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RESEARCH ARTICLE

CLOSED PRODUCTION FOR WET PROCESSING OF ARABICA COFFEE

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Abstract

The wet processing of Arabica coffee consumes energy and water, and generate large amounts of by-products. These by-products contain organic materials that cause environmental pollution and degradation. Some of the by-products are energy containingcompounds that can be used to supply energy needs in the production process. This study aims to develop a closed model of energy-independent Arabica coffee production. The model was developed based on mass flows in the coffee production process.One mass balance equation can be made for each stage of the process. The model showed that the optimal yield of green coffeebean production was 28%. Coffee production of a capacity of 5,500 kg of cherries per day has energy potential of by-products of 6,161,286 kcal originating from the outer skin, pulp and parchment. Energy conversion using boiler can meet production energy needs of 117.20 kWh per day. This study concluded that Arabica coffee wet processing can be developed as an energy independent production by optimally utilising of by-products.

Introduction:-

The use of coffee as a beverage has a significant positive impact to social and economic aspect, and a negative impact on the environment (1). Arabica coffee has a high selling price and good taste quality, so this type of coffee is widely used as a raw material for production of beverages (2). The majority of Arabica coffee is produced using wet process of the aim at maintaining the distinctive flavor quality of the brewed coffee (3).

The wet process of Arabica coffee use large amounts of energy and water (4). Every ton of coffee cherry processed consumes 117 kWh of energy. Processing is always accompanied by the generation of by-products in the form of solid and liquid wastes (5). Disposal of the waste without proper handling can cause pollution and environmental damage due to its high organic matter content. The impacts are poisoning aquatic organisms due to the low amount of dissolved oxygen and high acidity of the water, air pollution due to decomposition processes by microorganisms, and pollution of water bodies (6,7,8).

Pulp and parchment are solid wastes generated from the wet process of Arabica coffee. The waste contains cellulose, hemicellulose, lignin, crude fiber, caffeine, tannin, carbohydrates, phenolic compounds, and organic acids in different percentages (8,9,10). The generated by-product consistsof energy containing compoundsthat can be used as energy sources of supplying the energy needs of coffee processing (11,12). It has been estimated the potential electrical energy from solid and liquid waste from one ton of coffee cherries to be 816 kW (13). This energy

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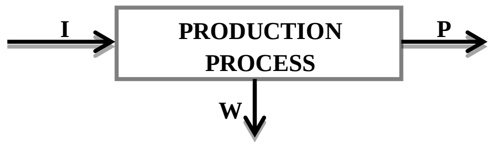
potential allows the development of a closed model of energy-independent Arabicawet coffee processing through optimal utilization of by-products.



This study aims to develop a closed model of the wet process of Arabica coffee processing using the principle of mass and energy balances. The expected results are obtained by calculating mass balance, measurement energy requirements, and determine energy potency of by-products in the wet process of Arabica coffee production.

Materials and Method:-

Scope

This research was limited to the wet process of Arabica coffee which processes coffee cherries into green coffee beans and generate by-products in the form of pulp, parchment, and wastewater. A coffee primary processing plant with a capacity of 5,500 kg of coffee cherry per day was used as the basis of model development. The analysis of mass flows, energy use, and analysis of the potential energy of by-products generated underlied the development of the model. Energy calculations were separated from solid and liquid waste to determine the adequacy of each of these sources.

Data

Most of the data used in this research were secondary data. The main data sources are literature in the form of books, journals, theses, electronic articles and other scientific articles.

System Boundary

The Arabica coffee production process consists of five main compartments, namely pulping, demucilaging, drying, hulling and grading. The inputs used are coffee cherries assuming 5,500 kg per day and a certain amount of water. The main product is green coffee beans with by-products in the form of pulp, parchment, and wastewater.

Model Description

The mass balance model was developed based on mass flow which describes the actual production process. The inputs used are independent variables and the resulting outputs are dependent variables. A ratio (efficiency coefficient) based on the principle of linear equations were used in the model. Microsoft Excel 2020 support the calculation. The basis used in the development of this model was the production flow of Arabica coffee with a capacity of 5,500 kg per day. The results of the mass calculation were used to calculate the amount of potential energy in meeting the needs of the production process.

Mass Balance

The mass balance model was established by identifying each compartment that describes the production process. At the initial stage, the mass balance equation was determined with the input of Arabica coffee berries and water with the output of green coffee beans. Some efficiency equations for each compartment were built using secondary data on mass flow in the processing of coffee cherries into green coffee beans. Figure 1 illustrates a simple mass flow in a compartment with respective mass balance and efficiency equation.

$$I = P + W \qquad \text{Efficiency } (a) = \frac{P}{I}$$

I = Input, P = Product, W = Wastes

Figure 1. A simple mass balance of the production

Energy Potential of by-Product

The energy potential of by-products generated in the wet process of Arabica coffee processing can be calculated using the following equation:

Potential Energy (kCal) = Mass (kg) × Caloric Value (kCal/kg)

Mass Balance Model of Coffee Green Beans Production

The development of the balance equation model in each compartment was carried out to determine the processed inputs and the resulting output in each compartment.Model was developed for each coffee production process. The model has 22 variables consisting of 4 independent variables (I_{11}, I_{12}, I_{41}, and I_{51}) and 18 dependent variables (X_{11} to X_{81}, W_{11} to W_{91}, and P_{91}) (Figure 2). Therefore,it needs 18 equations to solve the problem. There are 9 mass balance equations can be formulated one from each compartment and another 9 equations must be developed from efficiency equations as follows:

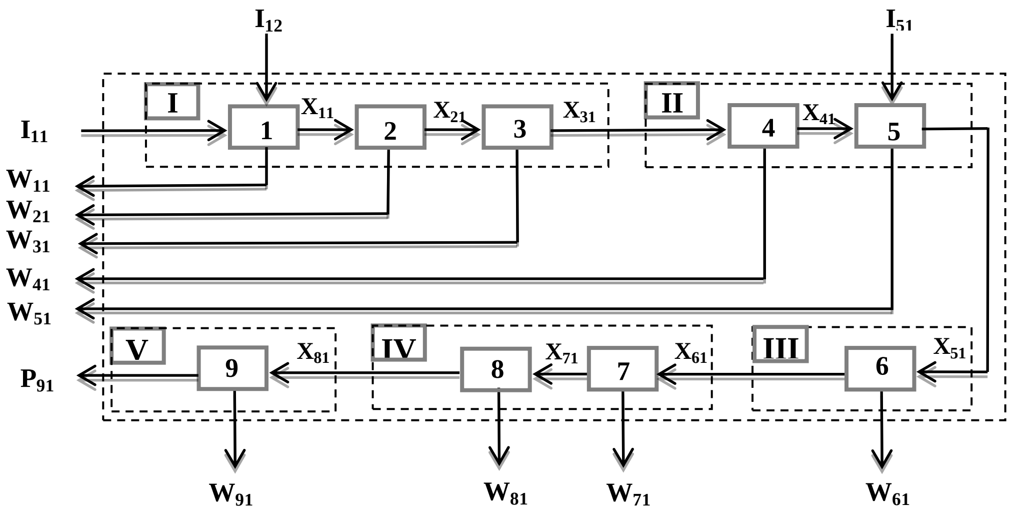


Figure 2:- Balance model of Arabicawet process of green beans production (see Tabel 1 for description).

Table 1:- Description of symbols used in Figure 1.

Symbol	Description
I	Pulping station
II	Demucilaging station
III	Drying station
IV	Hulling station
V	Grading station
1	Soaking of coffee cherries
2	Coffee cherries selection (sorting)
3	Peeling of the skin and pulp of the coffee cherries (pulping)
4	Wet coffee beans fermentation process (fermentation)
5	The process of washing fermented coffee beans (washing)
6	Drying process (drying)
7	The process of stripping parchment (hulling)
8	Green coffee bean polishing process (polishing)
9	The final sorting process of green coffee beans (grading)
I_{11}	Coffee cherries
I_{12}	Water
I_{51}	Water
X_{11}	Coffee cherries submerged in water
X_{21}	Good quality coffee cherries
X_{31}	Wet coffee beans with mucilage layer
X_{41}	Fermented coffee beans
X_{51}	Washed wet coffee beans
X_{61}	Dried coffee beans
X_{71}	Green beans
X_{81}	Polished green beans
P_{91}	Graded coffee beans
W_{11}	Coffee bean soaking wastewater

W_{21}	Defective coffee cherries
W_{31}	Pulp
W_{41}	Coffee fermented wastewater
W_{51}	Coffee washing wastewater
W_{61}	Water vapour
W_{71}	Parchment
W_{81}	Silverskin
W_{91}	Defective green coffee beans

Mass Balance Equations:

Compartment 1 : $I_{11} + I_{12} - X_{11} - W_{11} = 0$ …… (1)
Compartment 2 : $X_{11} - X_{21} - W_{21} = 0$ …… (2)
Compartment 3 : $X_{21} - X_{31} - W_{31} = 0$ …… (3)
Compartment 4 : $X_{31} - X_{41} - W_{41} = 0$ …… (4)
Compartment 5 : $X_{41} + I_{51} - X_{51} - W_{51} = 0$ …… (5)
Compartment 6 : $X_{51} - X_{61} - W_{61} = 0$ …… (6)
Compartment 7 : $X_{61} - X_{71} - W_{71} = 0$ …… (7)
Compartment 8 : $X_{71} - X_{81} - W_{81} = 0$ …… (8)
Compartment 9 : $X_{81} - P_{91} - W_{91} = 0$ …… (9)

Efficiency Equations:

The process of soaking coffee cherries

$$a_1 = \frac{X_{11}}{I_{11}} = \frac{\text{Coffee cherries in soaking}}{\text{Coffee cherries}} \ldots\ldots\ldots\ldots \quad (10)$$

The soaking coffee cherries is the initial process before sorting. At this stage, a certain amount of water is added to the coffee cherries that are put into the tank so that they are completely submerged to separate good quality (sink) from the floating coffee cherries. At this stage the coffee cherries do not experience any weight losses (14, 15). Based on this statement, it can be concluded that the efficiency of this process (a_1) is 1. This is the raw material to be further processed.

Coffee cherries selection (sorting)

$$a_2 = \frac{X_{21}}{X_{11}} = \frac{\text{Good quality of coffee cherries}}{\text{Submerged coffee cheries}} \ldots\ldots\ldots\ldots \quad (11)$$

The process of separating good quality coffee cherries (sinking) from floating cherries is done by soaking the coffee cherries in a tank filled with water. The separation processes obtained an average of 903 kg of good coffee beans from every 1,000 kg of coffee harvested (5). This value shows the average percentage of the results of the sorting process of 90.3% with an efficiency value (a_2) of 0.9.

Peeling of the skin and pulp of the coffee cherries (pulping)

$$a_3 = \frac{X_{31}}{X_{21}} = \frac{\text{Pulped cherries}}{\text{Good quality cherries}} \ldots\ldots\ldots\ldots \quad (12)$$

The pulping process obtained an average of 704.6 kg of wet coffee beans from a total average of 903 kg of good quality coffee cherries (5). This value shows the average percentage of pulping process results of 78% and therefore a_3 is 0.78.

Wet coffee bean fermentation process

$$a_4 = \frac{X_{41}}{X_{31}} = \frac{\text{Fermented beans}}{\text{Wet coffe beans}} \ldots\ldots\ldots\ldots \quad (13)$$

The fermentation processes produces an average of 450.5 kg of fermented coffee beans from an average of 459.7 kg of pulped coffee beans (5). This value shows the average percentage of the results of the fermentation process of 97%, so $a_4$is 0.97.

The process of washing fermented coffee beans (washing)

$$a_5 = \frac{X_{51}}{X_{41}} = \frac{\text{Washed fermented beans}}{\text{Feremented beans}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

The fermented coffee beans are then washed so that the remnants of the material on the surface of the beans disappear. Washing uses 100 liters of water for every 10 kg of the beans (14). An analysis of traces on water uses shows that after going through the mucus removal process, the washed coffee beans were about 90% of the pulped coffee beans. It is, therefore the washing process efficiency (a_5) is 0.90 (16).

Drying process (drying)

$$a_6 = \frac{X_{61}}{X_{51}} = \frac{\text{Dried beans}}{\text{Washed coffee beans}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

In the drying process, an average of 217.3 kg of coffee beans was obtained from drying of a total average of 316.5 kg of washed coffee beans (5). This value shows the average percentage of drying process results of 68.6%, then the efficiency value(a_6) is 0.68.

The process of stripping parchment (hulling)

$$a_7 = \frac{X_{71}}{X_{61}} = \frac{\text{Green beans}}{\text{Dried beans}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

The hulling process of 23.3 kg of dried coffee produces 19 kg of green beans. Based on these results, it is known that the efficiency of the hulling process is 81% (17), then the efficiency value (a_7) is 0.81.

Green coffee bean polishing process (polishing)

$$a_8 = \frac{X_{81}}{X_{71}} = \frac{\text{Polished green beans}}{\text{Green beans}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

The process of polishing green coffee beans (polishing) is carried out to remove the remaining silver skin or epidermis of the coffee beans. This process is carried out after the hulling process and is optional in the coffee production process. Coffee beans that go through the polishing process have a cleaner and shiny surface. The mass loss in this process is very small (not significant) (14). Therefore, the efficiency value (a_8) is assumed to be 1.

The final sorting process of green coffee beans (grading)

$$a_9 = \frac{P_{91}}{X_{81}} = \frac{\text{Graded beans}}{\text{Polished beans}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

The grading process produced 1,000 kg of good quality green coffee beans from 1,186 kg of polished green beans. This value is in accordance with the water footprint analysis on coffee washing process which shows that the final sorting process obtained 80% of good quality polished green beans. Based on these data, it is known that the efficiency value of the final sorting process (grading) in the coffee processing is 80% (16), then the efficiency value of the sorting process (a_8) is 0.80.

From the description above, the efficiency equation coefficients were summarised in Table 2.

Tabel 2:- Coefficient values used in the efficiency equations.

Symbol	Value	References
a_1	1	14,15
a_2	0.90	5
a_3	0.78	5
a_4	0.97	5
a_5	0.90	14,16
a_6	0.68	5
a_7	0.81	17
a_8	1	14
a_9	0.84	16, 18

Results and Discussion:-

Mass Equilibrium in the Wet Process of Arabica Coffee Production

Each compartment in Arabica coffee production was divided into sub-compartments that describe the mass flow and machine usage at each stage of the production process (Figure 3). The yield obtained in this model was 28% which is higher than data of some coffee processing industries in Pangalengan, Aceh, Kenya, and Costa Rica (4,5,11,18). A detailed calculation shows a more specific mass change, so that this model can describe the process flow conditions in a more actual condition.

Energy Needs and Energy Potential of By-products in the Wet Process of Arabica Coffee Production

The wet process of Arabica coffee use electricity to meet the energy needs of production. This energy is used to run tools and machines in each stage of the process. The energy requirements for Arabica coffee production can be seen in Table 3.

Wet production of Arabica coffee produces green coffee beans as a product. In addition, the process also generates by-products such as pulp, parchment, and defective beans as well as wastewater. The high content of carbohydrate and fiber in pulp and parchment make these by-products possible to be used as an energy source (12,9,19).

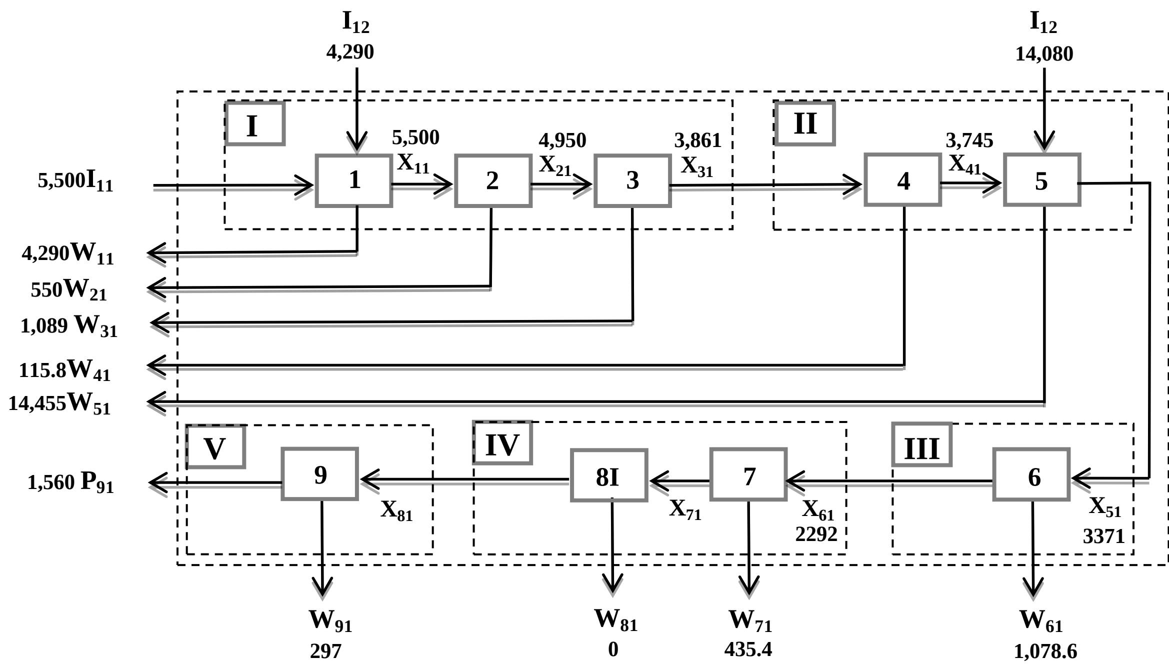


Figure 3:- Model of Arabica coffee production (Description of symbols as in Table 1).

Tabel 3:- Energy requirement in wet process of Arabica coffee.

Process (Compartment)	Input (kg)	Capacity and Energy		Number of Machines	Operation time	Energy (kWh)
		(kg/day)	(kW)		(hour)	
Soaking and Sortation (1 and 2)	5,500	5,500	7.50	1	1	7.50
Pulping (3)	4,950	5,000	16	1	0.99	15.84
Washing (5)	3,745	1,000	5.59	1	3.74	20.93
Drying (6)	3,371	1,000	3	1	3.37	10.11
Hulling (7)	2,292	500	5.59	2	4.58	51.24
Polishing (8)	1,857	1,857	6	1	1	6
Grading (9)	1,857	1,000	3	1	1.85	5.57
Total energy requirement						117.20

Source: Vincent (31)

Parchment is the inner layer of coffee skin with strong fibers, which functions to cover and separates the two pieces of beans. Parchment content is 40-49% cellulose, 25-32% hemicellulose, 35% xylan, and 33-35% lignin (20,19,21), and that parchment has a calorific value of 6,676.4 kcal/kg (21).

Pulp is the huge by-product of coffee production that can be used as a carbon source. The main content of pulp is crude fiber, tannin, caffeine, and several phenolic components (22, 23). In addition, the pulp also contains 10% crude protein, 31% nitrogen, 6.5% pectin, and 2% chlorogenic acid (12). The pulp has a calorific value of 2,987.8 kcal/kg (24). The energy potential of coffee pulp and parchment can be seen in Table 4.

Table 4:- The energy potential of coffee pulp and parchment.

By-product	Mass (kg)[a]	Calorific value (kcal/kg)	Energy potency (kcal)	References
Pulp	1,089	2,987.8	3,253,714.20	24
Parchment	435.5	6,676.4	2,907,572.20	21
Total			6,161,286.40	

[a]Capacity 5,500 kg coffee cherry per day

The calorific value of coffee pulp and parchment is equivalent to 12.50 MJ/kg and 27.95 MJ/kg, respectively, which can be used as feed in a steam boiler. Boilers convert thermal energy from chemical potential energy into steam (25) which is obtained through saturated steam which is further dried until the pressure is constant (26). The steam pressure is then used to turn a turbine which produces electrical energy. Furthermore, the energy is converted into mechanical energy that can drive various machine tools (27). The efficiency of converting steam to electricity through the turbine is about 43.5% (28). The calculation of the conversion biomass to electrical energy can be seen in Table 5.

Table 5:- Calculation of Arabica coffee genenerated wastes conversion to electrical energy.

Parameter	Unit	Value
Waste Generation	kg/day	5,500
Pulp	kg/day	1,089
Parchment	kg/day	436
Energy Content		
Pulp	kcal/kg	2,987[a]
Parchment	kcal/kg	6,676[b]
Total biomass energy		
Pulp	kcal	3,253,714
Parchment	kcal	2,907,572
Total	kcal	6,161,286
The heat required to produce 1 kg of steam at 30 Bar and a saturated temperature	kcal/kg	670
Steam Generation		
Pulp	kg/day	4,857
Parchment	kg/day	4,340
Total	kg/day	9,197
Average Boiler Efficiency	%	76.83[c]
Actual steam		
Pulp	kg/day	3,732
Parchment	kg/day	3,335
Total steam generated	kg/day	7,066
Total power generated		
Turbine steam conversion	kg/s	61[d]
Turbine effieciency	%	43.5[d]
Turbine Power	kWh	833,000[d]
Electrical Generated	kWh/day	486

Electrical requirement for production	kWh/day	117[e]
Electrical generation from wastewater	kWh/day	172[f]
Surplus	kWh/day	541

Source: [a]24, [b]21, [c]30; [d]28,[e]11,[f]see Table 6.

Low-quality coffee cherries include overripe, immature, or insect defects. These rejected coffee cherries are obtained at the early stage of sorting the process (29). The rejected cherries can be used as input for dry coffee production (dry method) (31). Defective coffee beans from the final grading can be extracted to obtain products in the form of oil and bioactive components (32).

The high demand for water in Arabica coffee processing causes the amount of wastewater produced to be relatively large (33). Wastewater contains high nutrients so it has the potential for biogas production (11). The low pH value requires neutralisation to increase it to 6. Furthermore, the wastewater can be inputted to a bioreactor for the production of methane gas ($CH_{4)}$ (34). The biogas produced can be used as an additional source of energy for power plants that can supply the energy needs of coffee production (15). The conversion of potential wastewater into electrical energy can be seen in Table 6.

Table 6:- Potency of wastewater to generate electricity.

	Mass (kg)	Methane ($CH_{4)}$ equivalent (g/kg)	Electrical (kWh/day)
Wastewater	18,860[a]	241[b]	4,136[b]

[a] Processed cherry of 5,500 kg; [b]35

Each ton of coffee cherries requires 780 liters of water for pulping and 2,560 liters for washing (36). Wastewater has the potential to produce as much as 241 g of methane for every 1 kg of processed wastewater input. The potential for electrical energy from the methane is 3,290 KJ/kg or equivalent to 0.91 kWh of electrical energy (35). Further calculations show that every ton of coffee bean production produces 191 m^3 of methane with an electrical energy potential for 668.51 kWh (9). The difference in the amount of methane produced is influenced by the characteristics of the wastewater content formed in the coffee production process. The higher the mucilage contents in wastewater, the lower the cellulose and xylan content, while the carbon and nitrogen (C/N) ratio increase. This condition determines the activity and performance of microbe in forming methane gas due to nutrient balance and inhibitor of the ammonia formation (35).

Closed Production of Green Beans of Arabica Coffee

Wet production of Arabica coffee produces products (green coffee beans) and by-products generated in the form of pulp and parchment obtained at the pulping and hulling stages. In addition, there are coffee cherries and coffee beans of low quality (defects) originating from the sorting stage as well as wastewater obtained from the pulping, demucilaging, and washing stages.

The main by-product have the potential to be used as an energy source to supply the energy needs of coffee production. Defective or low-quality coffee cherries can be used as raw material for coffee production using the dry method. Low quality (defect) green coffee beans can be extracted to produce oil and bioactive components of coffee beans. The wastewater can be used for biogas production which can be converted into electrical energy. The water vapor formed in the drying stage is collected through the condenser for water input in the pulping, demucilaging, and washing processes. Closed production of the wet process of Arabica coffee can be seen in Figure 4.

Conclusion and Recommendation:-

The mass balance calculations show that the yield of Arabica coffee processing is 28%. Coffee production of a capacity of 5,500 kg per day has an energy potential for 6,161,286 kcal which comes from the skin, pulp and parchment. This energy potential can meet the production energy needs of 117.20 kWh per day. This study explained that the wet process of Arabica coffee can be an energy-independent production by optimally utilising by-products.

Further research is recommended to developing a closed model of Arabica coffee production using the dry method. Comparison between wet and dry processing provides necessary information on the most optimal alternatives to technology from the aspect of energy sufficiency to develop energy independent production processes.

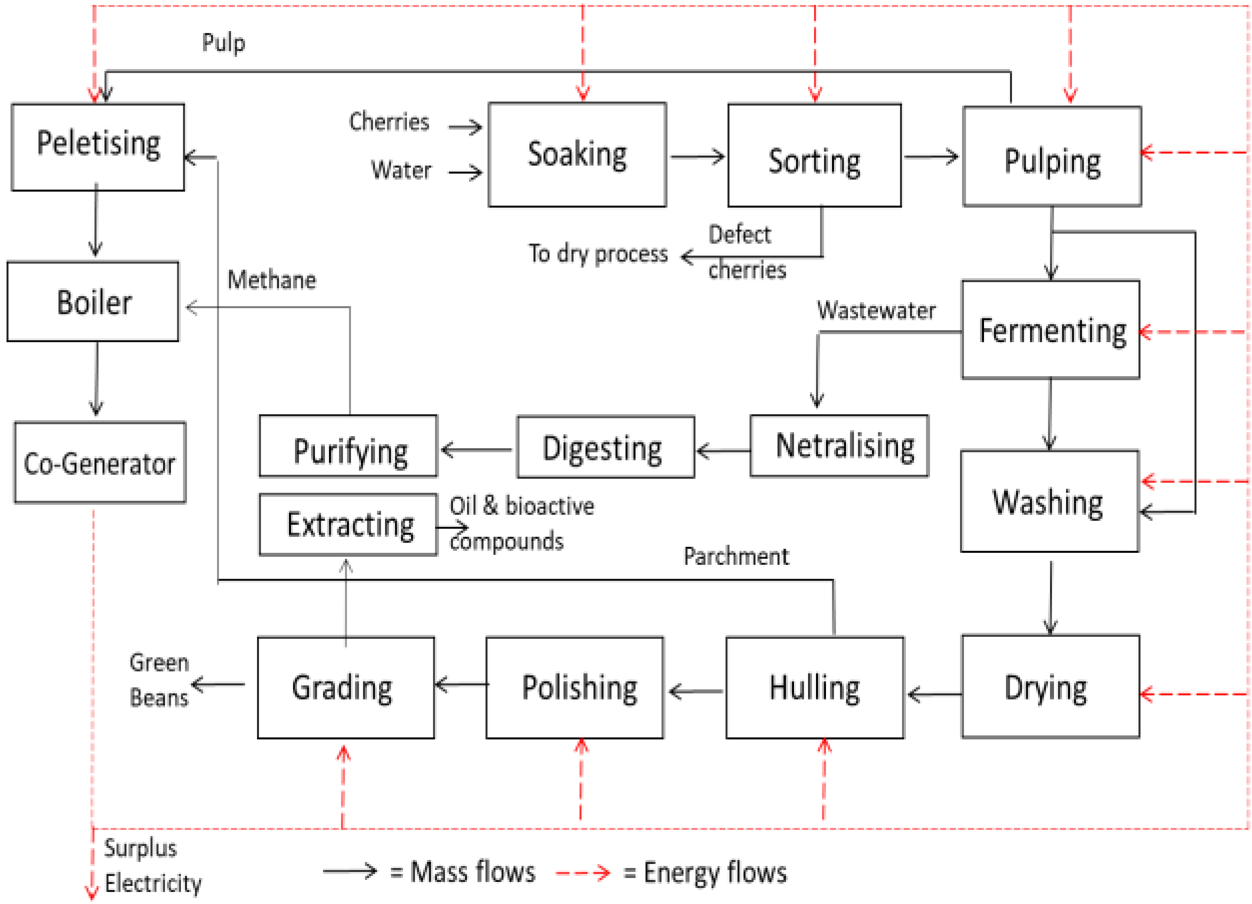


Figure 4:- Closed production of wet process of Arabica coffee.

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