from a unit of m\(^3\) to a unit of Nm\(^3\)
- \( LH_v \) = Low Heating Value of methane (=35.8 MJ/Nm\(^3\)) [17] [18]
- 0.35 = conversion efficiency from biogas to electricity [18]

The potential energy value obtained from the calculation was expressed in electric potential per ton of cherry coffee (kWh/ton of cherry coffee).

3. Result and Discussion

3.1. **Material Flow in Coffee Primary Processing**
Production Model of Arabica coffee was managed by the cooperatives involving the parties from the cultivation activities, primary processing, packaging, and delivering. Cultivation used the agroforestry system with a shade tree of lamtoro (*Leucaena leucocephala*), fruits (avocado (*Persea Americana*),
orange (*Citrus reticulate*), and Dutch eggplant (*Solanum betaceum*), forest trees (such as silk tree (*Albizia Chinensis*), local trees that grow in specific area (such as bishop wood (*Bischofia javanica*)). The primary processing of wet and semi-wet methods was common in Gayo plateau. Packing with a burlap was conducted by the cooperative. Activities carried out by cooperatives were receiving coffee beans from collectors, sorting, and assessments based on SNI standards for export of coffee beans, packaging, storage, and shipping to the port (Belawan, North Sumatra) using cargo truck.

Since 2016 the cooperative has implemented a good coffee bean processing policy at the collector level to develop milling facilities. Before, the removal of husk skin (parchment) was carried out in cooperatives by burning. During peak harvest (October - November), there were often untreated coffee beans in the drying process. Burning parchment produced smoke and pollution. Also, the by-product from primary processing (dry skin, broken coffee beans, gravel, twigs) became waste and untreated. Burning and waste accumulation caused pollution around the cooperative and adversely affects the aesthetics (causing bad odors and view), soil (washing process), and human health (from burning smoke). The cooperatives have developed 10 Huller facilities in the selected collectors. The mass balance and energy used models followed the following stages of pulping, peeling, drying, and finishing processes (figure 1).

**Figure 1.** The processing process of the primary semi-wet method.
**Pulping.** Pulping is a process to remove skin components and pulp in the cherry coffee. Cherry coffee was processed on a pulper by adding water to produce “labu” coffee that will be further processed. This process also generated pulp as the by-product. Mass balance in the pulping process indicated that 1 kg of cherry coffee (100%) with a moisture content of 60% will produce 0.41 kg of “labu” coffee (41%) with the water content of 40%, and 0.59 kg of pulp (59%) with water the content of 60%. The pulping required 2 L water per 1 kg of processed coffee (2:1), so that about 2 L wastewater will be generated. The pulping was carried out by the farmer, the resulting “labu” coffee will be sold to the collector and then sold to the cooperative.

**Drying Phase 1.** The drying was conducted to decrease the water content of “labu” coffee from 40% to ±27%. The mass balance on drying shows that 1 kg of cherry coffee or 0.6 kg of “labu” coffee will produce 0.33 kg of dry “labu” coffee (33%) and 0.07 kg of water vapor (7%). Drying Phase 1 was conducted by the cooperative.

**Hulling.** Hulling is the removing of husk skin and silver components found in “labu” coffee. Coffee was processed on the huller to produce grain coffee that will be processed further, and the husk skin (by-product). The mass balance in the reprocess conducted in Gayo, Indonesia indicates that 1 kg of cherry coffee or 0.33 kg of dried “labu” coffee with a moisture content of ±27% will produce 0.28 kg of green coffee (28%) with water content of ±27% and 0.05 kg of husk skin (5%) with water content of ±27%. The hulling process was conducted by selected collectors.

**Drying Phase 2.** The drying process was done to reduce the beans’ water content from ±27% to ±16%. The mass balance in the drying process indicates that 1 kg of cherry coffee or 0.28 kg of green coffee will produce 0.23 kg of green bean (23%) and 0.05 kg of water vapor (5%). The drying phase 2 was conducted by the cooperative.

### 3.2. Energy Potential Production

The policy to build ten hullers as a factory for the hulling process built a network between farmers and collectors based on the proximity to the huller. Therefore, the utilization of by-products was based on their availability in certain huller production networks. Table 1 shows the value of electricity potential per 1 ton of coffee cherry against the waste category (wastewater, pulp, and parchment) produced. Energy generated from each waste category can be estimated based on the potential of methane generated in each waste category.

Potential calculation (table 1) shows that from the pulping of 1 ton of cherry coffee, 20.53 kWh of electricity was generated from liquid waste and 13.70 kWh from solid waste (pulp). The hulling of 1 ton of cherry coffee or 0.4 ton of “labu” coffee beans produces an electrical energy potential of 0.09 kWh. Therefore, energy potential and organic fertilizer generated is varied between the production networks.

At 29,500 tonnes/yr wastewater with a BOD content of 4290 mg/L can produce CH₄ of 86,979 Nm³/yr. The resulting CH₄ was multiplied by the Low Heating Value of methane (35.8 MJ/Nm³) to obtain Heat Potential 3,113,848 MJ/yr. The resulting Heat Potential is multiplied by conversion efficiency from biogas to electricity (0.35) to a Power Potential of 302,759 kWh or 20.61 kWh/ton of coffee cherry.

At pulp of 8,702 ton/yr, it can produce CH₄ of 57,067 Nm³/yr during the composting process. The resulting CH₄ was multiplied by the Low Heating Value of methane (35.8 MJ/Nm³) to obtain Heat Potential 2,042,998 MJ/yr. The resulting Heat Potential is multiplied by the conversion efficiency from biogas to electricity (0.35) to a potential of 198,641 kWh or 13.52 kWh/ton of coffee cherry.

A parchment of 735 tonnes/yr can produce CH₄ of 392 Nm³/yr during the combustion process. The resulting CH₄ was multiplied by the Low Heating Value of methane (35.8 MJ/Nm³) to obtain a Heat Potential of 14,050 MJ/yr. The resulting Heat Potential is multiplied by conversion efficiency from biogas to electricity (0.35) to a Power Potential of 1,366 kWh or 0.09 kWh/ton of coffee cherry.
Table 1. Potential methane produced from coffee wastewater, pulp, and parchment into electrical energy.

| Waste Category (Equation) | Waste Treatment Method | Methane Generated (m³/yr) | Methane Potential (Nm³/yr) | Heat Potential (MJ/yr) | Power Potential (kWh) | Electricity Potential (kWh/ton cherry coffee) |
|---------------------------|------------------------|---------------------------|---------------------------|-----------------------|-----------------------|-----------------------------------------------|
| Wastewater (3)            | Anaerob WWTP           | 74,054                    | 86,643                    | 3,101,829             | 301,591               | 20.53                                         |
| Pulp (4)                  | Composting             | 49,413                    | 57,814                    | 2,069,732             | 201,240               | 13.70                                         |
| Parchment (5),(6)         | Burning                | 335                       | 392                       | 14,050                | 1,366                 | 0.09                                          |
| **Total**                 |                        |                           |                           |                      | 504,197               | 34.31                                         |

4. Conclusions
Potential by-products that can be utilized as renewable energy and organic fertilizer were derived from pulping and hulling processes. Pulping activities produce pulp (59% by weight of cherry coffee) and liquid waste (200% by weight of cherry coffee). The handling of pulp and liquid waste as a source of methane production has an electrical potential of 34.23 kWh per 1 ton of cherry coffee using the Anaerobic WWTP and Composting methods. Hulling activities produce parchment (0.05% by weight of cherry coffee). Handling parchment through combustion has an electrical potential of 0.09 kWh per 1 ton of cherry coffee.

The amount depends on the availability of cherry coffee and wastes treatment methods. The amount of electricity potential differs at the farmer and huller level. On a 1-ton cherry coffee basis, the ratio of waste heat potential (352 MJ/year/ton) is higher to energy consumption at the farm level (194 MJ/year/ton). But on the same basis, the heat potential at the collector level (0.96 MJ/year/ton) is lower than energy consumption (38.28 MJ/year/ton). Therefore, further studies are needed to be related to waste allocation planning and the feasibility of waste management technology. Research integrating waste and energy management is needed to optimize the economic and ecological benefits of the coffee production system.

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