

Life Cycle Sustainability Assessment of Staple Food Processing: A Double and Dynamic Materiality Approach

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Supplementary materials

S1: LCSA/MEFA FIELD FORM 1: HARVESTING TO PACKAGING

Life Cycle Sustainability Assessment (LCSA) of cassava processing: Guiding questions for the Material and Energy Flow Analysis (MEFA) from Harvesting to the market

| | |
|----------------------|-------------------------------------|
| Facility name | |
| Location | |
| Date | |
| Time | From: _____ To: _____ |

Introduction to the participants

We appreciate your willingness to take part in this study. Understanding the life cycle sustainability of cassava processing, with an emphasis on material and energy flows from the farm to the market, is the aim of this interview. The purpose of this study is to examine important procedures and pinpoint areas where sustainability must be improved. All information will be kept private and used only for research.

Answer: _____

1. Question: How much space do you allot each season for cassava cultivation?

*(Please be very mindful of the time, the number of employees, their gender, and the precise weight. Most of the questions are made to be asked without interfering with the work's progress. Direct most of the inquiries to one of the leaders who participates in the activities less, if at all feasible).

Section 1: Cassava Harvesting

Start time: _____ **End time:** _____

Objective: To understand the type of cassava grown, costs, labour, transportation and wastes management.

2. Question: Could you tell me the kinds of cassava you grow? (e.g., sweet, bitter or others)

3.

Answer: _____ hectares.

4. Question: What is the average amount of cassava roots produced per hectare?

Answer: _____ kg

5. Question: How much biomass waste (stems, leaves, peels, etc.) is produced overall per hectare during harvesting?

Answer: _____ kg

6. Question: Weigh the cassava roots and wastes produced. To make weighing each row easier, encourage the harvested roots and wastes to be piled in rows. For all field and cassava root harvests, about 50% of the harvested rows should be weighed, and the wastes estimated.

Roots harvested: _____ kg, Wastes (whole plant): _____ kg

7. Question: How is the biomass waste from cassava farming handled?
 Answer: _____ kg
8. Question: How much does it cost to grow one hectare of cassava? (For instance, seeds, labour, irrigation, and fertilizers).
 Answer: _____.
9. Question: How many people are involved in harvesting?
 Answer: Men _____ Women _____
10. Question: Have you noticed any health issues related to your work?
 Answer: _____
11. Question: What protective measures do you take during the roasting process to protect your health?
 Answer: _____
12. Question: How much are you paid for your work?
 Answer: _____ (CFA)Local currency.
13. Question: How much is the price of the cassava roots?
 Answer: Per Hectare: _____ (CFA/Ha), Per kg: _____ (CFA/kg).
 (Whatever the measure of sale, kindly weigh and aggregate with the price).
14. Question: When is the peak period of cassava harvest and how does it relate to the approximate prices?
 Answer: Peak/price: _____ (CFA/kg), off peak/price: _____ (CFA/kg).

Section 2: Transportation

Start time: _____ **End time:** _____

15. Question: What type of transport do you use to transport the cassava to the processing facility?
 Answer: _____
16. Question: How much does it cost?
 Answer: _____ (CFA).
17. Question: Does the transport belong to the cooperative?
 Answer: _____.
18. Question: How much fuel is used? (Decant the fuel and measure with a labelled container before and after transportation).
 Answer: before _____ litres, After _____ litres.
19. Question: What is the weight of the cassava transported?
 Answer: _____ kg
20. Question: Have you noticed any health issues related to your work?
 Answer: _____.
21. Question: How many people are involved in transportation?
 Answer: Men _____ Women _____
22. Question: What protective measures do you take during the roasting process to protect your health?
 Answer: _____.
23. Question: How much are you paid for your work?
 Answer: _____

Section 3: Peeling

Start time: _____ **End time:** _____

24. Question: How much cassava did you receive from the field?
 Answer: _____ kg
25. Question: what time did peeling start and end?
 Answer: Start _____ End _____
26. Question: How many people are involved in peeling?
 Answer: Men _____ Women _____

27. Question: What are the challenges faced during peeling?

Answer: _____

28. Question: What is the final weight of the cassava after peeling?

Answer: _____ kg

29. Question: What is the weight of peelings?

Answer: _____ kg

30. Question: Have you noticed any health issues related to your work?

Answer: _____

31. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

32. Question: How much are you paid for your work?

Answer: _____

Section 4: Washing

Start time: _____

End time: _____

33. Question: How much cassava did you receive from the peeling?

Answer: _____ kg

34. Question: What is the quantity of water used?

35. Answer: _____ kg

36. Question: How many people are involved in washing?

Answer: Men _____ Women _____

37. Question: What are the challenges faced during washing?

Answer: _____

38. Question: What is the final weight of the cassava after washing?

Answer: _____ kg

39. Question: What is the weight of the wastewater?

Answer: _____ kg

40. Question: How do you dispose off the wastewater?

Answer: _____ kg

41. Question: Have you noticed any health issues related to your work?

Answer: _____

42. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

43. Question: How much are you paid for your work?

Answer: _____

Section 5: Grating

Start time: _____

End time: _____

44. Question: How much cassava did you receive from washing stage?

Answer: _____ kg

45. Question: What is the quantity and type of fuel used for grating?

46. Answer: Type: _____ Quantity: _____ Litres

47. Question: How many people were involved in grating?

Answer: Men _____ Women _____

48. Question: What are the challenges faced during grating?

Answer: _____

49. Question: What is the final weight of the cassava mash grated?

Answer: _____ kg

50. Question: What is the weight of the wastes at grating?

Answer: _____ kg

51. Question: Was the grating machine hired or belongs to the cooperative?

Answer: _____

52. Question: Have you noticed any health issues related to your work?

Answer: _____

53. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

54. Question: How much are you paid for your work?

Answer: _____

Section 6: Fermentation

Start time: _____

End time: _____

55. Question: How much **cassava mash** did you receive from the grating stage?

Answer: _____ kg

56. Question: How many people were involved in batching?

Answer: Men _____ Women _____

57. Question: What are the challenges faced during Fermentation?

Answer: _____

58. Question: What is the final weight of the cassava mash fermented?

Answer: _____ kg

59. Question: What is the weight of the wastes at fermentation?

Answer: _____ kg

60. Question: Have you noticed any health issues related to your work?

Answer: _____

61. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

62. Question: How much are you paid for your work?

Answer: _____

Section 7: De-watering

Start time: _____

End time: _____

63. Question: How much **cassava mash** did you receive from the fermentation stage?

Answer: _____ kg

64. Question: How many people were involved in de-watering?

Answer: Men _____ Women _____

65. Question: What are the challenges faced during de-watering?

Answer: _____

66. Question: What is the final weight of the **cassava cake** de-watered?

Answer: _____ kg

67. Question: What is the weight of the wastes at de-watering?

Answer: _____ kg

68. Question: Have you noticed any health issues related to your work?

Answer: _____

69. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

70. Question: How much are you paid for your work?

Answer: _____

Section 8: Sifting and sieving

Start time: _____

End time: _____

71. Question: How much **cassava mash** did you receive from the de-watering stage?

Answer: _____ kg

72. Question: How many people were involved in sifting and sieving?

Answer: Men _____ Women _____

73. Question: What are the challenges faced during sifting and sieving?

Answer: _____

74. Question: What is the final weight of the cassava mash sifted and sieved?

Answer: _____ kg

75. Question: What is the weight of the wastes at sifting and sieving?

Answer: _____ kg

76. Question: Have you noticed any health issues related to your work?

Answer: _____

77. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

78. Question: How much are you paid for your work?

Answer: _____

Section 9: Roasting

Start time: _____

End time: _____

79. Question: How much **cassava mash** did you receive from the sifting and sieving stage?

Answer: _____ kg

80. Question: What was the opening stock of woodfuel and closing stock at roasting.

pan _____? (For roasting batch evaluation use the appropriate sheet).

Answer: Opening _____ kg Closing stock _____ .kg

81. Question: How many people were involved in roasting?

Answer: Men _____ Women _____

82. Question: What are the challenges faced during roasting?

Answer: _____

83. Question: What is the final weight of the **gari** roasted?

Answer: _____ kg

84. Question: What is the weight of the wastes at roasting?

Answer: _____ kg

85. Question: what is the weight of the wood ash?

Answer: _____ kg

86. Question: Have you noticed any health issues related to your work?

Answer: _____.

87. Question: What protective measures do you take during the roasting process to protect your health?

Answer: _____

88. Question: How much are you paid for your work?

Answer: _____

Section 10: Grading and sieving

Start time: _____

End time: _____

89. Question: How much **gari** did you receive from the roasting stage?
 Answer: _____ kg
90. Question: How many people were involved in sieving and grading?
 Answer: Men _____ Women _____
91. Question: What are the challenges faced during sieving and grading?
 Answer: _____
92. Question: What is the final weight of the gari sieved and graded?
 Answer: _____ kg
93. Question: What is the weight of the wastes at sieving and grading?
 Answer: _____ kg
94. Question: Have you noticed any health issues related to your work?
 Answer: _____
95. Question: What protective measures do you take during the roasting process to protect your health?
 Answer: _____
96. Question: How much are you paid for your work?
 Answer: _____.

Section 11: Packaging

Start time: _____ **End time:** _____

97. Question: How much **graded gari** did you receive from the sieving and grading stage?
 Answer: _____ kg
98. Question: How many people were involved in packaging?
 Answer: Men _____ Women _____
99. Question: What are the challenges faced during packaging?
 Answer: _____
100. Question: What is the final weight of the packaged gari?
 Answer: _____ kg
101. Question: What is the weight of the wastes at packaging stage?
 Answer: _____ kg
102. Question: How much packaging materials did you use?
 Answer: PP _____ kg, PE: _____ kg
103. Question: Have you noticed any health issues related to your work?
 Answer: _____
104. Question: What protective measures do you take during the roasting process to protect your health?
 Answer: _____
105. Question: How much are you paid for your work?
 Answer: _____

Consent Statement

I agree to participate in this research and understand that my responses will be used for academic purposes only. I acknowledge that my participation is voluntary and that I can withdraw at any time.

Signature: _____

Date: _____

S2: LCSA/MEFA FIELD FORM 2: ROASTING STAGE

Life Cycle Sustainability Assessment (LCSA) of cassava processing: Guiding questions for the Material and Energy Flow Analysis from Harvesting to the market

| | |
|----------------------|-------------------------------------|
| Facility name | |
| Location | |
| Date | |
| Time | From: _____ To: _____ |

Objective: To understand the batch sizes, time taken to roast a batch, costs, labour and productivity management.

Introduction to the participants

We appreciate your willingness to take part in this study. Understanding the life cycle sustainability of cassava processing, with an emphasis on material and energy flows from the farm to the market, is the aim of this interview. The purpose of this study is to examine important procedures and pinpoint areas where sustainability must be improved. All information will be kept private and used only for research.

*(Please be very mindful of the time, the number of employees involved, their gender, and the precise weight. Most of the questions are made to be asked without interfering with the work's progress. Direct inquiries to one of the leaders who participates in the activities less, if at all feasible).
***Print as many forms as possible.**

Section 1: Material Flow

| Cookstove #: | | | | |
|--------------|-------|-----|---------------------------------|--------------------------|
| Batch #: | Start | End | Input: Cassava mash weight (kg) | Output: Gari weight (kg) |
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | | | | |
| 20 | | | | |
| 21 | | | | |
| 22 | | | | |

Section 2: Energy Flow

Objective: To understand the amount of woodfuel used for roasting, costs, labour, transportation and wastes management.

| | |
|---|--|
| COOKSTOVE #: | |
| Input-Woodfuel opening stock (kg) (A): | |
| Output-Woodfuel closing stock (kg) (B): | |
| *Used woodfuel (A-B) (kg) | |
| *Weight of woodfuel ash (kg) | |
| COOKSTOVE #: | |
| Input-Woodfuel opening stock (kg) (A): | |
| Output-Woodfuel closing stock (kg) (B): | |
| *Used woodfuel (A-B) (kg) | |
| *Weight of woodfuel ash (kg) | |
| COOKSTOVE #: | |
| Input-Woodfuel opening stock (kg) (A): | |
| Output-Woodfuel closing stock (kg) (B): | |

| | |
|---|--|
| *Used woodfuel (A-B) (kg) | |
| *Weight of woodfuel ash (kg) | |
| COOKSTOVE #: | |
| Input-Woodfuel opening stock (kg) (A): | |
| Output-Woodfuel closing stock (kg) (B): | |
| *Used woodfuel (A-B) (kg) | |
| *Weight of woodfuel ash (kg) | |
| COOKSTOVE #: | |
| Input-Woodfuel opening stock (kg) (A): | |
| Output-Woodfuel closing stock (kg) (B): | |
| *Used woodfuel (A-B) (kg) | |
| *Weight of woodfuel ash (kg) | |

Questions

106. Question: What are some of the factors affecting your work?

Answer: _____

107. Question: Why have you adopted the type of roasting system and the tools (Stirrer)?

Answer: _____

108. Question: What do you control the temperatures of the roasting pan?

Answer: _____

109. Question: Do you have any other concern to share?

Answer: _____

110. Question: How much are you paid?

Answer: _____

111. Question: Any health concerns?

Answer: _____

Consent Statement

I agree to participate in this research and understand that my responses will be used for academic purposes only. I acknowledge that my participation is voluntary and that I can withdraw at any time.

Signature: _____

Date: _____

S3: LCSA/MEFA FIELD FORM 3: MARKET PRICES

Life Cycle Sustainability Assessment (LCSA) of cassava processing: Guiding questions for the Material and Energy Flow Analysis from Harvesting to the market

| | |
|----------------------|--|
| Facility name | |
| Location | |

| | |
|-------------|-------------------------------------|
| Date | |
| Time | From: _____ To: _____ |

Objective: To understand the costs related to gari from the processing facilities and to the market.

Introduction to the participants

We appreciate your willingness to take part in this study. Understanding the life cycle sustainability of cassava processing, with an emphasis on material and energy flows from the farm to the market, is the aim of this interview. The purpose of this study is to examine important procedures and pinpoint areas where sustainability must be improved. All information will be kept private and used only for research.

*(Please be very mindful of the weight of the bowl of gari at the market and the actual price (indicate the weight of the empty bowl and then indicate the filled-up bowl weight). Use the digital scale provided and ensure that the Bluetooth function is switched on for real time recording).

***Print as many forms as possible.**

Section 1: Material Flow

| Seller #: | Gender | Weight of filled bowl (kg) | Weight of empty bowl (kg) | Price of a bowl (CFA) |
|------------------|---------------|-----------------------------------|----------------------------------|------------------------------|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | | | | |
| 5 | | | | |
| 6 | | | | |
| 7 | | | | |
| 8 | | | | |
| 9 | | | | |
| 10 | | | | |
| 11 | | | | |
| 12 | | | | |
| 13 | | | | |
| 14 | | | | |
| 15 | | | | |
| 16 | | | | |
| 17 | | | | |
| 18 | | | | |
| 19 | | | | |
| 20 | | | | |
| 21 | | | | |
| 22 | | | | |

Questions

112.Question: What are some of the factors affecting the prices?

Answer: _____

113.Question: When is the peak period of gari sales?

Answer: _____

114.Question: When do you make more profits?

Answer: _____

115.Question: What are the challenges faced during selling?

Answer: _____

116.Question: What are the types of packaging materials used?

Answer: _____

117. Question: Any health concerns?

Answer: _____

Consent Statement

I agree to participate in this research and understand that my responses will be used for academic purposes only. I acknowledge that my participation is voluntary and that I can withdraw at any time.

Signature: _____

Date: _____

S4: Appendix A; Detailed methodology

Detailed methods

1. Processing system definition and boundary

Gari is produced by harvesting cassava, transporting it to the processing facilities, peeling, washing, grating, fermenting, de-watering (pressing), sifting and sieving cassava cake, roasting of cassava mash, sieving and grading and packaging). Many researchers have provided physical detailed descriptions of the unit processes (Abass et al., 2012; Agricedemy, 2022; Ajewole and Adeosun, 2018; Ajibola et al., 1987; Jekayinfa and Olajide, 2007).

In order to successfully implement MEFA, the following requirements had to be met: (a) the definition, monitoring, documenting of every energy and material flow at each stage and understanding of the study areas, (b) all process description, (c) process material flow and energy data acquisition, (d) process material flow and energy modeling and scenario building, and (e) interpretation of the data (results and discussion) (Brunner and Rechberger, 2016; Taulo and Sebitosi, 2016). The processes examined in this work are highlighted in Figure 2(a).

2. Process data acquisition

To fully integrate MEFA in the LCSA, this study employed the field based mixed methods applying quantitative measurements, observational data and survey responses. Primary data on the types of cassava planted and how much was taken from the field (roots and wastes), firewood used, important players (labor/gender division), and typical raw material sources were collected using semi-structured questionnaires (qualitative research methods). At each facility, the processes were monitored and recorded in triplicate. The mixed methods have been applied by other researchers (Kurtaliqi et al., 2024; Pérez Bentancur and Tiscornia, 2024; Polisetty et al., 2024).

To achieve data correction, the interview approach was adopted and questions asked and data recorded highlighted in supplementary materials; LCSA/MEFA FORM 1 (harvesting packaging), LCSA/MEFA FORM 2 (Roasting stage) and LCSA/MEFA FORM 3 (Market prices). The data was first recorded in excel before automation to in python.

Sensors were used to mine data sets such as temperatures and moisture content, thereby achieving proximate and thermal parameters as described in Mwape et al (2023).

2.1 Process material and energy flow modeling scenario building

The following conditions were adopted in order to formulate the theoretical expressions of the material and energy balance;

- Cassava field activities flagged the starting point of the process and the whole plant (cassava trees inclusive of roots) formed the total biomass input,
- Harvesting entailed separating the useable cassava roots from the remaining plant biomass, including stems and leaves, which are considered agricultural waste (Biomass wastes at farm stage),
- Materials from the prior stage that could not be accounted for at weighing time in a subsequent step comprised the wastes.
- The analytical parameters included the type of energy consumed, the amount of time required, and the amount of material processed at each stage,
- The combustion chamber flame (hot gasses) under the roasting pan to be single dimensional with a steady and parallel flow,
- Material used for the pans was plate 6-9 mm with high thermal conductivity, hence one dimensional steady state heat conduction was assumed,
- Feeding and stirring of the cassava mash granules into the roasting pan was a steady, one dimensional and homogenous to achieve even roasting,
- Under thin layer conductive drying.

2.1.1. Material Flow Analysis (MFA) (mathematical models integrated into python)

The boundaries set enabled the tracking of materials by accounting for the cassava root input at the harvesting stage and its conversion into the final product gari, intermediate by-products, and all waste streams at each subsequent stage. This was achieved by employing the; observe, weigh and record techniques in the three fields assessed (Xie et al., 2023). The mass conservation and balance expressed by unit rate as given in Equation 1, was used to generally calculate the flow of materials.

$$Input_i = Output_i + Waste_i \quad (1)$$

Where;

- $Input_i$ represents the mass (kg) of the raw materials entering stage i ,
- $Output_i$ represents the mass (kg) of product or intermediate output (e.g., cassava roots, cassava mash, cassava cake or gari),
- $Waste_i$ consisting of any material waste produced during the process at each stage (biomass, fibres, peelings, effluent, or water evaporated during roasting).

In general, methods and techniques employed by other researchers were applied in this study to account for both materials and wastes at each stage efficiently (Bello Bugallo et al., 2012; Mwape et al., 2023; Sahin and Sumnu, 2007; Taulo and Sebitosi, 2016).

2.2 Energy Flow Analysis (EFA)

Energy flow analysis quantified the energy consumption at each stage. The energy balance techniques were used at each stage to account for both direct energy inputs and associated losses.

Gari production from cassava comprised three major energy regimes: mechanical for motor cycles and grating machines powered by gasoline engines, thermal from firewood, and human labor. As a result, all energy sources

were evaluated in this research as and when they were used. The energy balance of each unit process was achieved by comparing the summation of the total rate of energy input (\dot{E}_{in}) and output (\dot{E}_{out}) in kWh using the energy conservation expression (COMSOL, 2023);

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (2)$$

2.2.1. Human energy

Modern equipment and techniques have unquestionably reduced the need for human labor in industry, but in most of farming activities like cassava harvesting and gari production, human power is still crucially important.

Energy consumption was calculated by using the following expressions;

Total energy contributed by women

$$E_{HW} = (L_H \times EC_W) \times w_N \quad (3)$$

Total energy contributed by men

$$E_{HM} = (L_H \times EC_M) \times m_N \quad (4)$$

Total human energy used

$$\sum EH = (E_{HW} + E_{HM}) \quad (5)$$

Where, E_{HW} and E_{HM} , represented the energy contributed by women and men respectively, L_H stands for the actual labor hours spent, EC_w and EC_M denotes the human energy coefficients of women (0.22 kWh) and for men (0.54 kWh), respectively (Black, 1971; Norman, 1978; Safa et al., 2011). The total human energy expended was symbolized by $\sum EH$. Men and women involved at each unit level are denoted by the symbols m_N and w_N , respectively. and, stands for the number of women and men involved at each unit stage respectively.

2.2.2. Petroleum Fuel (Gasoline)

The mechanical energy to power the prime movers for transportation (motor cycles) and grating machines was supplied by gasoline. By the decanting, measuring and recording method, the actual fuel consumption (litres) per unit time spent (hrs) for each unit operation was calculated.

In this study a fuel to energy coefficient of 8.8 kWh/litre of gasoline was adopted, as well as internal combustion engine efficiency of 20 % resulting in 1.76 kWh litre⁻¹ useful mechanical energy (Feng et al., 2015; Motorcycle et al., 1988; Schuerg et al., 2012). The total energy consumed was calculated using the fuel to energy conversion factors and expressed in kWh (Adekanye and Oni, 2022) as;

$$\text{Energy consumed by an ICE } (E_{ICE}) = 1.76 \times (l_{G1} - l_{G2}) \quad (6)$$

Where $(l_{G1} - l_{G2})$ was the actual fuel used by the ICE consumed for cassava grating to mash, $(l_{G1}$ and l_{G2} are the initial fuel measured in the measuring cylinder in litres and after each operation, respectively.

2.2.3. Woodfuel

A combination of questionnaire surveys and physical weighing of the woodfuel before and after each day's roasting operation, were used to gather the data on actual consumption. Total wood consumption was calculated using Equation 28;

$$Wf_C = Wf_1 - Wf_2 \quad (7)$$

Where Wf_c = weight of wood fuel consumed in kg, Wf_i in kg was the initial weight of the wood fuel and Wf_2 was the weight of the wood fuel after the roasting process in kg.

The net heat energy generated (H_E) in kWh from the Wf_c was worked out using the following Equation;

$$H_E = Wf_c \times CalWf_c \quad (8)$$

Where $CalWf_c$ was the calorific gross calorific value (GCV) of the woodfuel of 20 MJ kg⁻¹ (5.5 kWh kg⁻¹) adopted from other research work on some west African wood species (Jekayinfa and Olajide, 2007; Montes et al., 2011; Ojelel et al., 2015; Scurlock and Hall, 1990).

After roasting, the amount of wood ash produced at each location was measured by weighing it.

2.2.4. Specific Energy Consumption (SEC) and Energy productivity (EP)

The SEC (kWh kg⁻¹) and EP (kg kWh⁻¹) at each stage were calculated as Equations 25 and 26;

$$SEC = \frac{\text{Energy input}}{\text{Product output}} \quad (9)$$

$$EP = \frac{\text{product output}}{\text{Energy input}} \quad (10)$$

2.2.5. Roasting process energy balance

The energy balance for the roasting system was divided into two subsystems; the combustion chamber and the roasting pan.

2.2.6. Combustion chamber energy balance

The firewood is burned in the combustion chamber to produce hot fumes that heated the roasting pan, which in turn is conducted to the roasting pan. The energy balance was calculated as;

$$E_{in}^{CC} = E_{out}^{CC} + E_{lost}^{CC} \quad (11)$$

Where;

- E_{in}^{CC} : is the total energy input to the combustion chamber from the woodfuel and is given by Equation 8.
- E_{lost}^{CC} is energy lost in the combustion chamber due to inefficiencies (Conduction, radiation and incomplete combustion).

$$E_{out}^{CC} = Q_{to \text{ roasting pan input}} + Q_{to \text{ exhaust gases}} \quad (12)$$

- E_{out}^{CC} is useful energy released from the combustion chamber,
- $Q_{to \text{ roasting pan input}}$ is energy transferred to the roasting pan,
- $Q_{to \text{-exhaust gases}}$ is energy lost to the surrounding via the exhaust gases.

2.2.7. Energy balance in the roasting pan

Since the roasting process takes place in the roasting pan, the energy balance was determined by measuring the amount of energy that the pan really got ($E_{in}^{RP} = Q_{to\ roasting\ pan\ input}$) from the combustion chamber and the amount that the roasted cassava mash subsequently absorbed (E_{out}^{RP}). Energy loss was defined as the energy that was not accounted for (E_{lost}^{RP}). Therefore, energy balance for the roasting subsystem was calculated as;

$$E_{in}^{RP} = E_{out}^{RP} + E_{lost}^{RP} \quad (13)$$

Where; E_{out}^{RP} is the useful energy output from the pan and absorbed by the product been roasted. Therefore E_{out}^{RP} was assumed to be the energy absorbed by the product been roasted ($Q_{product}$). The energy absorbed by the product was calculated by considering the sensible heat and the latent heat (Mathew et al., 2023). Sensible energy was calculated by multiplying the mass (kg) of the product been roasted with its specific heat capacity (C_p in J kg °C) and the temperature change from ambient ($T_{initial}$) to the final roasting temperature (T_{final}) while the latent heat was worked out by multiplying the evaporated water from the product (m_{water} in kg) with the latent heat of vaporization of water (λ , 2260 kJ kg⁻¹ at 100 °C) (Wang et al., 2024). The following expression was used to calculate energy absorbed by the $Q_{product}$:

$$Q_{product} = m_{product} \times (T_{final} - T_{initial}) + m_{water} \times \lambda \quad (14)$$

2.2.8. Roasting process efficiency

To calculate the roasting efficiency (η_R) of the cookstoves, the ratio of the useful energy ($Q_{product}$) and the total energy input was E_{in} was multiplied by 100 as expressed below;

The acquisition of all energy data was critical to carrying out the double materiality evaluation, as well as the

$$\eta_R = \frac{Q_{product}}{E_{in}} \times 100 \quad (15)$$

dynamic materiality assessment, which examined how material and energy flow might change as the energy system crossed over from biomass and gasoline to a hybrid solar and biogas system.

3. Double materiality

Double materiality was incorporated into the MEFA to assess both environmental and economic dimensions of the cassava to gari value chain.

3.1.1. Environmental dimensions

From an environmental perspective, the carbon emissions associated with the energy consumption (woodfuel, human and gasoline) and waste generation (biomass, wastewater, cassava juice and cyanide), were tracked. The Global Warming Potential (GWP) of each stage and stream of wastes or materials at each stage was calculated using emission factors for each energy or waste source, as shown below:

$$GWP (kgCO_2eq) = Act_{data} \times E_{factor} \quad 16$$

Where; Act_{data} = quantity of the environmental issue been considered (fuel category/water consumption or any waste in kg or litres); E_{factor} = emission factors from the standards (Olaniran et al., 2020; Taulo and Sebitosi, 2016). The secondary data such as the GWP emission factors and some wastes factors were collected from the literature (0.05 kgCO₂eq per kWh for human labor, gasoline at 0.265 kgCO₂eq/kWh, 0.44 kgCO₂eq/kWh from woodfuel, 1.8 kgCO₂eq/kWh for biomass wastes left to rot in the field, 0.03 kgCO₂eq/kWh from water use and waste water, 0.1 kgCO₂eq/kWh for Cyanide, 0.02 kgCO₂eq/kWh for cassava juice, 0.005 kgCO₂eq/kWh for

woodfuel and 2 kgCO₂eq/kWh attributed to the use of packaging materials from plastics) (Alsabri et al., 2021; Bailis et al., 2015; FAO, 2024; IPCC, 2021; Manaye et al., 2022; Piao and Managi, 2023; Wiese et al., 2024).

3.1.2. Financial (Economic) dimensions

The main financial indicators that were applied to evaluate the efficiency and profitability of cassava processing into gari are described in this section. These metrics include Specific Operation Costs (SC_{Ops}), Total Revenue (Rev_{Total}), Net Profit Margin (NPM) and Return on Capital (ROC). The data on prices of each cost centre was identified using the Activity-Based Costing (ABC) techniques and they represent the cost of 1 kg of gari which is normally sold in bowls (1 bowl is approximately 2 kg) (Quesado and Silva, 2021).

Operational costs: The expenses necessary to produce a kilogram of gari (SC_{Ops}) considered in these case study were limited to monitoring operations-related duties and consisted of the following direct costs incurred:

- **Labor costs (C_{Lab}):** computed by multiplying the total number of workers by the number of hours per process unit and the workers' hourly rate.
- **Energy costs (C_{Energy}):** By aggregating the cost of each energy stream used during the studies the total energy expenses were estimated. The cost of woodfuel per kilogram was taken into account, while the pump price of \$0.13/kWh or \$1.19 per litre in Lome was taken into account for gasoline (GlobalPetrolPrices, 2024).
- **Water costs (C_{Water}):** The amount per litre utilized was multiplied by the cost per litre.
- **Packaging costs (C_{Pack}):** Both the polypropylene (PP) and polypropylene (PE) total costs were taken into account.
- **Fresh cassava raw material ($C_{Raw materials}$):** The entire weight of cassava utilized was multiplied by the cost of cassava per kilogram.

The total cost was calculated by;

$$SC_{Ops} (\$/kg) = \frac{(C_{Lab} + C_{Energy} + C_{Water} + C_{Pack} + C_{Raw materials})}{Total\ product\ (kg)} \quad (17)$$

The total revenue, which is the total income generated was calculated using the following equation;

$$Rev_{Total} (\$) = Gari\ sold\ (kg) \times Cost\ per\ kg \quad (18)$$

Net profit margin: The percentage of revenue that remained as profit after all expenses were subtracted (NPM) was calculated by the following expression;

$$NPM(\%) = \frac{Net\ Profit}{Rev_{Total}} \times 100 \quad (19)$$

Return on capital: The effectiveness with which the investment (capital) was employed to generate profits (ROC) was measured using the following formula:

$$ROC(\%) = \frac{Net\ profit}{SC_{Ops}} \times 100 \quad (20)$$

Market and production surveys were conducted during the pick and low pick seasons in order to assess the seasonal variations. These methodologies support well-informed decisions-making for sustainable cassava processing into gari by offering a through framework for evaluating the financial and environmental implications (Magna et al., 2023).

3.2 Dynamic materiality

Dynamic materiality highlights the evolving importance of certain ESG issues over time. In the context of gari production in this case study, the energy transition and waste management practices to enhance sustainability and profitability are proposed. It is ensured that the operations are able to adjust to changing environmental, market, supply chain, and regulatory conditions by taking into account the dynamic materiality (IFRS, 2020; Svensson, 2024).

Key concepts

Evolving issues and triggers of change: Over dependence on woodfuel at the roasting stage and gasoline powered motor cycles for transporting cassava from the farms to the processing centres, and waste management (biomass and effluents) are becoming increasingly significant due to scarcity and high costs (woodfuel), market trends, stakeholder expectations and expected climate change propelled regulations. This could be achieved by comparing two scenarios (IFRS, 2020).

3.2.1. Scenario building

- **Scenario1: Continue current status of using gasoline and woodfuel:** depicts the current practices of using gasoline for transportation and grating, and woodfuel for roasting. It was also used to compare the dynamic change of prices during peak and off peak cassava seasons. It underlines the high operational costs and severe environmental impacts, as well as the consequences of noncompliance with future legislation.
- **Scenario 2:** depicts a potential transition to electric motorcycles with solar charged batteries for transportation, solar powered grating machines, and the hybrid solar/biogas roasting system. It demonstrates the advantages of lower operational expenses, less environmental impacts and better regulatory compliance.

3.2.2. Energy transition

3.2.2.1. Transportation and grating

Dynamic materiality consideration: The importance of decreasing carbon emissions and fuel costs is likely to grow in response to potential regulatory changes and rising fuel prices. Moreover, solar PV systems costs have reduced dramatically.

Benefits: Lower GWP, low energy costs, improved working environment and improved efficiency.

The following formula was used for calculating energy cost savings (ΔC_{Energy})

$$\Delta C_{Energy} = C_{Gasoline} - C_{PV} \quad (21)$$

Where: $C_{Gasoline}$ was energy from gasoline at transportation and grating stages and C_{PV} the energy generated from solar PV systems to substitute the gasoline.

This analysis assumes that the average energy required for roasting and charging the E-cycle batteries is properly sized to be supplied by the solar PV stem.

3.2.2.2. Roasting

Dynamic materiality consideration: The ever increasing consumer demand for eco-friendly products, scarcity of woodfuel, driven by the importance of using more sustainable energy sources, is projected to result into increased environmental laws

Benefits: reduced reliance on woodfuel and energy costs, lower GWP and use of more renewable energy sources.

The following formula was used for calculating the total energy (E_{total}) from the solar PV (E_{solar}) and the biogas (E_{biogas});

$$E_{total} = E_{solar} + E_{biogas} \quad (22)$$

3.2.2.3. Waste reduction

Dynamic materiality consideration: Reinforced waste disposal laws and the possibility of waste to energy solutions have made waste management techniques more crucial.

Benefits: reduced wastes resulting into sustainable waste management, reduced energy costs, lower GWP and use of more renewable energy sources from locally available resources.

The following formula was used for calculating the total biogas production (B_{total}) from multiplying the total wastes (solids and liquid- ($W_{cassava+liquidwastes}$)) with the biogas yield of cassava wastes of 0.0366 kWh per litre of biogas (Energylopedia, 2016; Jaro et al., 2021);

$$B_{total} = W_{cassava+liquidwastes} \times biogass\ yield \quad (23)$$

3.2.2.4. Environmental and social impacts

(i). Reduction in GWP

The following formula was used to calculate the reduction in the global warming potential (ΔGWP) by subtracting the scenario 1 ($GWP_{scenario1}$) emissions from scenario 2 ($GWP_{scenario2}$).

$$\Delta GWP = GWP_{Scenario1} - GWP_{Scenario2} \quad (24)$$

3.2.3. Social dimensions

The social dimension of the Life Cycle Sustainability Assessment (LCSA) was investigated by assessing gender participation in cassava processing stages. Structured conversations and surveys were conducted with local farmers, processors, and community members to better understand the roles of men and women in the production chain. The investigation especially sought to define the division of work (Padilla-Rivera et al., 2023).

Data was collected through semi-structured interviews and consultations, focus group discussions and observations. The many considerations where; reasons the type of operations are adapted, any challenges faced at each stage and there probable health implications, prices of raw materials such as cassava, woodfuel, labor, market price dynamics and transportation (Andersson et al., 2016).

For the double materiality, gender participation was quantified using indicators such as the percentage of each gender present at various phases and hours contributed. Furthermore, qualitative information was obtained about

the socioeconomic elements that influence these roles, such as access to resources, decision-making authority, and barriers faced by women in the agricultural industry (Susan and Natu, 2023).

For the dynamic Materiality, the proposed energy transition and waste minimization solutions represent a holistic approach to improving the sustainability and efficiency of staple food production that might also result in gender participation changes. Electric mobility, motorized graters, hybrid solar and biogas roasting and waste-to-biogas generation reduce environmental impact while optimizing operational costs. Scenario creation aids in visualizing prospective outcomes and informs decision-making, ensuring the operation stay adaptive to changing materiality considerations (Miller et al., 2023).

Limitations: This methodology emphasizes the need for additional study while acknowledging the limits of the available data, particularly the lack of complete education and health measures. Future research should focus on how gender dynamics affect agricultural practices' effects on health and education, in order to provide a more comprehensive knowledge of the social effects of cassava processing.

In order to enhance the efficiency, transparency, and reproducibility of the analysis in this work, the theoretical models are incorporated into Python scripts. This contributes to the scientific rigor and credibility of our work by guaranteeing that our methods can be repeated and verified by other researchers.

4. Python based automation of MEFA, double and dynamic materiality-analysis

All the above highlighted mathematical models were integrated into the python scripts for automation, data analysis and visualization.

4.1.1. Material and energy flow analysis scripts

The MEFA models established a theoretical and mathematical foundation for calculating cassava processing's, materials, energy, labor-social, environmental and financial implications. These models were developed into python computational scripts, allowing for the accurate calculation and visualization of materials and energy consumption, waste outputs, emissions, financial of all scenarios at each stage of the process (and cumulative figures). The pandas library scripts were developed to compile data on material input and output quantities with associated wastes, energy consumption and generate the sankey and heatmap diagrams using the plotly libraries to illustrate the flow and distribution of resources (Mckinney, 2010). The python scripts, in particular, allowed for the automatic integration of input parameters such as energy consumption (kg, kWh and kWh kg-gari⁻¹) and material flows (kg), with emission factors used to calculate GWP (kgCO₂eq kg-gari⁻¹ at each stage.

The cassava to gari MEFA sankey diagrams created with Python's plotly packages visually depict this material and energy fluxes, allowing for dynamic updates and sensitivity analysis based on changes in input data. This automated approach sped up the scenario-building process, allowing for the comparison of energy transition pathways such as the transition from gasoline-powered grating to electricity systems, as well as the move from unsustainable woodfuel use at the roasting stage to hybrid solar and biogas systems (Hunter, 2007).

4.1.2. Double and dynamic materiality scripts

The matplotlib, plotly and seaborn libraries facilitated the integration of financial and environmental data, enabling a dynamic and comprehensive analysis (Waskom, 2021). The visualization systems were created to identify the stages and material/energy streams responsible for greater financial and environmental impacts. Bar charts and line graphs were developed to compare cumulative costs and market prices, with annotations indicating key financial metrics such as profits and margins for both scenario 1 and 2 (Hunter, 2007; Mckinney, 2010).

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S5: Appendix A Table S1; Aggregated MEFA data from the 3 Facilities

| Material and Energy Flow Analysis Data from the Field | | | |
|---|-----------|-----------|-----------|
| Parameters | Facility1 | Facility2 | Facility3 |
| | | | |

| 1. Harvest | | | |
|---|--------|--------|--------|
| All plant harvested (Roots and all leaf materials and stems) kg | 484.06 | 159.77 | 85.89 |
| Harvested cassava roots (kg) | 282.82 | 94.90 | 52.00 |
| Wastes (cassava plants) (kg) | 201.24 | 64.87 | 33.89 |
| Waste/root ratio | 0.71 | 0.68 | 0.65 |
| Percentage of wastes (%) | 41.57 | 40.60 | 39.46 |
| Time spent for harvesting (hr) | 0.49 | 0.67 | 1.95 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Coefficient for Human power contribution per hour (kW/h/woman) | 0.22 | 0.22 | 0.22 |
| Number of women | 10.00 | 11.00 | 0.00 |
| Number of men | 4.00 | 1.00 | 3.00 |
| Total Women hours (hrs) | 4.90 | 7.37 | 0.00 |
| Total Men hours (hrs) | 1.96 | 0.67 | 5.85 |
| Energy from Women (kWh) | 1.08 | 1.62 | 0.00 |
| Energy from men (kWh) | 1.06 | 0.36 | 3.16 |
| Total Energy used for harvesting (kWh)-human energy | 2.14 | 1.98 | 3.16 |
| Cassava harvested per hour (kg/hr) | 581.27 | 141.64 | 26.67 |
| Specific energy used for harvesting (kWh/kg) | 0.01 | 0.02 | 0.06 |
| Energy productivity (kg/kWh) | 132.38 | 47.85 | 16.46 |
| pH | 6.93 | 7.20 | 7.91 |
| HCN content (ppm) | 21.12 | 26.58 | 48.68 |
| Cassava prices (\$/kg) | 0.03 | 0.03 | 0.03 |
| Total costs (\$) | 9.62 | 2.94 | 1.72 |
| 2. Transport to the processing center | | | |
| Transported | 282.82 | 94.90 | 52.00 |
| Time spent for transportation (hr) | 0.75 | 0.25 | 0.13 |
| Fuel used (gasoline) litres | 5.30 | 0.80 | 0.50 |
| Energy used for transportation from fuel (kWh) | 9.33 | 1.41 | 0.88 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Number of women | 0.00 | 0.00 | 0.00 |
| Number of men | 1.00 | 1.00 | 1.00 |
| Total Women hours (hrs) | 0.00 | 0.00 | 0.00 |
| Total Men hours (hrs) | 0.75 | 0.25 | 0.13 |
| Human energy used for transporting (kWh) | 0.41 | 0.14 | 0.07 |
| Cassava transported per hour (kg/hr) | 377.09 | 379.60 | 400.00 |
| Total energy used for transporting cassava (kWh) | 9.73 | 1.54 | 0.95 |
| | | | |
| Total Specific energy used for transportation (kWh/kg) | 0.03 | 0.02 | 0.02 |
| Energy productivity (kg/kWh) | 29.06 | 61.50 | 54.73 |
| emmissions from fossil fuel () | | | |
| 3. Peeling | | | |
| Peeled (kg) | 193.68 | 62.65 | 34.30 |
| Time spent for peeling (hr) | 2.60 | 3.50 | 1.45 |
| Peeling loss (kg) | 89.14 | 32.25 | 17.70 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |

| | | | |
|--|--------|--------|--------|
| Coefficient for Human power contribution per hour (kW/h/woman) | 0.22 | 0.22 | 0.22 |
| Number of women | 6.00 | 4.00 | 2.00 |
| Number of men | 0.00 | 0.00 | 0.00 |
| Total Women hours (hrs) | 15.60 | 14.00 | 2.90 |
| Total Men hours (hrs) | 0.00 | 0.00 | 0.00 |
| Cassava peeled per hour (kg/hr) | 74.49 | 17.90 | 23.66 |
| Energy from Women (kWh) | 3.43 | 3.08 | 0.64 |
| Energy from men (kWh) | 0.00 | 0.00 | 0.00 |
| Energy used for peeling (kWh) (human energy) | 3.43 | 3.08 | 0.64 |
| Specific energy used for peeling (kWh/kg) | 0.02 | 0.05 | 0.02 |
| Energy productivity (kg/kWh) | 56.43 | 20.34 | 53.76 |
| Wastes created (kg) peelings | 89.14 | 32.25 | 17.70 |
| Peeling loss (%) | 31.52 | 33.98 | 34.04 |
| 4. Washing | | | |
| Washed (kg) | 193.68 | 62.65 | 34.30 |
| Time spent on washing (hr) | 0.25 | 0.18 | 0.22 |
| Number of women | 6.00 | 3.00 | 3.00 |
| Number men | 0.00 | 0.00 | 0.00 |
| Total Women hours (hrs) | 1.50 | 0.54 | 0.66 |
| Total Men hours (hrs) | 0.00 | 0.00 | 0.00 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Coefficient for Human power contribution per hour (kW/h/woman) | 0.22 | 0.22 | 0.22 |
| Energy from Women (kWh) | 0.33 | 0.12 | 0.15 |
| Energy from men (kWh) | 0.00 | 0.00 | 0.00 |
| Energy used on washing (kWh) (human energy) | 0.33 | 0.12 | 0.15 |
| Cassava washed per hour (kg/hr) | 774.72 | 348.06 | 155.91 |
| Energy productivity (kg/kWh) | 586.91 | 527.36 | 236.23 |
| Specific energy used for washing (kWh/kg) | 0.00 | 0.00 | 0.00 |
| Water used for washing (kg) or L | 78.80 | 66.92 | 25.85 |
| Water (m ³) | 0.08 | 0.07 | 0.03 |
| Specif water consumption (kg-water/kg-cassava) | 0.41 | 1.07 | 0.75 |
| Water Productivity (kg-cassava/kg-water) | 2.46 | 0.94 | 1.33 |
| HCN content (ppm) | | | |
| Wash water | | | |
| Moisture content | | | |
| Fresh cassava moisture content (%) wet basis | 64.90 | 68.90 | 66.80 |
| 5. Grating | | | |
| Grated (kg) | 192.85 | 62.20 | 33.70 |
| Time spent for grating (hr) | 0.58 | 0.10 | 0.22 |
| Grating loss (kg) | 0.83 | 0.45 | 0.60 |
| Cassava grated per hour (kg/hr) | 332.50 | 622.00 | 153.18 |
| Fuel used (litres) | 1.12 | 0.83 | 1.07 |
| Energy used for grating from Fuel (kWh) | 1.97 | 1.46 | 1.88 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |

| | | | |
|---|---------|---------|--------|
| Coefficient for Human power contribution per hour (kW/h/wonman) | 0.22 | 0.22 | 0.22 |
| Number of women | 1.00 | 1.00 | 1.00 |
| Number of men | 1.00 | 1.00 | 1.00 |
| Total Women hours (hrs) | 0.58 | 0.10 | 0.22 |
| Total Men hours (hrs) | 0.58 | 0.10 | 0.22 |
| Energy from Women (kWh) | 0.13 | 0.02 | 0.05 |
| Energy from men (kWh) | 0.31 | 0.05 | 0.12 |
| Total Energy from human (kWh) | 0.44 | 0.08 | 0.17 |
| Total energy used (Human and fuel) | 2.41 | 1.54 | 2.05 |
| Specific energy used for grating (kWh/kg) | 0.01 | 0.02 | 0.06 |
| Energy productivity (kg/kWh) | 79.95 | 40.47 | 16.44 |
| Cassava mash Stack in the machine/dropped (kg) | 0.83 | 0.45 | 0.60 |
| Grating loss (%) | 0.03 | 0.05 | 0.21 |
| | | | |
| 6. Fermentation | | | |
| Fermented cassava mash | 192.85 | 62.20 | 33.70 |
| Women | 1.00 | 1.00 | 1.00 |
| Men | 1.00 | 1.00 | 1.00 |
| Time spent for fermentation preps | 0.19 | 0.03 | 0.07 |
| Total Time spent (women) | 0.19 | 0.03 | 0.07 |
| Total Time spent (men) | 0.19 | 0.03 | 0.07 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Coefficient for Human power contribution per hour (kW/h/wonman) | 0.22 | 0.22 | 0.22 |
| Energy from Women (kWh) | 0.04 | 0.01 | 0.02 |
| Energy from men (kWh) | 0.10 | 0.02 | 0.04 |
| Total Human energy (kWh) | 0.15 | 0.03 | 0.06 |
| Energy productivity (kg/kWh) | 1313.81 | 2457.72 | 605.27 |
| | | | |
| 7. De-watering | | | |
| De-Watered (kg) | 141.86 | 48.15 | 24.00 |
| Time spend de-watering (hr) | 1.50 | 0.54 | 0.50 |
| Water content (kg) | 50.99 | 14.05 | 9.70 |
| Dry matter (kg) | 72.07 | 25.13 | 12.41 |
| De-watering loss (kg) | 50.99 | 14.05 | 9.70 |
| Cake de-watered per hour (kg/hr) | 94.57 | 89.17 | 48.00 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Coefficient for Human power contribution per hour (kW/h/woman) | 0.22 | 0.22 | 0.22 |
| Number of women | 1.00 | 1.00 | 1.00 |
| Number of men | 1.00 | 1.00 | 1.00 |
| Total Women hours (hrs) | 1.50 | 0.54 | 0.50 |
| Total Men hours (hrs) | 1.50 | 0.54 | 0.50 |
| Energy from Women (kWh) | 0.33 | 0.12 | 0.11 |
| Energy from men (kWh) | 0.81 | 0.29 | 0.27 |
| Energy used for de-watering (kWh) | 1.14 | 0.41 | 0.38 |

| | | | |
|--|--------|--------|--------|
| Specific energy for de-watering (kWh/kg) | 0.01 | 0.01 | 0.02 |
| Energy productivity (kg/kWh) | 124.44 | 117.32 | 63.16 |
| pH | 6.54 | 6.55 | 7.82 |
| HCN (ppm) | 17.84 | 24.65 | 45.69 |
| Cassava juice waste (kg) | 50.99 | 14.05 | 9.70 |
| De-watering loss (%) | 26.44 | 22.59 | 28.78 |
| Moisture content | | | |
| De-water mash (%) wet basis | 49.20 | 47.80 | 48.30 |
| 8. Sifting/Sieving | | | |
| Sieved (kg) | 139.20 | 47.30 | 23.30 |
| Time spent sieving (HR) | 1.85 | 0.68 | 0.35 |
| Number of women | 2.00 | 3.00 | 1.00 |
| Number of men | 0.00 | 0.00 | 0.00 |
| Coefficient for Human power contribution per hour (kW/h/man) | 0.54 | 0.54 | 0.54 |
| Coefficient for Human power contribution per hour (kW/h/woman) | 0.22 | 0.22 | 0.22 |
| Total Women hours (hrs) | 3.70 | 2.04 | 0.35 |
| Total Men hours (hrs) | 0.00 | 0.00 | 0.00 |
| Energy from Women (kWh) | 0.81 | 0.45 | 0.08 |
| Energy from men (kWh) | 0.00 | 0.00 | 0.00 |
| Sieve loss (kg) | 2.66 | 0.85 | 0.70 |
| Cake sieved/sifted per hour (kg/hr) | 75.24 | 69.56 | 66.57 |
| Human Energy used for sieving (kWh) | 0.81 | 0.45 | 0.08 |
| Specific energy for sieving (kWh/kg) | 0.01 | 0.01 | 0.00 |
| Energy productivity (kg/kWh) | 171.01 | 105.39 | 302.60 |
| Fibres (kg) | 2.66 | 0.85 | 0.70 |
| sieving loss (%) | 1.88 | 1.77 | 2.92 |
| 9. Roasting | | | |
| Roasted (kg) | 79.75 | 28.90 | 13.30 |
| Time spent for roasting (hrs) | 16.05 | 8.77 | 3.12 |
| Roasting Loss (kg) | 59.45 | 18.40 | 10.00 |
| Gari produced /hour (kg-gari/hr) | 4.97 | 3.30 | 4.26 |
| Fire wood used (kg) | 46.05 | 43.55 | 16.20 |
| Ash produced | 3.09 | 5.84 | 3.11 |
| Ash produced (%) | 6.70 | 13.40 | 19.20 |
| Coefficient for Human power contribution per hour (kWh/woman) | 0.22 | 0.22 | 0.22 |
| Coefficient for Human power contribution per hour (kWh/man) | 0.54 | 0.54 | 0.54 |
| Number of women | 4.00 | 1.00 | 1.00 |
| Number of men | 0.00 | 0.00 | 0.00 |
| Total Women hours (hrs) | 64.20 | 8.77 | 3.12 |
| Total Men hours (hrs) | 0.00 | 0.00 | 0.00 |
| Energy from Women (kWh) | 14.12 | 1.93 | 0.69 |
| Energy from men (kWh) | 0.00 | 0.00 | 0.00 |
| Energy contributed by humans (kWh) | 14.12 | 1.93 | 0.69 |

| | | | |
|---|--------|--------|--------|
| Energy used on roasting from firewood (kWh) | 253.28 | 239.53 | 89.10 |
| Total energy used for roasting (Firewood+Human) | 267.40 | 241.45 | 89.79 |
| Specific energy for roasting (kg-wood/kg-gari) | 0.58 | 1.51 | 1.22 |
| Specific energy of wood (kWh/kg) | 3.18 | 8.29 | 6.70 |
| Specific energy for roasting (kWh/kg) (woodfuel+Humanenergy) | 3.35 | 8.35 | 6.75 |
| Energy productivity (kg/kWh) | 0.30 | 0.12 | 0.15 |
| Energy productivity (kg-gari/kg-wood) | 1.73 | 0.66 | 0.82 |
| HCN lost (ppm) | 14.60 | 20.12 | 39.29 |
| Roasting loss (%) | 42.71 | 38.90 | 42.92 |
| | | | |
| 10. Gari Sieving/grading | | | |
| Gari Sieved (kg) | 78.52 | 28.10 | 13.10 |
| Time spent on Gari sieving (hr) | 0.20 | 0.14 | 0.13 |
| Sieve loss (kg) | 1.23 | 0.80 | 0.20 |
| Number of women | 5.00 | 2.00 | 1.00 |
| Number of men | 0.00 | 0.00 | 0.00 |
| Total Women hours (hrs) | 1.00 | 0.28 | 0.13 |
| Total Men hours (hrs) | 0.00 | 0.00 | 0.00 |
| Coefficient for Human power contribution per hour (kWh/woman) | 0.22 | 0.22 | 0.22 |
| Coefficient for Human power contribution per hour (kWh/man) | 0.54 | 0.54 | 0.54 |
| Energy from Women (kWh) | 0.22 | 0.06 | 0.03 |
| Energy from men (kWh) | 0.00 | 0.00 | 0.00 |
| Gari sieved/sifted per hour (kg/hr) | 392.60 | 200.71 | 100.77 |
| Total Human Energy used for Gari sieving (kWh) | 0.22 | 0.06 | 0.03 |
| Specific energy for Gari sieving (kWh/kg) | 0.00 | 0.00 | 0.00 |
| Energy productivity (kg/kWh) | 356.91 | 456.17 | 458.04 |
| Gari sieving loss (%) | 1.54 | 2.77 | 1.50 |
| Losses as Gari lumps | 1.23 | 0.80 | 0.20 |
| Garification | 0.28 | 0.30 | 0.25 |
| Yield (cassava roots)(%) | 27.57 | 29.61 | 25.19 |
| | | | |
| TRY Yield (%) | 27.76 | 29.61 | 25.19 |
| TBY yield (%) | 16.22 | 17.59 | 15.25 |
| pH | 4.24 | 3.72 | 4.50 |
| HCN (ppm) | 3.24 | 4.53 | 6.40 |
| | | | |
| 11. Packaging | | | |
| Gari Packaged (kg) | 78.52 | 28.1 | 13.1 |
| Time spent on Gari sieving (hr) | 0.33 | 0.09 | 0.04 |
| Packaging loss (kg) | 0.00 | 0.00 | 0.00 |
| Number of women | 1.00 | 1.00 | 1.00 |
| Number of men | 1.00 | 1.00 | 1.00 |
| Total Women hours (hrs) | 0.33 | 0.09 | 0.04 |
| Total Men hours (hrs) | 0.33 | 0.09 | 0.04 |

| | | | |
|---|--------|--------|--------|
| Coefficient for Human power contribution per hour (kWh/woman) | 0.22 | 0.22 | 0.22 |
| Coefficient for Human power contribution per hour (kWh/man) | 0.54 | 0.54 | 0.54 |
| Energy from Women (kWh) | 0.07 | 0.02 | 0.01 |
| Energy from men (kWh) | 0.18 | 0.05 | 0.02 |
| Total Human Energy used for Gari sieving (kWh) | 0.25 | 0.07 | 0.03 |
| Specific energy for Gari sieving (kWh/kg) | 0.00 | 0.00 | 0.00 |
| Energy productivity (kg/kWh) | 313.08 | 410.82 | 430.92 |
| Packaging materials used (kg) | 0.09 | 0.08 | 0.05 |

S6: Table S2: Specific material flow data for all facilities

| Table S2: Average Specific Material Consumption for all the facilities | | | | | | | | | |
|--|------------------------------|-----------------------------------|----------------------------------|------------------------------------|-------------------------------|-------------------------------------|--------------------------------|--|-------------------------------|
| Process | Specific Inputs (kg/kg-gari) | Specific Clean Water (kg/kg-gari) | Specific PP/PE Bags (kg/kg-gari) | Specific Woodfuel Ash (kg/kg-gari) | Specific Outputs (kg/kg-gari) | Specific Biomass Waste (kg/kg-gari) | Specific Effluent (kg/kg-gari) | Specific Evaporated Water (kg/kg-gari) | Specific Cyanide (kg/kg-gari) |
| Harvesting | 6.136 | | | | 3.650 | 2.486 | | | |
| Transportation | 3.650 | | | | 3.650 | 0.000 | | | |
| Peeling | 3.650 | | | | 2.438 | 1.211 | | | |
| Washing | 2.438 | 1.786 | | | 2.438 | 0.000 | 1.786 | | |
| Grating | 2.438 | | | | 2.414 | 0.024 | | | |
| Fermentation | 2.414 | | | | 2.414 | 0.000 | | | |
| Dewatering | 2.414 | | | | 1.784 | 0.000 | 0.630 | | |
| Sifting and Sieving | 1.784 | | | | 1.745 | 0.039 | | | |
| Roasting | 1.745 | | | 0.162 | 1.020 | 0.000 | | 0.725 | 0.000001300414 |
| Sieving and Grading | 1.020 | | | | 1.000 | 0.020 | | | |
| Packaging | 1.000 | | 0.002 | | 1.000 | 0.000 | | | |

S7: Table S3, S4 and S5: Facility 1, 2 and 3 specific material flow data

| Table S3: Facility1 Specific Material Consumption for all the facilities (kg/kg-gari) | | | | | | | | | |
|---|-----------------|----------------------|---------------------|-----------------------|------------------|------------------------|-------------------|---------------------------|------------------|
| Process | Specific Inputs | Specific Clean Water | Specific PP/PE Bags | Specific Woodfuel Ash | Specific Outputs | Specific Biomass Waste | Specific Effluent | Specific Evaporated Water | Specific Cyanide |
| Harvesting | 6.165 | | | | 3.602 | 2.563 | | | |
| Transportation | 3.602 | | | | 3.602 | 0.000 | | | |
| Peeling | 3.602 | | | | 2.467 | 1.135 | | | |
| Washing | 2.467 | 1.004 | | | 2.467 | 0.000 | 1.004 | | |
| Grating | 2.467 | | | | 2.456 | 0.011 | | | |
| Fermentation | 2.456 | | | | 2.456 | 0.000 | | | |
| Dewatering | 2.456 | | | | 1.807 | 0.000 | 0.649 | | |
| Sifting and Sieving | 1.807 | | | | 1.773 | 0.034 | | | |
| Roasting | 1.773 | | | 0.039 | 1.016 | 0.000 | | 0.757 | 0.000 |
| Sieving and Grading | 1.016 | | | | 1.000 | 0.016 | | | |
| Packaging | 1.000 | | 0.002 | | 1.000 | 0.000 | | | |

| Table S5: Facility3 Specific Material Consumption for all the facilities (kg/kg-gari) | | | | | | | | | |
|---|-----------------|----------------------|---------------------|-----------------------|------------------|------------------------|-------------------|---------------------------|------------------|
| Process | Specific Inputs | Specific Clean Water | Specific PP/PE Bags | Specific Woodfuel Ash | Specific Outputs | Specific Biomass Waste | Specific Effluent | Specific Evaporated Water | Specific Cyanide |
| Harvesting | 6.556 | | | | 3.969 | 2.587 | | | |
| Transportation | 3.969 | | | | 3.969 | 0.000 | | | |
| Peeling | 3.969 | | | | 2.618 | 1.351 | | | |
| Washing | 2.618 | 1.973 | | | 2.618 | 0.000 | 1.973 | | |
| Grating | 2.618 | | | | 2.573 | 0.046 | | | |
| Fermentation | 2.573 | | | | 2.573 | 0.000 | | | |
| Dewatering | 2.573 | | | | 1.832 | 0.000 | 0.740 | | |
| Sifting and Sieving | 1.832 | | | | 1.779 | 0.053 | | | |
| Roasting | 1.779 | | | 0.237 | 1.015 | 0.000 | | 0.763 | 0.000 |
| Sieving and Grading | 1.015 | | | | 1.000 | 0.015 | | | |
| Packaging | 1.000 | | 0.003 | | 1.000 | 0.000 | | | |

| Table S4: Facility2 Specific Material Consumption for all the facilities (kg/kg-gari) | | | | | | | | | |
|---|-----------------|----------------------|---------------------|-----------------------|------------------|------------------------|-------------------|---------------------------|------------------|
| Process | Specific Inputs | Specific Clean Water | Specific PP/PE Bags | Specific Woodfuel Ash | Specific Outputs | Specific Biomass Waste | Specific Effluent | Specific Evaporated Water | Specific Cyanide |
| Harvesting | 5.686 | | | | 3.377 | 2.309 | | | |
| Transportation | 3.377 | | | | 3.377 | 0.000 | | | |
| Peeling | 3.377 | | | | 2.230 | 1.148 | | | |
| Washing | 2.230 | 2.381 | | | 2.230 | 0.000 | 2.381 | | |
| Grating | 2.230 | | | | 2.214 | 0.016 | | | |
| Fermentation | 2.214 | | | | 2.214 | 0.000 | | | |
| Dewatering | 2.214 | | | | 1.714 | 0.000 | 0.500 | | |
| Sifting and Sieving | 1.714 | | | | 1.683 | 0.030 | | | |
| Roasting | 1.683 | | | 0.208 | 1.028 | 0.000 | | 0.655 | 0.000 |
| Sieving and Grading | 1.028 | | | | 1.000 | 0.028 | | | |
| Packaging | 1.000 | | 0.003 | | 1.000 | 0.000 | | | |

S8: Table S6: Actual average wastes in kilograms per stage for all Facilities

| Process | Table S6: Actual Wastes Across the processes (kg) | | | | |
|--------------------------|---|------------------|--------------------------|-----------------|----------------------|
| | Average Biomass Waste | Average Effluent | Average Evaporated Water | Average Cyanide | Average Woodfuel Ash |
| Harvesting (kg) | 99.990 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Transportation (kg) | 0.000 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Peeling (kg) | 46.363 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Washing (kg) | 0.000 | 57.190 | 0.000 | 0.000000 | 0.000 |
| Grating (kg) | 0.627 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Fermentation (kg) | 0.000 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Dewatering (kg) | 0.000 | 24.913 | 0.000 | 0.000000 | 0.000 |
| Sifting and Sieving (kg) | 1.403 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Roasting (kg) | 0.000 | 0.000 | 29.283 | 0.000025 | 4.013 |
| Sieving and Grading (kg) | 0.743 | 0.000 | 0.000 | 0.000000 | 0.000 |
| Packaging (kg) | 0.000 | 0.000 | 0.000 | 0.000000 | 0.000 |

S9: Table S7, S8 and S9: Actual average Material Flow Accounting in kilograms per stage for all Facilities with Sankey diagrams

| Process | Table S7: Facility 1 Actual Material and Flow Analysis Data | | | | | | | | |
|--------------------------|---|---------|---------------|----------|------------------|-----------|-------------|------------|--------------|
| | Inputs | Outputs | Biomass Waste | Effluent | Evaporated Water | Cyanide | Clean Water | PP/PE Bags | Woodfuel Ash |
| Harvesting (kg) | 484.06 | 282.82 | 201.21 | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation (kg) | 282.82 | 282.82 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Peeling (kg) | 282.82 | 193.68 | 89.14 | 0 | 0 | 0 | 0 | 0 | 0 |
| Washing (kg) | 272.48 | 193.68 | 0 | 78.8 | 0 | 0 | 78.8 | 0 | 0 |
| Grating (kg) | 193.68 | 192.85 | 0.83 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fermentation (kg) | 192.85 | 192.85 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dewatering (kg) | 192.85 | 141.86 | 0 | 50.99 | 0 | 0 | 0 | 0 | 0 |
| Sifting and Sieving (kg) | 141.86 | 139.2 | 2.66 | 0 | 0 | 0 | 0 | 0 | 0 |
| Roasting (kg) | 142.29 | 79.75 | 0 | 0 | 59.449 | 0.0000146 | 0 | 0 | 3.09 |
| Sieving and Grading (kg) | 79.75 | 78.52 | 1.23 | 0 | 0 | 0 | 0 | 0 | 0 |
| Packaging (kg) | 78.668 | 78.52 | 0 | 0 | 0 | 0 | 0 | 0.148 | 0 |

Sankey Diagram for Facility 1

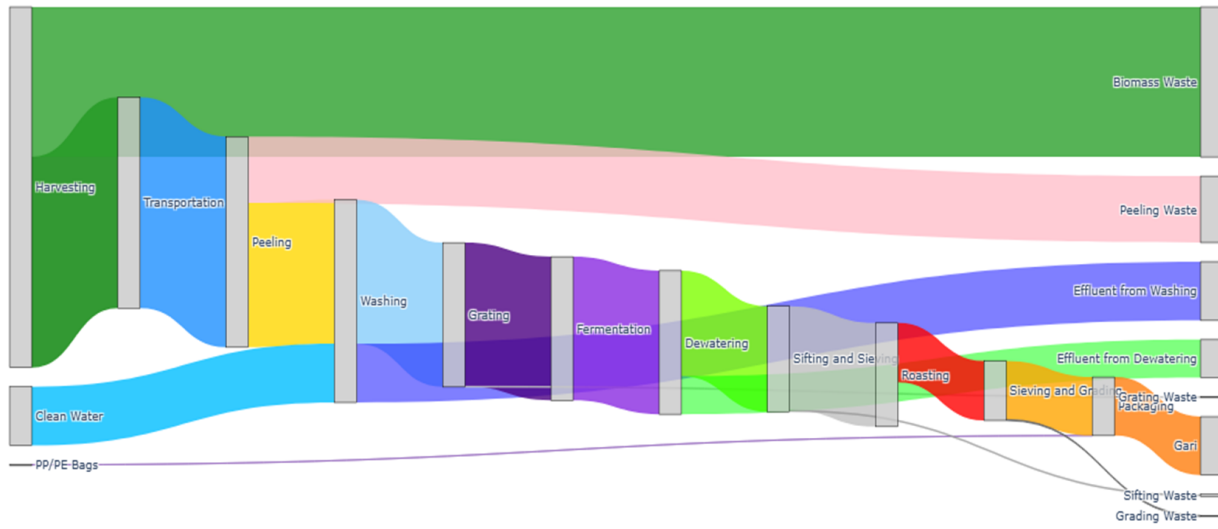


Table S8: Facility 2 Actual Material and Flow Analysis Data

| Process | Inputs | Outputs | Biomass Waste | Effluent | Evaporated Water | Cyanide | Clean Water | PP/PE Bags | Woodfuel Ash |
|--------------------------|--------|---------|---------------|----------|------------------|-----------|-------------|------------|--------------|
| Harvesting (kg) | 159.77 | 94.9 | 64.87 | 0 | 0 | 0 | 0 | 0 | 0 |
| Transportation (kg) | 94.9 | 94.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Peeling (kg) | 94.9 | 62.65 | 32.25 | 0 | 0 | 0 | 0 | 0 | 0 |
| Washing (kg) | 129.57 | 62.65 | 0 | 66.92 | 0 | 0 | 66.92 | 0 | 0 |
| Grating (kg) | 62.65 | 62.2 | 0.45 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fermentation (kg) | 62.2 | 62.2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Dewatering (kg) | 62.2 | 48.15 | 0 | 14.05 | 0 | 0 | 0 | 0 | 0 |
| Sifting and Sieving (kg) | 48.15 | 47.3 | 0.85 | 0 | 0 | 0 | 0 | 0 | 0 |
| Roasting (kg) | 53.14 | 28.9 | 0 | 0 | 18.4 | 0.0000201 | 0 | 0 | 5.84 |
| Sieving and Grading (kg) | 28.9 | 28.1 | 0.8 | 0 | 0 | 0 | 0 | 0 | 0 |
| Packaging (kg) | 28.174 | 28.1 | 0 | 0 | 0 | 0 | 0 | 0.074 | 0 |

Key Diagram for Facility 2

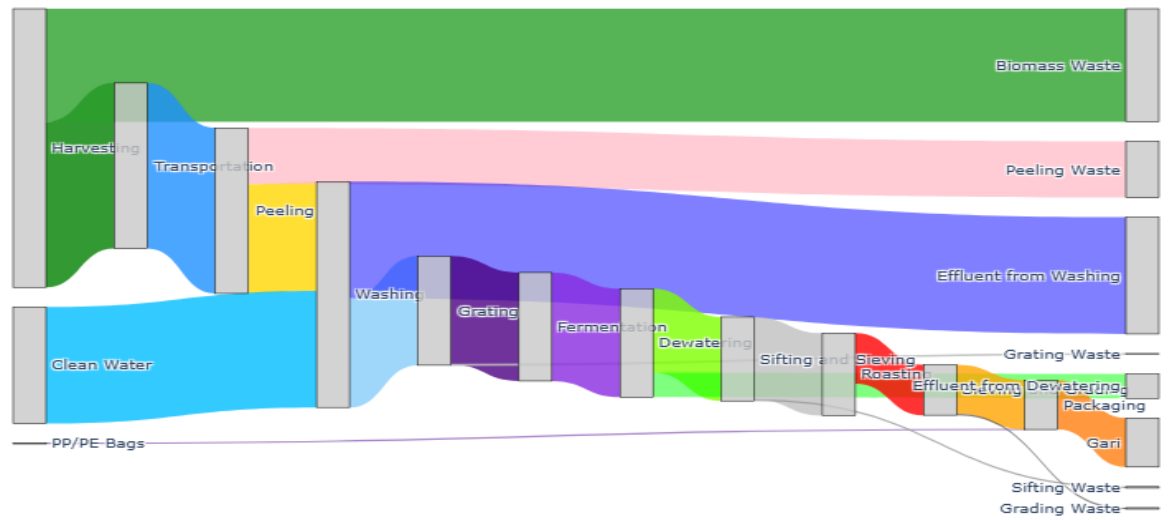
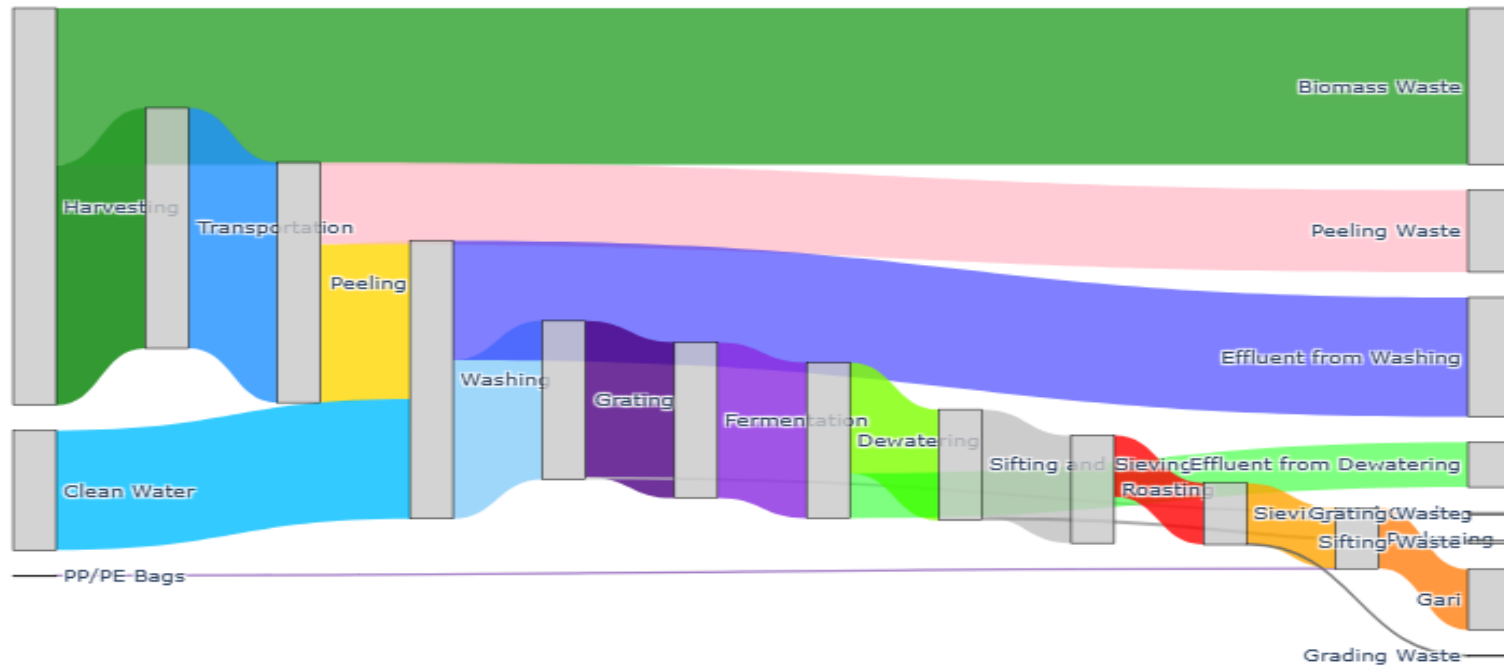


Table S9: Facility 3 Actual Material and Flow Analysis Data

| Process | Inputs | Outputs | Biomass Waste | Effluent | Evaporated Water | Cyanide | Clean Water | PP/PE Bags | Woodfuel Ash |
|--------------------------|--------|---------|---------------|----------|------------------|---------|-------------|------------|--------------|
| Harvesting (kg) | 85.89 | 52.00 | 33.89 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Transportation (kg) | 52.00 | 52.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Peeling (kg) | 52.00 | 34.30 | 17.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Washing (kg) | 60.15 | 34.30 | 0.00 | 25.85 | 0.00 | 0.00 | 25.85 | 0.00 | 0.00 |
| Grating (kg) | 34.30 | 33.70 | 0.60 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fermentation (kg) | 33.70 | 33.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Dewatering (kg) | 33.70 | 24.00 | 0.00 | 9.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sifting and Sieving (kg) | 24.00 | 23.30 | 0.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Roasting (kg) | 26.41 | 13.30 | 0.00 | 0.00 | 10.00 | 0.00 | 0.00 | 0.00 | 3.11 |
| Sieving and Grading (kg) | 13.30 | 13.10 | 0.20 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Packaging (kg) | 13.14 | 13.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.04 | 0.00 |

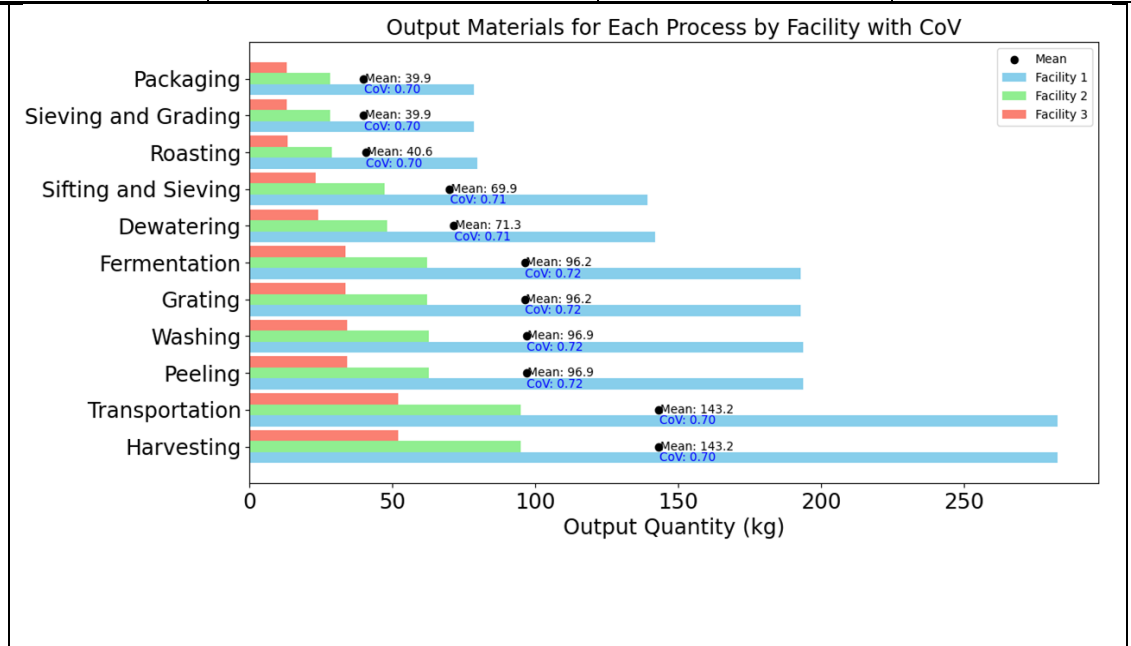
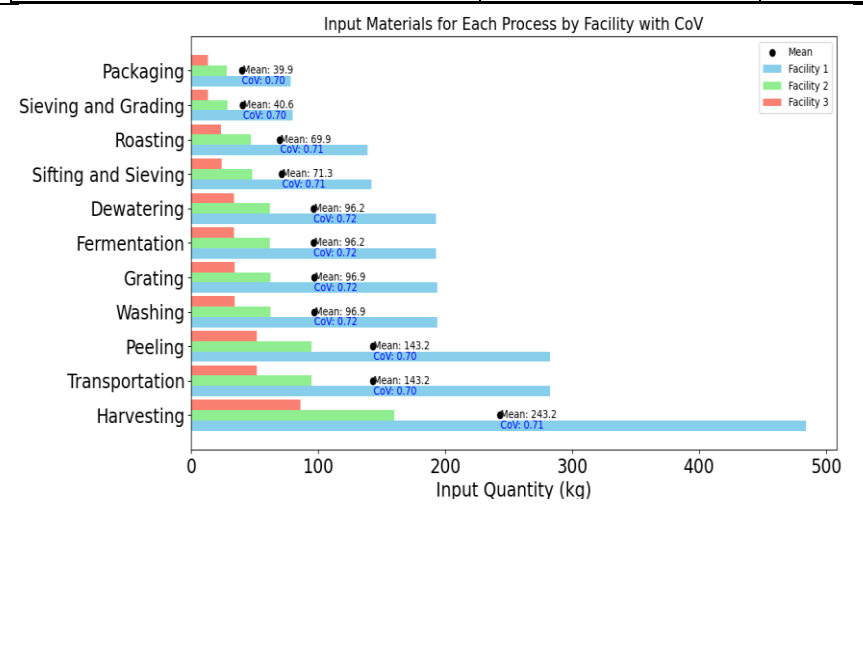
Key Diagram for Facility 3



S10: Table S10: Actual average Material Flow Accounting in kilograms per stage for all Facilities with input and outputs bar charts

Table S10: All Facilities Average Material and Flow Accounting Data

| Process | Average Inputs | Average Outputs | Average Clean Water | Average PP/PE Bags | Average Woodfuel Ash |
|--------------------------|----------------|-----------------|---------------------|--------------------|----------------------|
| Harvesting (kg) | 243.240 | 143.240 | 0.000 | 0.000 | 0.000 |
| Transportation (kg) | 143.240 | 143.240 | 0.000 | 0.000 | 0.000 |
| Peeling (kg) | 143.240 | 96.877 | 0.000 | 0.000 | 0.000 |
| Washing (kg) | 154.067 | 96.877 | 57.190 | 0.000 | 0.000 |
| Grating (kg) | 96.877 | 96.250 | 0.000 | 0.000 | 0.000 |
| Fermentation (kg) | 96.250 | 96.250 | 0.000 | 0.000 | 0.000 |
| Dewatering (kg) | 96.250 | 71.337 | 0.000 | 0.000 | 0.000 |
| Sifting and Sieving (kg) | 71.337 | 69.933 | 0.000 | 0.000 | 0.000 |
| Roasting (kg) | 73.947 | 40.650 | 0.000 | 0.000 | 4.013 |
| Sieving and Grading (kg) | 40.650 | 39.907 | 0.000 | 0.000 | 0.000 |
| Packaging (kg) | 39.907 | 39.907 | 0.000 | 0.086 | 0.000 |



S11: Table S12: Comparative specific energy consumption per stage for all Facilities

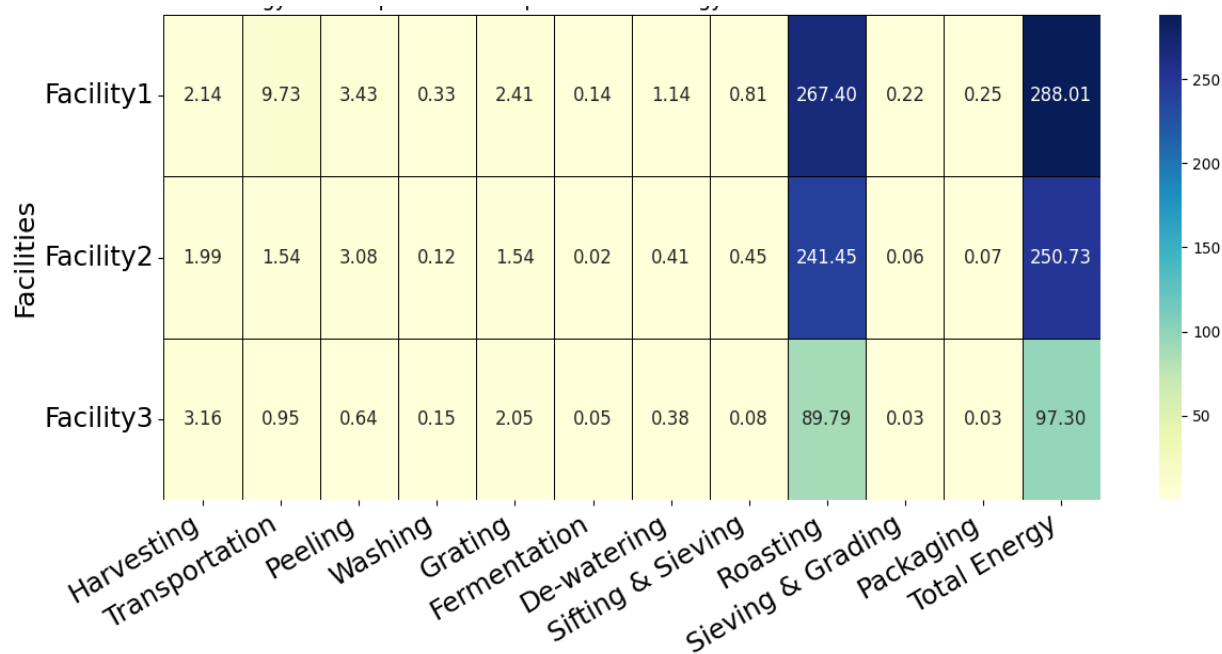
| | | | | | | | Table S12: Comparative specific energy consumption per process for all facilities | | | | | |
|-------------------------|------------|----------------|---------|---------|---------|--------------|---|-------------------|----------|-------------------|-----------|-------------------------------|
| Description | Harvesting | Transportation | Peeling | Washing | Grating | Fermentation | De-watering | Sifting & Sieving | Roasting | Sieving & Grading | Packaging | Per Facility Average (kWh/kg) |
| Facility1 (kWh/kg-gari) | 0.0272 | 0.12 | 0.04 | 0.00 | 0.03 | 0.002 | 0.01 | 0.01 | 3.41 | 0.00 | 0.00 | 3.67 |
| Facility2 (kWh/kg-gari) | 0.0707 | 0.05 | 0.11 | 0.00 | 0.05 | 0.001 | 0.01 | 0.02 | 8.59 | 0.00 | 0.00 | 8.92 |
| Facility3 (kWh/kg-gari) | 0.2411 | 0.07 | 0.05 | 0.01 | 0.16 | 0.004 | 0.03 | 0.01 | 6.85 | 0.00 | 0.00 | 7.43 |
| Mean (kWh/kg-gari) | 0.1130 | 0.08 | 0.07 | 0.01 | 0.08 | 0.002 | 0.02 | 0.01 | 6.28 | 0.00 | 0.00 | 6.67 |
| StD | 0.0923 | 0.03 | 0.03 | 0.00 | 0.05 | 0.001 | 0.01 | 0.00 | 2.16 | 0.00 | 0.00 | 2.38 |
| CoV | 81.6765 | 34.95 | 44.49 | 49.78 | 67.63 | 60.622 | 35.14 | 38.45 | 34.30 | 12.10 | 14.64 | 43.07 |

S12: Table S11 and Fig S13; Specific emissions data at each stage for all facilities

Table S11: Emissions Data (kgCO₂eq/kg-gari)

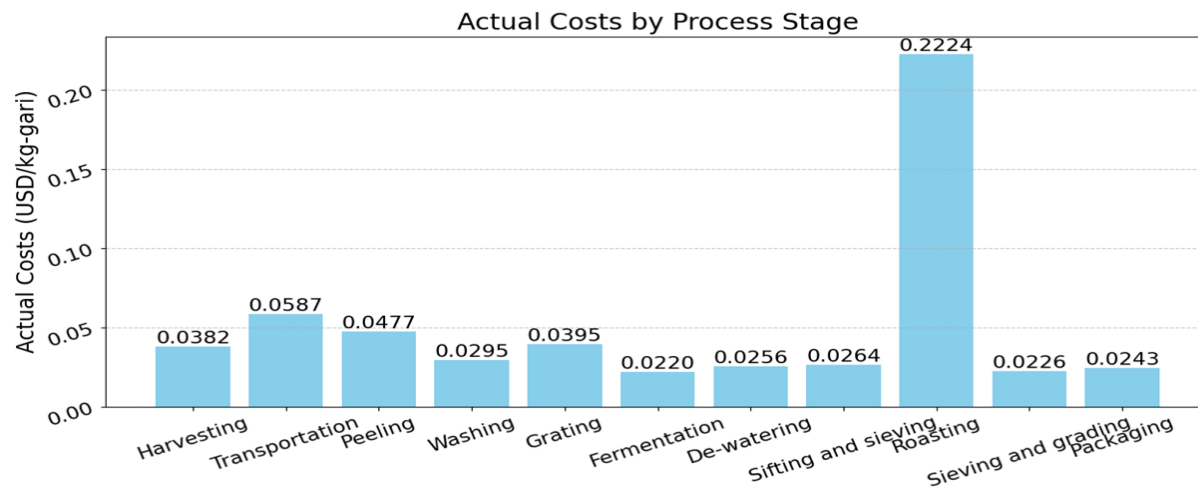
| Process | Biomass input (kg/kg-gari) | Biomass waste (kg/kg-gari) | Water used (kg/kg-gari) | Waste Water (kg/kg-gari) | Cassava Juice (kg/kg-gari) | Evaporated water (kg/kg-gari) | Cyanide (kg/kg-gari) | Men Manual energy (kWh/kg-gari) | Women Manual energy (kWh/kg-gari) | Gasoline energy (kWh/kg-gari) | Woodfuel Energy (kWh/kg-gari) | Woodfuel Ash (kg/kg-gari) | PP/PE Bags (kg/kg-gari) | Total Emissions (kgCO ₂ e/kg-gari) |
|---------------------|----------------------------|----------------------------|-------------------------|--------------------------|----------------------------|-------------------------------|----------------------|---------------------------------|-----------------------------------|-------------------------------|-------------------------------|---------------------------|-------------------------|---|
| Harvesting | 6.095 | 2.506 | 0 | 0 | 0 | 0 | 0 | 0.03825 | 0.022545728 | 0 | 0 | 0.00 | 0 | 4.51384 |
| Transportation | 3.5891 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00510 | 0 | 0.09702 | 0 | 0.00 | 0 | 0.02597 |
| Peeling | 3.5891 | 1.161697 | 0 | 0 | 0 | 0 | 0 | 0.00000 | 0.059717698 | 0 | 0 | 0.00 | 0 | 2.09404 |
| Washing | 2.4274 | 0 | 1.4 | 1.4 | 0 | 0 | 0 | 0.00000 | 0.004961163 | 0 | 0 | 0.00 | 0 | 0.08425 |
| Grating | 2.4274 | 0.0157 | 0 | 0 | 0 | 0 | 0 | 0.00288 | 0.001653721 | 0.0444 | 0 | 0.00 | 0 | 0.04025 |
| Fermentation | 2.4117 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00135 | 0.000550689 | 0 | 0 | 0.00 | 0 | 0.00010 |
| De-watering | 2.4117 | 0 | 0 | 0 | 0.624 | 0 | 0 | 0.01146 | 0.004667168 | 0 | 0 | 0.00 | 0 | 0.01329 |
| Sifting and sieving | 1.7875 | 0.03508 | 0 | 0 | 0 | 0 | 0 | 0.00000 | 0.011190178 | 0 | 0 | 0.00 | 0 | 0.06370 |
| Roasting | 1.7522 | 0 | 0 | 0 | 0 | 0.7337 | 0.00002467 | 0.00000 | 0.139812912 | 0 | 4.86 | 0.10 | 0 | 2.15075 |
| Sieving and grading | 1.0185 | 0.01854 | 0 | 0 | 0 | 0 | 0 | 0.00000 | 0.002590829 | 0 | 0 | 0.00 | 0 | 0.03350 |
| Packaging | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00207 | 0.000845235 | 0 | 0 | 0.00 | 0.001854 | 0.00385 |

Fig S13: Energy consumption heatmap with Total Energy across process and facilities



S13: Table S13 and graph; Specific Cost of production per stage for all facilities

| Table S13: Costs of Production (\$/kg-gari) | | | | | | | | | | | | |
|---|--------------------|--------------------|--------------------|-------------------|-------------------|--------------------|--------------------|---------------------|--------------------|---------------------|--------------------|---------------------------------|
| Process | Harvest | Transportation | Peeling | Washing | Grating | Fermentation | De-watering | Sieving and sifting | Roasting | Sieving and grading | Packaging | Total cost per cost center (\$) |
| Human energy (\$) | 0.016767422 | 0.000913118 | 0.026261407 | 0.002181784 | 0.00145452 | 0.000484356 | 0.004104978 | 0.004921135 | 0.061485898 | 0.001139376 | 0.000743424 | 0.12045742 |
| Gasoline (\$) | 0 | 0.036307041 | 0 | 0 | 0.01659126 | 0 | 0 | 0 | 0 | 0 | 0 | 0.052898296 |
| Cassava (\$) | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.0214784 | 0.236262403 |
| Woodfuel (\$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.13946742 | 0 | 0 | 0.13946742 |
| Water (\$) | 0 | 0 | 0 | 0.005817875 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.005817875 |
| Packaging (\$) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.00212144 | 0.00212144 |
| Total cost per process (\$) | 0.038245823 | 0.058698559 | 0.047739807 | 0.02947806 | 0.03952418 | 0.021962756 | 0.025583378 | 0.026399535 | 0.222431718 | 0.022617776 | 0.024343264 | 0.557024855 |



S14: Table S14, S15 and S16; All facilities energy consumption

| Table S14: Facility1 actual Energy distribution | | | | | | | | | |
|--|---------------|-------------|-------------------|---------------|-------------------------|-----------------------|----------------------------|----------------------------|--------------------|
| Process | Women (Hours) | Men (Hours) | Gasoline (Liters) | Woodfuel (kg) | Energy from Women (kWh) | Energy from Men (kWh) | Energy from Gasoline (kWh) | Energy from Woodfuel (kWh) | Total Energy (kWh) |
| Harvesting | 4.90 | 1.96 | 0.00 | 0.00 | 1.08 | 1.06 | 0.00 | 0.00 | 2.14 |
| Transportation | 0.00 | 0.75 | 5.30 | 0.00 | 0.00 | 0.41 | 9.33 | 0.00 | 9.73 |
| Peeling | 15.60 | 0.00 | 0.00 | 0.00 | 3.43 | 0.00 | 0.00 | 0.00 | 3.43 |
| Washing | 1.50 | 0.00 | 0.00 | 0.00 | 0.33 | 0.00 | 0.00 | 0.00 | 0.33 |
| Grating | 0.58 | 0.58 | 1.12 | 0.00 | 0.13 | 0.31 | 1.97 | 0.00 | 2.41 |
| Fermentation | 0.19 | 0.19 | 0.00 | 0.00 | 0.04 | 0.10 | 0.00 | 0.00 | 0.14 |
| De-watering | 1.50 | 1.50 | 0.00 | 0.00 | 0.33 | 0.81 | 0.00 | 0.00 | 1.14 |
| Sifting & Sieving | 3.70 | 0.00 | 0.00 | 0.00 | 0.81 | 0.00 | 0.00 | 0.00 | 0.81 |
| Roasting | 64.20 | 0.00 | 0.00 | 46.05 | 14.12 | 0.00 | 0.00 | 253.28 | 267.40 |
| Sieving & Grading | 1.00 | 0.00 | 0.00 | 0.00 | 0.22 | 0.00 | 0.00 | 0.00 | 0.22 |
| Packaging | 0.33 | 0.33 | 0.00 | 0.00 | 0.07 | 0.18 | 0.00 | 0.00 | 0.25 |
| | | | | | | | | | |
| Total | 93.50 | 5.31 | 6.42 | 46.05 | 20.57 | 2.87 | 11.30 | 253.28 | 288.01 |

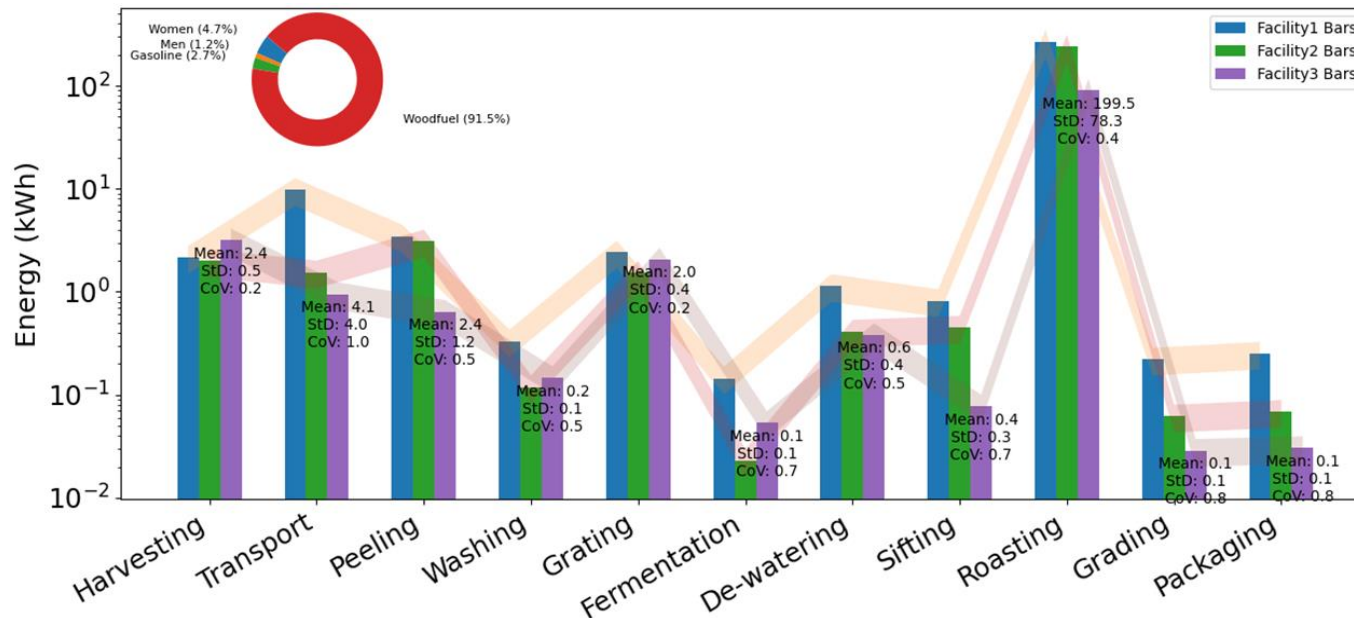
TableS15: Facility2 actual Energy distribution

| Process | Women (Hours) | Men (Hours) | Gasoline (Liters) | Woodfuel (kg) | Energy from Women (kWh) | Energy from Men (kWh) | Energy from Gasoline (kWh) | Energy from Woodfuel (kWh) | Total Energy (kWh) |
|-------------------|---------------|-------------|-------------------|---------------|-------------------------|-----------------------|----------------------------|----------------------------|--------------------|
| Harvesting | 7.39 | 0.67 | 0.00 | 0.00 | 1.63 | 0.36 | 0.00 | 0.00 | 1.99 |
| Transportation | 0.00 | 0.25 | 0.80 | 0.00 | 0.00 | 0.14 | 1.41 | 0.00 | 1.54 |
| Peeling | 14.00 | 0.00 | 0.00 | 0.00 | 3.08 | 0.00 | 0.00 | 0.00 | 3.08 |
| Washing | 0.54 | 0.00 | 0.00 | 0.00 | 0.12 | 0.00 | 0.00 | 0.00 | 0.12 |
| Grating | 0.10 | 0.10 | 0.83 | 0.00 | 0.02 | 0.05 | 1.46 | 0.00 | 1.54 |
| Fermentation | 0.03 | 0.03 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.02 |
| De-watering | 0.54 | 0.54 | 0.00 | 0.00 | 0.12 | 0.29 | 0.00 | 0.00 | 0.41 |
| Sifting & Sieving | 2.04 | 0.00 | 0.00 | 0.00 | 0.45 | 0.00 | 0.00 | 0.00 | 0.45 |
| Roasting | 8.77 | 0.00 | 0.00 | 43.55 | 1.93 | 0.00 | 0.00 | 239.53 | 241.45 |
| Sieving & Grading | 0.28 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 | 0.00 | 0.06 |
| Packaging | 0.09 | 0.09 | 0.00 | 0.00 | 0.02 | 0.05 | 0.00 | 0.00 | 0.07 |
| Total | 33.78 | 1.68 | 1.63 | 43.55 | 7.43 | 0.91 | 2.87 | 239.53 | 250.73 |

Table S16: Facility3 actual Energy distribution

| Process | Women (Hours) | Men (Hours) | Gasoline (Liters) | Woodfuel (kg) | Energy from Women (kWh) | Energy from Men (kWh) | Energy from Gasoline (kWh) | Energy from Woodfuel (kWh) | Total Energy (kWh) |
|-------------------|---------------|-------------|-------------------|---------------|-------------------------|-----------------------|----------------------------|----------------------------|--------------------|
| Harvesting | 0.00 | 5.85 | 0.00 | 0.00 | 0.00 | 3.16 | 0.00 | 0.00 | 3.16 |
| Transportation | 0.00 | 0.13 | 0.50 | 0.00 | 0.00 | 0.07 | 0.88 | 0.00 | 0.95 |
| Peeling | 2.90 | 0.00 | 0.00 | 0.00 | 0.64 | 0.00 | 0.00 | 0.00 | 0.64 |
| Washing | 0.66 | 0.00 | 0.00 | 0.00 | 0.15 | 0.00 | 0.00 | 0.00 | 0.15 |
| Grating | 0.22 | 0.22 | 1.07 | 0.00 | 0.05 | 0.12 | 1.88 | 0.00 | 2.05 |
| Fermentation | 0.07 | 0.07 | 0.00 | 0.00 | 0.02 | 0.04 | 0.00 | 0.00 | 0.05 |
| De-watering | 0.50 | 0.50 | 0.00 | 0.00 | 0.11 | 0.27 | 0.00 | 0.00 | 0.38 |
| Sifting & Sieving | 0.35 | 0.00 | 0.00 | 0.00 | 0.08 | 0.00 | 0.00 | 0.00 | 0.08 |
| Roasting | 3.12 | 0.00 | 0.00 | 16.20 | 0.69 | 0.00 | 0.00 | 89.10 | 89.79 |
| Sieving & Grading | 0.13 | 0.00 | 0.00 | 0.00 | 0.03 | 0.00 | 0.00 | 0.00 | 0.03 |
| Packaging | 0.04 | 0.04 | 0.00 | 0.00 | 0.01 | 0.02 | 0.00 | 0.00 | 0.03 |
| Total | 7.99 | 6.81 | 1.57 | 16.20 | 1.76 | 3.68 | 2.76 | 89.10 | 97.30 |

S15: Table S17; Average actual Energy Consumption across process facilities



S16: Table S18; Seasonal costs and supply dynamics analysis

| Scenario 1 Costs during the low cassava peak period harvest season | | | | | | | |
|--|-------------------|---------------|--------------|---------------|-------------|----------------|-----------------------------|
| Process | Human energy (\$) | Gasoline (\$) | Cassava (\$) | Woodfuel (\$) | Water (\$) | Packaging (\$) | Total cost per process (\$) |
| Harvest | 0.016767422 | 0 | 0.0362837 | 0 | 0 | 0 | 0.053051122 |
| Transportation | 0.000913118 | 0.02961751 | 0.0362837 | 0 | 0 | 0 | 0.066814327 |
| Peeling | 0.026261407 | 0 | 0.0362837 | 0 | 0 | 0 | 0.062545107 |
| Washing | 0.002181784 | 0 | 0.0362837 | 0 | 0.005817875 | 0 | 0.044283359 |
| Grating | 0.001454523 | 0.013179454 | 0.0362837 | 0 | 0 | 0 | 0.050917676 |
| Fermentation | 0.000484356 | 0 | 0.0362837 | 0 | 0 | 0 | 0.036768056 |
| De-watering | 0.004104978 | 0 | 0.0362837 | 0 | 0 | 0 | 0.040388678 |
| Sieving and sifting | 0.004921135 | 0 | 0.0362837 | 0 | 0 | 0 | 0.041204835 |
| Roasting | 0.061485898 | 0 | 0.0362837 | 0.229728412 | 0 | 0 | 0.32749801 |
| Sieving and grading | 0.001139376 | 0 | 0.0362837 | 0 | 0 | 0 | 0.037423076 |
| Packaging | 0.000743424 | 0 | 0.0362837 | 0 | 0 | 0.00212144 | 0.039148563 |
| | | | | | | | 0.800042811 |
| Total cost per cost center (\$) | 0.12045742 | 0.042796963 | 0.3991207 | 0.229728412 | 0.005817875 | 0.00212144 | 0.800042811 |

S16: Table S19; Energy transition from wood based to solar dynamics analysis

| Table S19: Total Costs with Solar | | | | | | | |
|--|-------------------|---------------|--------------|---------------|-------------|----------------|-----------------------------|
| Process | Human energy (\$) | Gasoline (\$) | Cassava (\$) | Woodfuel (\$) | Water (\$) | Packaging (\$) | Total cost per process (\$) |
| Harvest | 0.016767422 | 0 | 0.019980124 | 0 | 0 | 0 | 0.036747547 |
| Transportation | 0.000913118 | 0 | 0.019980124 | 0 | 0 | 0 | 0.020893242 |
| Peeling | 0.026261407 | 0 | 0.019980124 | 0 | 0 | 0 | 0.046241531 |
| Washing | 0.002181784 | 0 | 0.019980124 | 0 | 0.005817875 | 0 | 0.027979784 |
| Grating (labor reduced by 50%) | 0.000727262 | 0 | 0.019980124 | 0 | 0 | 0 | 0.020707386 |
| Fermentation | 0.000484356 | 0 | 0.019980124 | 0 | 0 | 0 | 0.02046448 |
| De-watering | 0.004104978 | 0 | 0.019980124 | 0 | 0 | 0 | 0.024085103 |
| Sieving and sifting | 0.004921135 | 0 | 0.019980124 | 0 | 0 | 0 | 0.024901259 |
| Roasting (labor reduced by 50%) | 0.030742949 | 0 | 0.019980124 | 0 | 0 | 0 | 0.050723073 |
| Sieving and grading | 0.001139376 | 0 | 0.019980124 | 0 | 0 | 0 | 0.02111195 |
| Packaging | 0.000743424 | 0 | 0.019980124 | 0 | 0 | 0.00212144 | 0.022844988 |
| | | | | | | | |
| | | | | | | | 0.316707894 |
| | | | | | | | |
| Total cost per cost center (\$) | 0.08898721 | 0 | 0.219781368 | 0 | 0.005817875 | 0.00212144 | 0.316707894 |