

Environmental and Economic Sustainability
Assessment of 4F (Food, Feed, Fuel and
Fertilizer) towards Industrial Ecology Coffee
(IEC)
(Case study on a pilot plant at Andungsari
Coffee Group-Bondowoso-Indonesia)

Andik IRAWAN

Environmental and Economic Sustainability
Assessment of 4F (Food, Feed, Fuel and
Fertilizer) towards Industrial Ecology Coffee
(IEC)
(Case study on a pilot plant at Andungsari
Coffee Group-Bondowoso-Indonesia)

Andik IRAWAN

This dissertation is submitted in partial fulfilment of the requirement for
the Doctor of Philosophy degree in Energy Science.

Supervised by
Prof. Benjamin McLellan

Graduate School of Energy Science
Kyoto University
2024

Abstract

Smallholder coffee farms play a crucial role in the global coffee supply chain, contributing significantly to both local economies and international markets. However, these farms face numerous challenges, including fluctuating market prices, environmental degradation, and limited access to resources and technology. To address these challenges, sustainable coffee production methods have become increasingly important. This study explores various aspects of Sustainable Coffee Production (SCP), focusing on the integration of Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) to improve the quality of coffee products while reducing environmental impacts. Additionally, the study examines the application of industrial ecology principles in coffee production.

The quality of coffee is a parameter for the economic viability of smallholder coffee farms. High-quality coffee can command specialty prices, thus enhancing the livelihoods of farmers. However, traditional coffee production methods often lead to significant environmental impacts, such as deforestation, soil erosion, and high greenhouse gas emissions. Sustainable coffee production aims to mitigate these impacts while maintaining or improving coffee quality.

This research employed a combination of surveys, interviews, experiments, and lifecycle assessment (LCA) and lifecycle costing (LCC). Primary data were collected from a 10 ha coffee plantation and pilot coffee processing plant in Andungsari, Bondowoso. Experimental data were supplemented with secondary data from existing databases, which were analyzed using SimaPro software. The study focused on the two main coffee processing methods: wet and dry processing. These methods were evaluated using LCA to assess their environmental impacts, and LCC to determine their economic viability.

The integration of life cycle assessment (LCA) and life cycle costing (LCC) provided a comprehensive view of different coffee processing methods environmental impact and economic benefits. The findings indicated that wet and dry processing generally affected environmental impacts due to wastewater and energy usage.

By applying industrial ecology principles, the study explored ways to enhance the sustainability of coffee production. For instance, the valorisation of coffee by-products, such as coffee cherry skin, into value-added products like cascara was investigated. This not only reduced waste but can also create additional revenue streams for farmers. Furthermore, implementing integrated farming systems combining coffee cultivation with other agricultural activities improved resource efficiency and reduced environmental impacts.

The study demonstrated that more sustainable coffee production was achievable through improved farming practices, efficient processing methods, and the application of IEC principles. By adopting these strategies, smallholder coffee farms can enhance the quality of their coffee products, lower their environmental impact, and improve their economic viability. Using LCA and LCC as analytical tools proved effective in identifying key areas for improvement and guiding decision-making towards more sustainable practices.

Acknowledgements

I would like to express my sincere gratitude to several individuals who played significant roles in the success of this thesis.

First and foremost, I am deeply indebted to Professor Benjamin McLellan. His guidance, insightful supervision, and meticulous evaluation were instrumental in the success of this research journey. His wealth of experience and unwavering dedication paved the way for a fruitful research experience through Japan Science and Technology (JST) at Kyoto University. Mentoring and encouraging me to contribute to reputable Journals. I am truly grateful for your invaluable contributions.

Furthermore, I am thankful to Fara Sensei for her invaluable suggestions, which significantly improved the quality of the paper. Her guidance taught me the importance of maintaining a coherent story flow in writing, a lesson I will share in my future academia.

I extended special thanks to Hung Mayumi, our lab secretary, for her diligent efforts in managing the administrative aspects of my research, particularly in research project JST. Her work ensured that all necessary documentation and procedural requirements were met smoothly. Your help was invaluable, and I sincerely thank you.

Finally, my deepest gratitude and thanks to my mother, lovely wife, and child. They strengthened me to achieve all this. Without their prayers and blessings, I would not have made this journey.

This academic achievement was not solely mine but was a testament to the support and guidance of many individuals who cannot all be mentioned. SPRING research fellowship from JST-Kyoto University support contributed significantly to my journey to reach this point. As I moved forward in my academic and professional career, I took the lessons, support, and encouragement they all provided, and I dedicated this achievement to all of them.

Contents

Abstract	i
Acknowledgements	iii
List of Tables.....	viii
List of Figures	x
List of Abbreviations.....	xii
1 Introduction and Background.....	13
1.1 Background.....	13
1.2 Research question and aim	14
1.3 Overview of this work	16
2 Background on coffee processing	19
2.1 Harvesting and quality control of smallholders.....	19
2.2 Flower and fruit development.....	19
2.3 Handpick method.....	20
2.4 Overview of coffee cherry beans	21
2.5 Processing of upstream coffee products	23
2.5.1 Full wash and semi wash processing.....	23
2.5.2 Natural processing.....	27
2.5.3 Hydro honey	27
2.5.4 Lactic	28
2.5.5 Anaerobic	28
2.5.6 Carbonic maceration.....	28
2.6 Processing of downstream coffee products – coffee roasting	29
3 A comparison of lifecycle assessment (LCA) towards lower environmental impact.....	30
3.1 Chapter introduction	30
3.2 Methodology.....	31
3.3 Goal and scope of LCA	32
3.4 Inventory analysis.....	33
3.5 Impact assessment	33
3.6 Interpretation.....	35
3.7 Coffee processing technologies towards lower environmental impact	36
3.7.1 Inventory data analysis.....	36
3.7.2 Animal husbandry and fertilizer operation.....	37
3.7.3 Mass balance for coffee processing.....	37
3.7.4 Product system inventory	38
3.7.5 Impact assessment for pilot plant incorporating industrial ecology.....	40
3.8 Conceptual and strategic frameworks.....	44
3.9 Conclusions.....	47
4 A comparison of lifecycle assessment for specialty coffee towards sustainable coffee production.....	48
4.1 Chapter introduction	48
4.2 Boundary and methodologies	50
4.2.1 Study area and boundary system	50

4.2.2	Coffee processing through dry methods.....	50
4.3	Environmental impact analysis.....	53
4.4	Comparison mass balance from dry methods coffee processing.....	55
4.4.1	Yield from different dry processing	55
4.5	Coffee fermentation, gas release and wastewater	56
4.6	Life cycle impact characterization.....	59
4.7	Comparison between GWP and total energy consumption	64
4.8	Conceptual frameworks	65
4.9	Conclusions.....	71
5	Biogas as a path towards industrial ecology coffee	72
5.1	Chapter introduction	72
5.2	Coffee production process	72
5.3	Case study.....	74
5.4	Materials and methodologies	75
5.5	Preliminary studies on biogas sampling	75
5.6	Preliminary study on the solar electricity generation	78
5.7	Economic analysis	79
5.8	Biogas frameworks and economic analysis.....	80
5.8.1	Biogas concentration.....	80
5.8.2	Coffee production.....	81
5.8.3	Energetic application.....	86
5.9	Economic aspect	88
5.10	Conclusions.....	95
6	Exploring the unique approach of evaluating the physical and sensory quality of coffee.....	96
6.1	Chapter introduction	96
6.2	Material and methodology	97
6.2.1	Study area and boundary of coffee processing.....	97
6.3	Biological material.....	98
6.4	Physical and sensory quality.....	99
6.5	Design and description of the stainless steel reactor	100
6.6	Environmental impact analysis.....	101
6.7	Results and discussion	102
6.7.1	Physical coffee quality	102
6.8	Sensory coffee quality	104
6.9	Impact assessment	106
6.10	Conclusion	110
7	Roasting impacts and by-products	111
7.1	Chapter introduction	111
7.2	Downstream coffee production (coffee roasting)	111
7.3	Case study and methodology	112
7.4	Environmental impact analysis.....	117
7.5	Summary of environmental assessment of coffee roasting	120
7.6	Valorization of coffee by-products	120
7.7	Observation and experimental method	121

7.8	Summary of novel food and potential fuel from coffee by-products	127
8	Pilot plant industrial ecology coffee framework and by-products	129
8.1	Chapter introduction	129
8.2	Materials and methodologies	131
8.2.1	Profile of case study area	131
8.2.2	Scope of coffee processing and valorization of by-products	133
8.3	Environmental impact assessment	133
8.4	Goal and scope.....	134
8.5	Inventory analysis	134
8.6	Impact assessment	136
8.7	Lifecycle costing (LCC)	136
8.8	Coffee production assessment	137
8.8.1	Mass balance for coffee processing	137
8.8.2	Energy supply in industrial ecology coffee.....	141
8.9	Environmental impact analysis	143
8.10	Life cycle cost analysis	148
8.11	Sustainable coffee production incorporating IEC.....	148
8.12	IEC and environmental aspects	149
8.13	Socio-economics of smallholder coffee production	150
8.14	IEC scenario.....	150
8.15	Conclusions of the case study.....	152
9	Conclusions and further work	153
9.1	Summary and novelty of this work.....	153
9.2	Conclusions.....	153
9.3	Further work	154
	References	156
	List of Publications.....	172

List of Tables

Table 2.1 CB color level to be maintained during harvesting	21
Table 3.1 Average coffee plantation and coffee shade/ha.....	32
Table 3.2 Environmental impacts considered in the ReCiPe 2016 database at the Midpoint Level (ML)	35
Table 3.3 Materials flow coffee and benefit of waste as a by-product	36
Table 3.4 Wastewater	36
Table 3.5 Parameter correction factor	37
Table 3.6 Mass Balance of Coffee Processing	38
Table 3.7 Coffee processing energy supply processing per ha	39
Table 3.8 Life Cycle Impact Assessment (LCIA) of SW and FW processing.....	43
Table 4.1 Parameters to quantity fuel consumption at each stage.....	54
Table 4.2 Factor correction to calculate CO ₂ from wastewater	54
Table 4.3 Comparison of the dry methods in input and output during coffee processing	56
Table 4.4 Total gas produce during fermentation	57
Table 4.5 Comparison of wastewater properties during fermentation in dry methods	59
Table 4.6 Impact category through dry method for CB to CP	61
Table 4.7 Comparison of the dry methods in their Global Warming Potential (GWP) On– and off–farm, as well as in their total energy consumption.....	65
Table 4.8 Comparison of the results of this study with previous research.....	69
Table 5.1 Biogas materials	77
Table 5.2 Parameters of the solar system	78
Table 5.3 Gas chromatography results for biogas from wastewater	81
Table 5.4 Coffee harvest at Andungsari Group 2022.....	83
Table 5.5 Mass balance for coffee processing (Part 1 – Wet processes)	84
Table 5.6 Waste type basis 1000kg cherry beans on processing.....	86
Table 5.7 Outputs from production of 1000kg cherry beans (wet basis)	87
Table 5.8 Process stages and the energy consumed	87
Table 5.9 Equipment investment cost	89
Table 5.10 Process mass flows in Andungsari group (harvest year 2022).....	89
Table 5.11 Equipment used in coffee processing.....	90
Table 5.12 Coffee price for green beans or coffee powder, cost of production, and coffee income by grade and processing route	91
Table 5.13 Economic assessment – current production case	93
Table 5.14 Simulation of Andungsari Coffee’s processing model	94
Table 6.1 Defect parameter score SNI	99
Table 6.2 Energy demand every stage.....	102
Table 6.3 Mass balance by processing method for Andungsari coffee	102
Table 6.4 Defect score analysis.....	104
Table 6.5 Sensory quality attributes for Andungsari coffee by processing method.....	105
Table 6.6 Total score, classification, and description by processing method	105
Table 6.7 Results of this study compared with other processes and by-products	109
Table 7.1 Roaster machine specifications	114

Table 7.2 Installation specifications	115
Table 7.3 Roasting parameters	116
Table 7.4 Fuel consumption parameters.....	116
Table 8.1 Possible status of Indonesian smallholder coffee farmers	132
Table 8.2 Average coffee plantation and coffee shade/ha/year.....	135
Table 8.3 Technological parameters used	136
Table 8.4 Organic fertilizer test.....	138
Table 8.5 Mass balance of coffee processing.....	139
Table 8.6 Pesticide analysis.....	141
Table 8.7 Coffee processing energy consumption	142

List of Figures

Figure 1.1: Structure of the research	16
Figure 2.1 Coffee processing and on-off farm categories	19
Figure 2.2 BO, B1, B2 terminology, handpicking and defect selection of CB by floating	24
Figure 2.3 De-pulping process for separation cherry skin and coffee pulp	24
Figure 2.4 Plastic reactor fermentation and multi-variant method of coffee fermentation	25
Figure 2.5 CB in wash, coffee pulp, and washing machine	26
Figure 2.6 Traditional drying, mechanical, and greenhouse dryer.....	26
Figure 2.7 Dehulling process and mechanical or manual sortation	27
Figure 2.8 Natural processing	27
Figure 2.9 (a) Stainless reactor with injection of CO ₂ , (b) Plastic reactor injection of CO ₂ at lower pressure.....	29
Figure 3.1 Scope of sustainable coffee production for pilot plant improvement	31
Figure 3.2 Flow processes full wash (FW) and semi wash (SW)	34
Figure 3.3 Andungsari arabica coffee harvest for farmer groups by month (in 2021).....	39
Figure 3.4 The flow of energy inputs, outputs and CO ₂ -eq emissions by stage and fuel	41
Figure 3.5 Impact contribution by stages of coffee processing - FW	42
Figure 3.6 Impact contribution by stages of coffee processing - SW	42
Figure 4.1 Limitations of the LCA study for the IEC pilot plant improvement.....	49
Figure 4.2 Coffee flow process and LCA scope	51
Figure 4.3 Anatomy of CB, processing steps and corresponding product as well as by-product...51	
Figure 4.4 (a) Reactor tank with gas capture observation, (b) gas produced during fermentation .52	
Figure 4.5 (a) CO ₂ , (b) CH ₄ , and (c) N ₂ O gas released during fermentation	58
Figure 4.6 Impact categories dry method coffee process	62
Figure 4.7 Impact characterization of natural in terms of GWP	63
Figure 4.8 Impact characterization of Hydro honey (a), Anaerobic (b), Lactic (c) and (d) CM Processing in terms of GWP	63
Figure 5.1 Coffee processing in Andungsari-Bondowoso	73
Figure 5.2 Coffee processing routes and coffee by-products	74
Figure 5.3 (a) Small 20L reactor, (b) 15L gas storage containers, (c) gas pressure gauge on storage, (d) biogas burning	76
Figure 5.4 Biogas production during the 45 day test period	76
Figure 5.5 Observation of average power at each hour taken across one week (Mid-August 2022), for series and parallel configurations	79
Figure 5.6 Timetable of coffee harvest for Andungsari group.....	82
Figure 5.7 (a) Unit digester, (b) gas pressure, and (c) sketch of unit	86
Figure 6.1 Classification of materials CB in coffee tree and options by-product	97
Figure 6.2 Scope of processing and assessment.....	98
Figure 6.3 Classification of raw material selection.....	99
Figure 6.4 Sketch of the fermentation reactor	101
Figure 6.5 The consumption of electricity per hour in the reactor	101
Figure 6.6 On-off farm handling on coffee processing	103
Figure 6.7 Sensory diagram of Andungsari variety of coffee based on processing method.....	106

Figure 6.8 CO ₂ production during fermentation	107
Figure 6.9 CH ₄ production during fermentation	107
Figure 6.10 N ₂ O gas release during fermentation	108
Figure 6.11 Chemical properties wastewater	108
Figure 6.12 Comparison of the contribution of anaerobic and inoculant.....	109
Figure 6.13 GMP contribution of mossto processing.....	110
Figure 7.1 The scope of the study is presented in the dash-line.....	113
Figure 7.2 The company's coffee roaster machine application	114
Figure 7.3 (a) Solar panel, (b) Coffee roaster machine, (c) AC power meter (black), DC power meter (white)	114
Figure 7.4 Roasting milestones	117
Figure 7.5 (a) Carbon Contribution of coffee roasting Arabica FW by LL energy source, (b) SB energy source.....	118
Figure 7.6 (a) Carbon Contribution coffee roasting Arabica Natural by LL energy source, (b) SB energy source.....	118
Figure 7.7 (a) Carbon contribution coffee roasting R FW by LL energy source, (b) SB energy source.	119
Figure 7.8 (a) Carbon contribution coffee roasting R Nat by LL energy source, (b) SB energy source.....	119
Figure 7.9 GWP coffee roasting based on stages	120
Figure 7.10 Scope of by-product cascara study	122
Figure 7.11 Weight loss of sample during roasting.....	123
Figure 7.12 Size distribution of sorted HS and manual sortation screens 7.5mm, 6.5mm, and 5.5mm	123
Figure 7.13 Raw HS (a) ; Sorted HS of size 7.5mm (b), 6.5mm (c), 5.5mm (d), and pixel (e)....	124
Figure 7.14 CS R (a), CS raw(b), HS R (c), HS raw(d)	124
Figure 7.15 CS roasted ground (a), CS roasted (b), CS raw ground (c), CS raw (d)	125
Figure 7.16 HS roasted ground (a), HS roasted (b), HS raw ground (c), HS raw (d)	125
Figure 7.17 TDS of cascara samples	125
Figure 7.18 Taste and mouthfeel (a), and aroma attributes (b)	126
Figure 7.19 Sustainable novel food and potential fuel from by-products	127
Figure 8.1 Industrial ecology coffee model.....	130
Figure 8.2 Scope of coffee processing and valorization of By-Products	133
Figure 8.3 Andungsari Arabica coffee smallholder harvest by month (2021-2023).....	135
Figure 8.4 Potential By-Product/ha	143
Figure 8.5 Comparison of GWP coffee processing.....	144
Figure 8.6 GWP contribution (a) Full wash, (b) Semi wash, (c) Natural, (d) Anaerobic	145
Figure 8.7 GWP contributions (a) CS, (b) HS	146
Figure 8.8 Impact on all categories and coffee processing methods for CB to CP and by-products (BP).	147
Figure 8.9 Life cycle costs (LCC) of coffee production for different processes.....	148
Figure 8.10 Base scenario and modeled scenario of IEC.....	151
Figure 9. 1 Combined comparison of GWP in this study with previous research	153

List of Abbreviations

An	Anerobic
BOD	Biological Oxygen Demand
CM	Carbonic Maceration
COD	Chemical Oxygen Demand
CP	Coffee Powder
CR	Coffee Roasted
CS	Cherry Skin
CSI	Coffee Science Institute
DO	Dissolved Oxygen
FU	Functional Unit
FW	Full wash
GB	Green Beans
GWP	Global Warming Potential
Hd	Hydro honey
HS	Husk Skin
ICCRI	Indonesian Coffee and Cocoa Research Institute
IEC	Industrial Ecology Coffee
IPCC	Intergovernmental panel on climate change
L	Lactic
LCA	Life Cyle Assessment
LCC	Life Cycle Costing
LPG	Liquid Petroleum Gas
Nat	Natural
NTU	Nephelometric Turbidity Units
SCP	Sustainable Coffee Production
SNI	Standard National Indonesia
SW	Semi Wash
TDS	Total Dissolved Solid
TSS	Total Suspended Solid

1 Introduction and Background

1.1 Background

Coffee is one of the major internationally traded commodities, but is heavily reliant on small-scale production, with around 70% of coffee grown by more than 25 million smallholder coffee farmers worldwide [79]. The international coffee trade can therefore potentially be a significant source of income for developing countries, particularly if they can produce high quality coffee. The current study is based on primary data directly obtained from coffee producers in Indonesia, the fourth-largest coffee-producing country in the world [80]. The production of coffee can have significant socio-economic impacts [81], but also impacts the environment, with a total of 1.2 million ha of land used (an average of 0.62 tons/ha) [82], in Indonesia, climate change emissions and the impact that climate change may have on production [83], and other global environmental sustainability impacts [84].

Coffee is grown in tropical and subtropical climates in more than 70 countries worldwide [1]. There are three main types of coffee worldwide: Arabica, Robusta and Liberica. Smallholder coffee farmers are pivotal in Indonesia's coffee industry, as in many of the world's leading coffee-producing countries. With a history dating back centuries, Indonesia's coffee cultivation has been predominantly driven by small-scale farmers who tend small plots of land, often intercropped with other crops. Smallholder coffee farming, a practice deeply rooted in the diverse regions of Indonesia, extends its impact far beyond its borders. These small-scale farmers, cultivating coffee from the highlands of Sumatra to the volcanic slopes of Java and the rugged terrain of Sulawesi, are the spirit of Indonesia's status as one of the world's top coffee exporters [3]. Their contributions, which are integral to the global coffee trade, connect them to coffee lovers and industry stakeholders worldwide.

Smallholder coffee farming sustains rural livelihoods and contributes to national economic development. In Indonesia, millions of families rely on coffee farming as their primary source of income, providing livelihoods for farmers and their communities. Furthermore, the varied coffee processing methods (wet-dry) present their own challenges for smallholders regarding energy source utilizations, wastewater management, and environmental impacts, in addition to the critical business of ensuring their livelihoods. A variety of options are available for reducing the carbon footprint and other environmental impacts of coffee processing, including intercropping, by-product optimization, organic farming, wastewater recycling, and renewable energy implementation as solutions for Sustainable Coffee Production (SCP) towards Industrial Ecology Coffee (IEC).

Coffee prices can encourage farmers to prosper; notably, the Indonesian coffee export situation is influenced by the price difference between local and international coffee prices, with Indonesian coffee prices being strongly driven (76% of fluctuation) by changes in international prices in the short term [3]. Proper handling of upstream (farming) and downstream coffee production is important to produce specialty coffees of high quality that can compete internationally. Quality coffee beans are the main reason coffee can be exported worldwide. Notably, the emergence of

markets for socially and environmentally sustainable coffee offers a significant business opportunity if farmer groups can appropriately manage production and access these emerging specialty markets. Capacity building for farmers can be carried out through the influence of government, companies, and across coffee business chains. Increasing farmers' competence, and a potential integrated plantation system with good manufacturing processes can further provide added value that can promote better prices for coffee beans [3].

In this study, SCP refers to coffee production that minimizes environmental impacts while maximizing socio-economic benefits to producers. IEC refers to the integration of waste management and valorization within and across agricultural and other activities for the production of low-waste and low environmental-impact coffee.

This study was conducted at Andungsari Coffee Group, Pakem village, Bondowoso Regency, Indonesia. This group has implemented organic farming since 1992. The author conducted an environmental impact assessment using Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Quality Product Assessment (QPA) based on the current situation and improvements including valorization of by-products as a pilot project towards Industrial Ecology Coffee (IEC) for Sustainable Coffee Production (SCP).

1.2 Research question and aim

Coffee processing is divided into two main types; wet methods: Full Wash (FW) and Semi Wash (SW); and, dry methods including: Natural (Nat), Anaerobic (An), Lactic (L), Hydro Honey (Hd), Carbonic Maceration (CM), Wine, and some innovations in dry methods such as Inoculant, and Mossto. The resulting coffee quality is determined by how the coffee process is managed, and implementation of clean coffee production minimising or eliminating defects, and producing coffee with good flavor. This processing generally has two categories. The on-farm category is the managed processing of coffee plantations such as application of fertilizers, pruning, pesticides, shade crops, irrigation, and cherry harvesting. Furthermore, coffee cherries are processed to produce dried coffee beans (including skin) or into green beans (GB). The on-farm process extends to this stage. The second category, off-farm, processes GB to Coffee Roasted (CR) or Coffee Powder (CP), and is carried out outside the farm, often by the Small-Medium Industry to produce commercial CP, cafes or coffee shops. Coffee processing is largely carried out by two processing groups:

1. Medium or large coffee industry: this coffee production is managed by medium or large companies. These companies buy coffee cherry beans (CB) from farmers, traders, coffee farmer groups, or coffee plantations owned by the companies themselves. These companies certainly already have technologies for coffee processing. However, most of this industry only processes coffee using a wet method (semi-wash). This method was considered because of the short time needed to process the coffee. Generally, this sub-sector processes commercial and premium-quality coffee. They typically process it into green beans (GB). Most of those products are distributed domestically or exported overseas.
2. Coffee Industry smallholder coffee farms: coffee production from smallholder coffee farms also processes coffee using wet and dry methods. The wet methods typically include FW and SW, while the dry method is Natural. With limited information and resources on coffee

processing accessible by smallholder farms, they typically produce commercial and premium quality coffee. Generally, smallholders sell their coffee only as GB to larger companies, or traders. Limited information and use of technology and processing is a problem for smallholder coffee farms, as it hinders their development and access to better production methods and more profitable products. However, smallholders have the potential to produce Specialty Grade coffee. This is intended to increase the GB price value and product quality. With this option for coffee production, smallholders can process CB to GB or to CP.

It is rare to find previous studies discussing upstream and downstream coffee processing through wet and dry methods, including by-product utilization. Valorization of wastewater to fuel and fertiliser, and Industrial Ecology Coffee (IEC) practices towards Sustainable Coffee Production (SCP) can be applied to smallholder coffee production and potentially improve the quality of coffee and the variety of coffee flavors. IEC towards SCP for improving the quality of coffee, producing specialty products, and environmentally friendly coffee products is crucial.

Based on this background, the main questions to be answered in this study were:

1. What is the environmental and economic impact on upstream to downstream coffee production from wet and dry methods when evaluated using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC)?
2. To what extent does increasing the use of by-products in coffee processing also produce quality coffee with lower environmental impact?

Three subsystems were identified as SCP achievement targets in IEC to solve this question. The first subsystem in coffee production involves coffee plantations to produce upstream and downstream coffee; smallholder coffee farms play an important role in this section. The second subsystem, the coffee industry, with the target of quality coffee processing, includes the technology for coffee processing. Smallholders typically have some access to this technology. The final subsystem was non-coffee farming: coffee farmers often have cows or goats that are either their own or managed livestock owned by others. This subsystem is often available on smallholder coffee farms, the challenge is how this coffee processing can integrate all subsystems effectively to support SCP in achieving IEC.

The aims of this study are therefore:

1. Evaluate coffee production environmental and economic impact by wet and dry methods using LCA and LCC, where previous studies have not discussed complete upstream-downstream coffee processing.
2. Integration between subsystems in the pilot plant to valorize wastewater and solid waste, support coffee production, generate additional energy sources, and improve product quality with lower environmental impacts.

To answer the objectives of this study, this work was conducted using surveys, informal interviews, experiments, and sample test product approaches. Experimental data and observations were conducted at the coffee group as a coffee pilot plant, on a combined cultivated area of approximately 10ha in Andungsari, Bondowoso. The research was relatively unique in using primary data from

experiments as basis input to analyze and compile with a secondary database in SimaPro software. The main point of novelty was that the evaluation covered multiple coffee processing routes, within the genres of wet and dry methods, which previous research had not described in detail. The second novelty was the coffee production evaluation, which used LCA and LCC methods to assess the GWP at risk to the environment, as well as the economic impact. LCA and LCC were applied to evaluate the GWP and economic aspects of the pilot plant. The improvement of economic value associated with alternative processes was compared with environmental impact. Finally, the third novelty of integrated farming was applied to SCP in coffee production to support IEC, contributing to a lower GWP impact than before and even improving the quality of coffee production.

1.3 Overview of this work

This work aimed to fill the knowledge gaps on multiple coffee processing routes to evaluate the environmental impact upstream and downstream through LCA, LCC, and Product Quality evaluation. The ultimate contribution is a conceptual framework and its application to an in situ pilot plant, bridging practical and theoretical approaches. This involved the evaluation of environmental impact and economic analysis in coffee processing at Andungsari Coffee Group using novel approaches, as outlined in Figure 1.1.

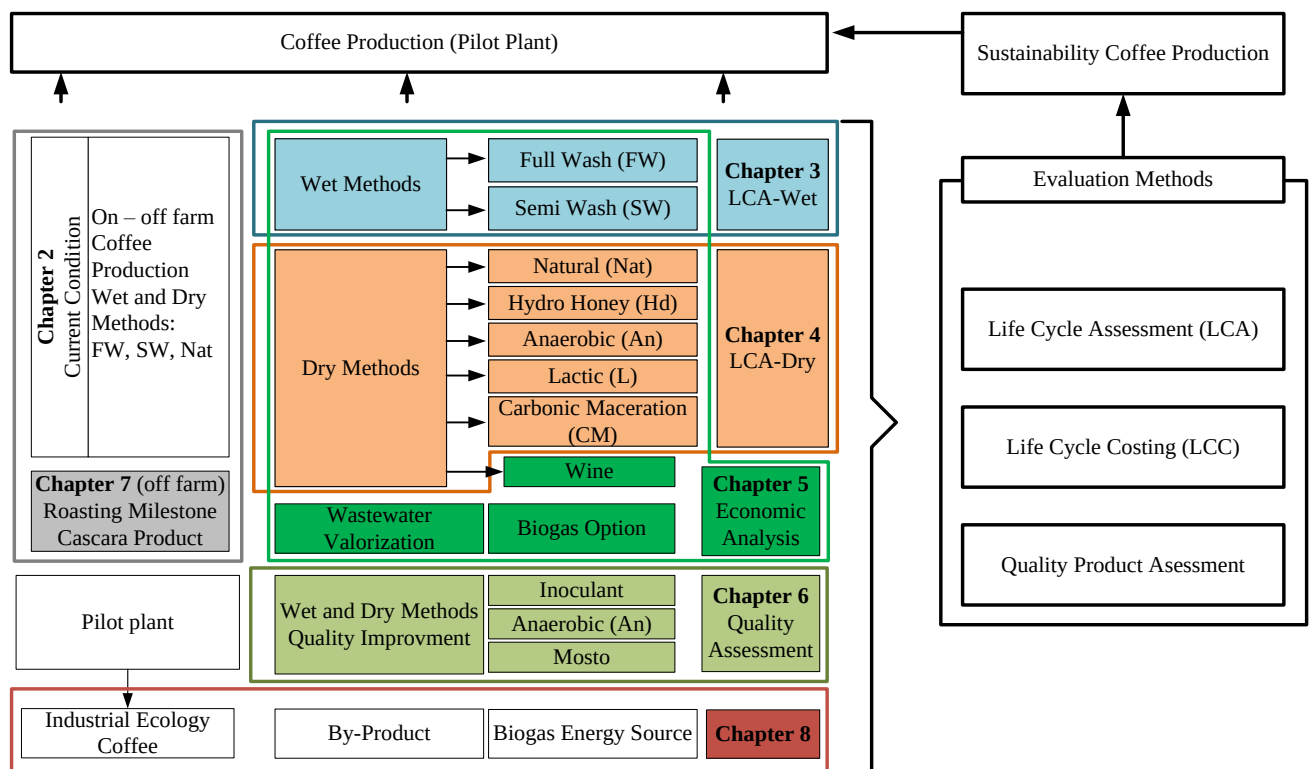


Figure 1.1: Structure of the research

This thesis comprises seven chapters. **Chapter 1** provides an overview of the coffee smallholder activities by introducing the concepts of coffee production. The research seeks to provide a comprehensive understanding of the environmental footprint of coffee processing activities from the initial stages of harvesting to the final stages of production. Additionally, the economic analysis will shed light on the financial implications of implementing sustainable practices and technologies

in coffee processing. Concluding this introductory chapter, the research question and aim will be stated.

Chapter 2 Describes the coffee production process from the farm through to the various off-farm processes. It explores upstream (on – farm) and downstream (off – farm) coffee processing and introduces the various processing types.

Chapter 3 provides a Life Cycle Assessment (LCA) on coffee production through wet processing, on the basis of testing in the pilot plant. The study outlines a comparison of the downstream and upstream coffee production in the full wash (FW) and semi wash (SW) methods. Observations and experiments were conducted to clarify the flows of production, energy, and waste in this work. Coffee cherry beans (CB) were harvested and processed into green beans (GB), then coffee powder (CP), to assess their Global Warming Potential (GWP). By conducting detailed assessments using LCA, the study aims to identify key areas of environmental impact and opportunities for improvement throughout the coffee supply chain in wet methods.

Chapter 4 presents the life cycle assessment (LCA) of coffee production using dry methods. This study focuses on the natural (Nat), anaerobic (An), lactic (L), hydro-honey (H), and carbonic maceration (CM) coffee processing routes. The work considers fermentation stages in the dry methods of coffee production, specifically in anaerobic, lactic, hydro-honey, and carbonic maceration. During the fermentation stages, gas production and wastewater were captured for consideration of gas emission. Then, gas content is used as input data in the LCA for analysis.

Chapter 5 explores the use of wastewater for biogas production in the context of coffee processing. The research examines the feasibility of using the wastewater from coffee processing, combined with cow dung, as raw materials for biogas production. The study includes an economic impact analysis comparing the use of biogas and fossil fuels in coffee production. It aims to support smallholders in choosing an energy source by considering the economic aspects, even if they are aiming for lower environmental impact through the use of biogas. Ultimately, we aim to facilitate the transition towards more environmentally friendly and economically viable coffee production methods, benefiting producers and the environment.

Chapter 6 elaborates on improving coffee quality using fermentation reactors. This reactor is designed using stainless steel and connected to a measurement monitor to measure gas content production; the measurement of wastewater during fermentation is also considered for environmental impact evaluation. This study combines LCA and LCC with the coffee quality score to understand the value of alternative processes holistically. Through this research, we aim to contribute valuable insights that can inform decision-making processes in the coffee industry, particularly at the smallholder level, through quality improvement.

Chapter 7 This chapter examines the production of alternative byproducts (coffee tea also known as cascara), and the evaluation of the coffee roasting process. The LCA at the off-farm stage is considered, discussing the potential impact on carbon of roasting milestones through the use of

biogas or fossil energy sources. The final part of this chapter introduces the valorization of by-product cherry skin and husk skin into cascara, and the final waste (dust skin) potential for briquettes.

Chapter 8 presents environmental assessment of IEC, an emerging concept that promotes integrating industrial ecological principles into coffee production systems. By adopting an IEC approach, we aim to minimize waste, utilize biogas energy sources, and enhance overall SCP. By developing a robust conceptual framework and applying scenarios to the pilot plant at the Andungsari Coffee Group, we seek to demonstrate the feasibility and benefits of adopting sustainable coffee-processing practices.

Conclusion - this chapter addresses the needs of policy makers through clarifying IEC principles to mitigate environmental impacts and foster synergies between coffee plantations, livestock, and coffee industries in the coffee value chain towards SCP. This includes exploring opportunities for co-locating coffee processing facilities with inter-cropping plants or industrial activities to improve the resource knowledge of smallholders and minimize environmental footprint. Through our study at Andungsari Coffee Group, we intend to showcase how implementing IEC principles can lead to more efficient and environmentally friendly coffee production practices. By integrating environmental considerations into decision-making processes, we can create a more sustainable coffee industry that benefits producers, consumers, and the environment.

2 Background on coffee processing

This chapter presents an overview of the major processes associated with the production of coffee. It starts with the farming of the coffee itself, then moves through the on-farm and off-farm processes used to convert coffee cherries into green beans, then finally to a variety of coffee products. It should be noted that depending on the type of processing, sometimes the on-farm and off-farm processes will not align across different processing types. The main stages are shown in Figure 2.1.

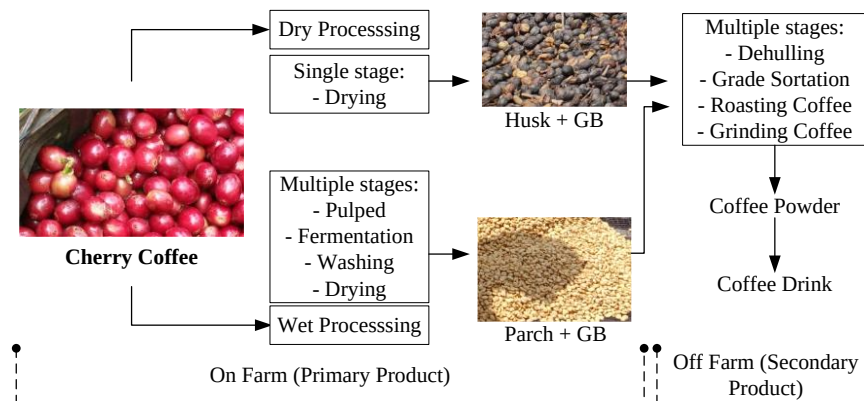


Figure 2.1 Coffee processing and on-off farm categories

2.1 Harvesting and quality control of smallholders

The type of coffee, harvest quality, planting location, agronomic system, processing methods, and sortation greatly influence the quality and taste of coffee products. Good coffee quality can only be obtained from ripe coffee fruit (coffee cherries) with proper processing. Harvested coffee cherries should be processed immediately because they are susceptible to chemical and biological damage. Delays in processing can lead to the loss of the distinctive taste of coffee and the appearance of taste defects. Internal changes in coffee fruit due to improper processing can result in taste defects such as fermentation, and aromas resembling medicine. Additionally, changes in external conditions that are unfavorable during the processing process can cause taste defects such as earthy and musty flavors. In general, coffee processing is divided into two methods: the dry method and the wet method.

The quality of commercial coffee is still unsatisfactory because it contains many defective coffee beans mixed with non-coffee ingredients. Deformed coffee beans include black, brown, cracked, and perforated beans. Quality improvement is essential, starting with improved handling before, during, and after harvest. Quality improvement before harvest focuses on pest and disease control, especially attacks from pests like *Hypothenemus hampei* that cause perforated seeds. During harvest, attention is given to selective picking, harvesting only ripe cherries. After harvesting, quality improvement should focus on using appropriate coffee processing equipment, such as good drying and sorting.

2.2 Flower and fruit development

Coffee blossoms are formed in the axils of leaves on branches. Each axil usually has 4-5 clusters, with each cluster consisting of 3-5 blossoms. Thus, each axil can produce 12-25 blossoms, and even

up to 50 in a single cluster. In Arabica coffee, the number of clusters is usually smaller, resulting in smaller cherry groups compared to Robusta. Under optimal conditions, a tree can produce between 6000 to 8000 blossoms, but only about 30 to 50% of them will develop into coffee cherries. The coffee blossom is white, with the number of petals varying depending on the type of coffee. Arabica typically has 5 petals, while Robusta and Liberica have 6-8. Pollination methods also differ between coffee types: Arabica is self-pollinating, while Robusta and Liberica are cross-pollinated.

Generally, coffee begins to produce blossoms at the age of 3 years and bears fruit at the age of 4 years. However, today, many researchers are developing types of coffee that can produce blossoms at the age of 1 year and begin to bear fruit at the age of 2 years. Coffee cherry beans reach maturity within 9-12 months, depending on the type: Arabica ripens in 9-10 months, Robusta in 10-11 months, and Liberica in 11-12 months. In Indonesia, coffee cherries usually begin to ripen between April/May and September/October. In wet areas, crop distribution is even greater than in arid ones. Sometimes, the growth of cherry beans will experience abnormalities, such as turning them into coffee *peaberries* or empty beans caused by *polyembryony*.

2.3 Handpick method

The main key to obtaining good coffee quality is harvesting coffee cherry beans. The quality of coffee firstly depends mainly on how harvesting is done. There are two commonly used harvesting methods: selective picking and mixed picking. Mixed picking involves harvesting all coffee berries, even those with mixed colors, usually at the end of the harvest. Coffee cherries harvested in this manner are generally left in sacks for two days before drying. Selective picking chooses only coffee cherries with specific colors and levels of ripeness.

To achieve the best results during the coffee harvest, farmers need to make careful preparations. The first step is to make sure that the coffee trees are in good condition. This involves regular maintenance such as proper fertilization, pest and disease control, and appropriate pruning. Land preparation is also vital. The land must be well-prepared to ensure good drainage and provide a suitable environment for coffee growth. Apart from plant growth, farmers also need to prepare the infrastructure and equipment for harvesting. This includes inspecting and preparing tools such as hand collectors and containers for collecting coffee cherry beans. Additionally, preparing a sufficient and trained workforce is necessary to carry out the harvest efficiently.

Farmers should create a proper harvest schedule to ensure efficient and high-quality coffee production. This involves estimating the optimal time to harvest based on the estimated ripeness of the coffee cherry beans and weather conditions that can affect crop quality and yield. Before starting the harvest, farmers must also ensure that the post-harvest processing system is ready, including the equipment for appropriate drying and processing of coffee cherry beans. With careful preparation before starting the harvest, farmers can increase the yield and quality of coffee produced while improving efficiency in the agricultural process.

It is best to pick coffee beans when they are fully ripe. This results in better quality coffee, as the taste and aroma are more consistent. Picking the beans when they are red also helps farmers select the best beans for harvesting, which produces more consistent and high-quality coffee. This method also reduces the risk of physical damage to the beans during harvesting. By employing this method, farmers can increase the value and competitiveness of the coffee they produce.

Mixed harvesting is a commonly used method in coffee plantations all over the world. This method involves harvesting the entire crop of coffee cherries, including both ripe and unripe cherries, in one harvest cycle. Farmers prefer mixed harvesting as it allows them to pick a large number of coffee cherries in a relatively short period of time, especially in the later stages of the harvest season. However, there are some drawbacks that need to be noted. One disadvantage of mixed harvesting is that immature or even overripe coffee cherries will be picked together. This can result in coffee that is uneven in terms of quality and taste, as immature beans tend to result in lower-quality coffee. In addition, by picking all the coffee cherries at once, the risk of physical damage to the beans also increases, because ripe beans may be injured by unripe ones. Despite this, mixed harvesting remains a popular choice in some areas due to its greater time and labor efficiency. However, the challenge for farmers is to maintain the quality of coffee and remain competitive in the global market.

2.4 Overview of coffee cherry beans

Based on the description provided, cherry bean picking significantly influences the resulting product. The following table illustrates how cherry beans are categorized according to their color level during survey and observation (Table 2.1).

Table 2.1 CB color level to be maintained during harvesting

Cherry beans (CB) color level	Notes
	If cherry beans are unripe, they exhibit a green color. If picked at this stage, the resulting green beans are pale, with weak aroma and taste. It is advisable not to pick cherries at this stage.
	Partially yellow, red, and green CB. Red cherry beans can be selectively picked without affecting the yellow or green cherry beans. This period requires extra care during picking due to the uneven distribution of red CB at the start and end of the harvest season.

	When harvesting, the most appropriate CB is full red, as it can give a good taste. Proper processing is required for handling CB correctly.
	CB should be harvested immediately as some are overripe and others have dried on the tree, resulting in poor taste.
	Mixed harvesting not only results in a poor taste but also causes labor inefficiency.
	At this stage, sorting is necessary to improve the quality of coffee beans since overripe harvest affects the taste.

Red picking of coffee is a challenging process, but it ensures that only ripe coffee CB are selected, resulting in high-quality coffee beans. Selective picking requires additional time and effort, as the

grower must manually choose those CB that have reached optimal maturity. However, it is well worth the effort because coffee CB picked at the right maturity stage tends to have more complex and delicious flavors. Moreover, red-picking coffee also provides economic incentives for farmers because high-quality coffee beans usually have a higher price in the market. By prioritizing quality picking, farmers can increase the selling value of their products and overall income. Despite the difficulties, an approach that focuses on selectively picking ripe coffee CB is an essential step in producing high-quality, sustainable coffee. Therefore, many coffee farmers are committed to practicing this method despite the challenges.

2.5 Processing of upstream coffee products

Coffee processing typically involves two methods: the wet method and the dry method [4][5]. The taste of coffee can vary depending on the processing and brewing method used, even if the quality of the coffee remains the same [6]. There are two main groups of coffee processing methods: wet and dry. Wet methods include Fullwash (FW) and Semiwash (SW), while dry methods include Natural (Nat) and Anaerobic (An). These four processing methods are considered effective for processing high-quality coffee production. Other methods like Carbonic Maceration (CM), Lactic, and Honey have lower market acceptance. The wet and dry methods have some processing stages in common, but there are some stages that are not included in the dry methods.

2.5.1 Full wash and semi wash processing

FW and SW processing are widely used processes carried out by the coffee industry, of course, this processing requires more water than dry processing. Smallholders with the potential for abundant water sources may find it easy to process coffee with these processes. On-farm coffee processing include the following common stages :

1. **Selective Harvest;** During the coffee harvest, the CB are sorted by being picked when they are red. This is done to minimize the impact of defects on the quality of the final coffee product. Additionally, selecting only the red coffee beans is also beneficial for the sustainability of the coffee tree branches during the next harvest period. If raw coffee beans are picked, it can negatively affect the growth of the coffee tree twigs. To avoid this, Indonesian coffee smallholders group the picking method and eventually need to trim the coffee branches. One option to keep the coffee twigs productive is to use B0, B1, B2 pruning methods. It is important to prune the twigs regularly to ensure their productivity [7], this process occurs annually for the first three years until the B2 twig stage. B0 is a young twig that hasn't yet produced any fruit. However, it will become the main twig and start bearing fruit the next year. B1 refers to a branch that has borne fruit for the first time, while B2 refers to a branch that has produced fruit for two consecutive years. To ensure optimal growth, the pruning cycle is carried out on B2 after it has borne fruit twice. This allows B0 to develop into B1, which will then develop into B2 after two years of fruiting (Figure 2.2). This cycle continues to ensure the healthy growth and fruit production of the plant.
2. **Flotation** - After selecting the ripest red cherries, they were submerged in water to collect floating coffee beans (Figure 2.2). Some of the floating coffee consists of beans with low density, typically belonging to premium or even commercial-grade coffee. Conversely, the sinking beans represent a higher quality, despite potentially having some defects in the final

product. Extracting coffee in this wet manner necessitates water; therefore, this treatment method is more suitable for high-altitude locations where water sources are abundant.

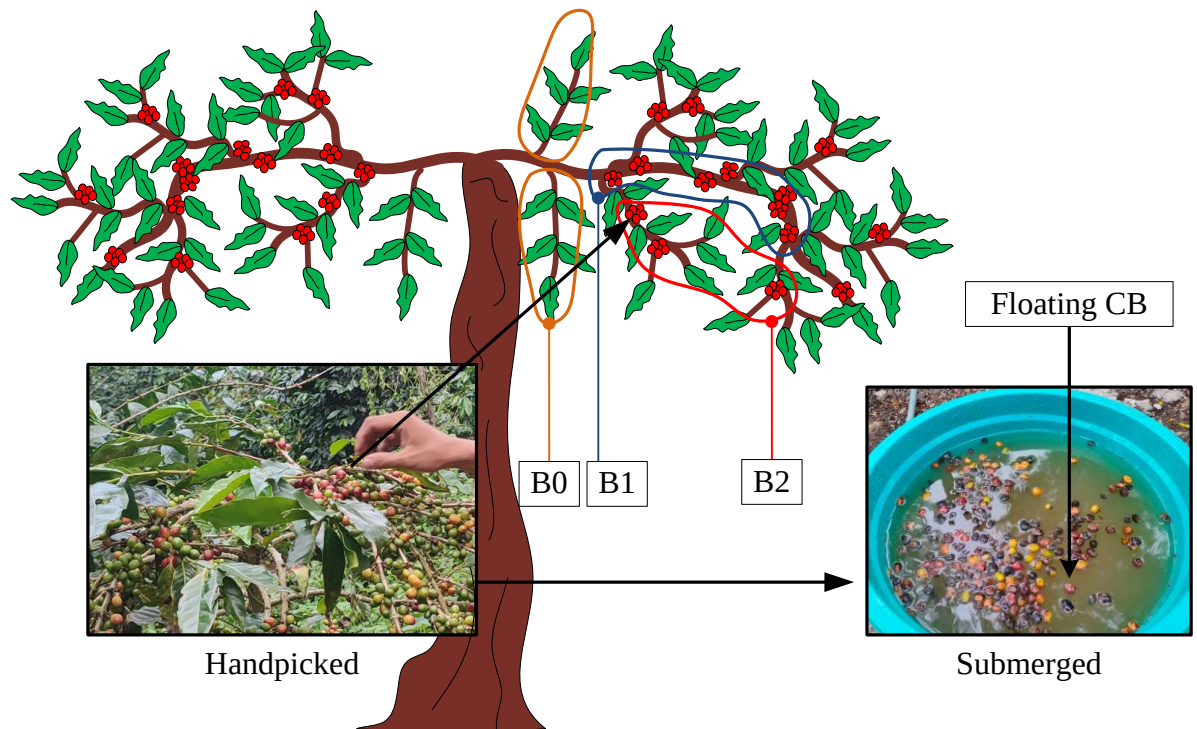


Figure 2.2 B0, B1, B2 terminology, handpicking and defect selection of CB by floating

3. **De-pulping** is the process of peeling the skin of the coffee cherry to separate it from the coffee beans (Figure 2.3). At this stage, two products are obtained: wet coffee beans, which are the main product, and coffee cherry skin, which is a by-product. The skin of the coffee cherry can be washed and dried in the sun to be processed into Cascara [8], whether roasted or not, stripping the fruit skin is intended to control coffee acidity and achieve a complex flavor profile [9].



Figure 2.3 De-pulping process for separation cherry skin and coffee pulp

4. **Fermentation;** Coffee fermentation is carried out on parchment-skinned coffee beans (Figure 2.4). The process aims to facilitate the decomposition of mucilage from the parchment skin [10]. Smallholders typically ferment the beans between 18 to 36 hours [11], depending on the target taste required. At 18h the coffee generally has a low sour taste and a relatively light body, while the 36h has high acidity and a strong body [12]. This method is used to improve the sour taste in coffee grown at elevations between 1,000 and 1,500 msal. The treatment is only applied during the FW process and not during SW, but fermentation is also used for some of the dry processes.

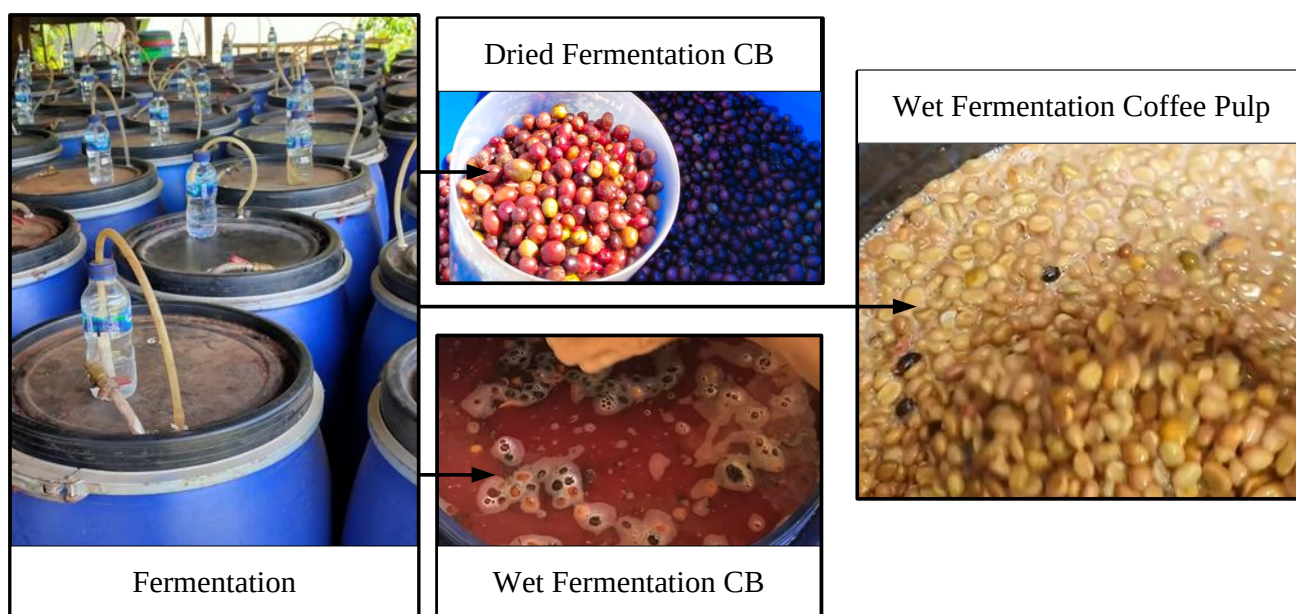


Figure 2.4 Plastic reactor fermentation and multi-variant method of coffee fermentation

5. **Washing;** During coffee processing, washing is a crucial step that aims to separate the mucilage from the parchment coffee (Figure 2.5). If the mucilage is not washed properly, it can result in honey-colored coffee that may also develop mold. Thorough washing is important for producing FW and SW in quality coffee. In the SW method, the fruit skin is peeled, and instead of being fermented, it is immediately washed clean. This helps to reduce the sour taste in the coffee. The water used for washing the coffee is often reused for cow dung mixtures as a raw material for biogas production [13][14]. Washing can be done manually or with a coffee-washing machine. This is an important step in the coffee cleaning process. It helps to prevent the natural fermentation process that can occur if the coffee beans are left in the fermentation liquid for too long. By washing the coffee, farmers can better control the fermentation process and produce coffee with the desired flavor profile. Additionally, washing the coffee prepares the beans for the drying process and ensures that they dry well. This also helps to prevent the growth of unwanted fungi or microorganisms.



Figure 2.5 CB in wash, coffee pulp, and washing machine

6. **Drying;** further drying is undertaken until the moisture content of parchment coffee reaches 10-12% in compliance with SNI dry quality standards [15]. Figure 2.6 shows coffee with parchment skin that can be stored or sold directly after undergoing the dry FW processing method. However, in the SW method, the moisture content is only reduced to 40%. This moisture level is necessary to halt the drying process during the skin stripping phase. After separating the GB from the parchment, the GB is dried again in the SW method to achieve a moisture content of 10 – 12%. This double drying process aims to give Arabica a more concentrated GB color compared to the FW method.



Figure 2.6 Traditional drying, mechanical, and greenhouse dryer

7. **Dehulling and sorting;** Dried coffee bean dehulling is done to separate GB and parchment, or Husk Skin (Hs) in the case of the dry method (Figure 2.7), this solid waste is useful as raw material for briquettes [16], for combustion for mechanical drying [17] or animal feed [18]. Mechanical sorting is used to separate the coffee into determined sizes. SNI defines three sizes 5.5; 6.5; and 7.5mm [15]. Manual sorting to select GB quality from cracked, black, and hole seeds is then used to separate the quality of coffee beans. This stage is the

last stage of On-Farm processing. GB is then stored in two-layer packaging (plastic and sacks).

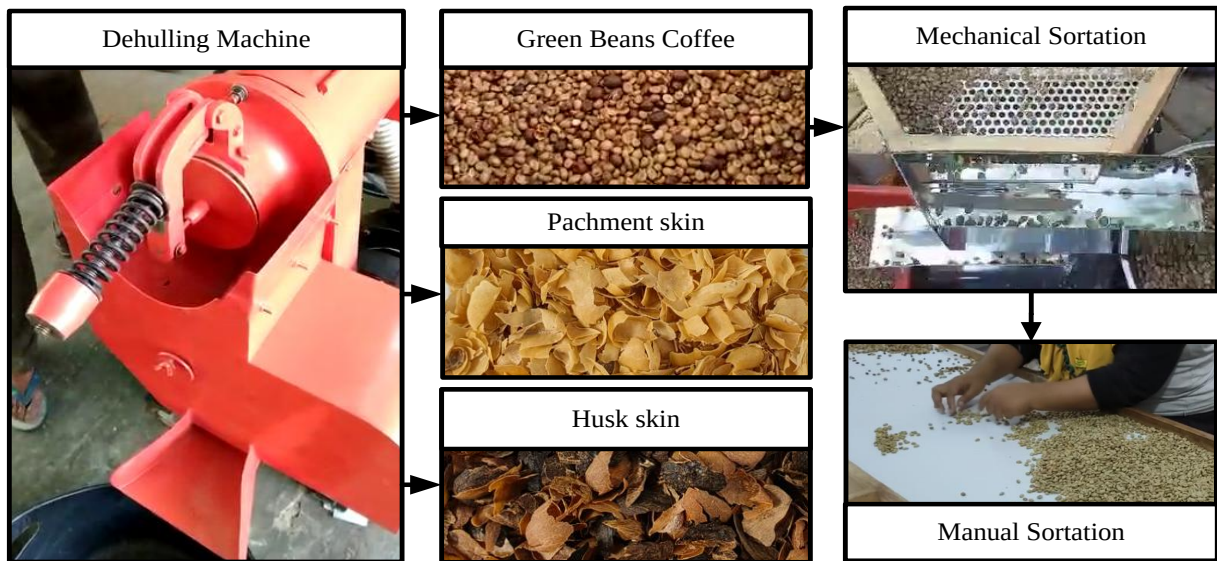


Figure 2.7 Dehulling process and mechanical or manual sortation

2.5.2 Natural processing

Natural processing is the most traditional processing method, and the *Off-Farm* processes and technology are more important than *On-Farm*. After harvesting, the CB is directly sundried for 9-12 days as described earlier, and goes through the *On-farm* (upstream) and *Off-farm* (downstream) processing shown in Figure 2.8. Generally, smallholders sell directly without dehulling, storing dried coffee with skin or Green Beans.



Figure 2.8 Natural processing

2.5.3 Hydro honey

The Hydro honey method is intended to meet market demand for coffee with the aroma of honey [19]. The honey color emerges as a result of the pulp being retained within a parchment layer until dried. Sharp aromas such as wine, fruity, and brown sugar can emerge from fermentation. However, this method may not be widely used because the market segment is limited and only for specialty

products. In this case, pulping is done before fermentation to separate the cherry skin from CB. CB are dried, and the coffee pulp was then fermented and dried. The dried coffee bean with parchment skin is further dehulled to obtain GB which goes through sorting, roasting and grinding to obtain CP.

2.5.4 Lactic

Processors require lactic processing to create a robust sour aroma by adding bacteria [10]. During fermentation, the mucilage in CB can increase acidity [20], while the expected flavors are fruit, berry, chocolate, and complex flavors [21]. Lactate processing is not the main target of commercial processors because it requires additional ingredients [22], which may impact wastewater, and pose a risk to soil and water [23]. In this case, lactic acid bacteria from a local company was added to the reactor before fermentation. After fermentation, further *On-farm* (upstream) and *Off-farm* (downstream) processing were performed to obtain CP.

2.5.5 Anaerobic

Coffee processors often use this processing method, which is easy to undertake because the CB only needs to be fermented with reduced or no oxygen [24] with the full tank of CB inside the reactor. In this study, water or other inoculants, such as microorganisms or enzymes were not added to the process (spontaneous fermentation). After fermentation, the CBs were dried, sorted, roasted and ground to CP.

2.5.6 Carbonic maceration

During CM processing, some CO₂ is injected into the reactor tank [25]. Figure 2.9 shows CO₂ injection, which aims to reduce the sour taste of coffee and reduce caffeine. This method requires pressure control during processing, reactor leaks can result in the failed production of flavors [6]. A gas pressure indicator was used during fermentation to keep a stable pressure of 50-100milibars. Some processors inject CO₂ every day until the end of fermentation, but in this study, it was only done once on the first day of fermentation.



Figure 2.9 (a) Stainless reactor with injection of CO₂, (b) Plastic reactor injection of CO₂ at lower pressure

2.6 Processing of downstream coffee products – coffee roasting

During the early stages, smallholder farmers start determining the flavor profile of their Green Beans (GB). GB can be roasted to meet the demands of the market. However, it's important to keep in mind that Roasted Beans (RB) can't be stored for as long as GB. Freshly roasted RB produces a good aroma and taste, particularly when it comes to making Coffee Powder (CP). The market demand determines the roasting profiles based on the type of brew that will be made for drinks. The roast profile is what determines the color and character of RB [26]. Each smallholder has their own way of producing RB based on market conditions. Finally, the beans are roasted to taste, which adds a unique aroma to the coffee.

3 A comparison of lifecycle assessment (LCA) towards lower environmental impact

3.1 Chapter introduction

There have been a number of studies on the environmental impact of coffee production, and the potential to improve this, while maintaining high quality production. Most studies have focused on the farming component of the production system, sometimes considering alternative inputs (e.g. organic versus inorganic fertilizer), or use of wastes (e.g. for bioenergy), or the impact of co-production of other agricultural products. For example, a farming system integrating coffee and livestock industry was examined to utilize coffee industry waste biomass as a sustainable energy source [86]. Life Cycle Assessment (LCA) has been used to estimate the quantitative environmental impacts and energy requirements in the roasted and ground coffee industry in Mexico, indicating the potential to save up to 41% in a waste-to-energy scenario based on processing from coffee cherry, with estimated emissions of 1.58 kg CO_{2-eq} / kg ground coffee compared to conventional processing (2.9 kg CO_{2-eq} / kg ground coffee) [36]. Integrating the coffee-pepper garden system in the cities of Kodagu and Chikkamagalur, India, was examined for environmental impact evaluation with emphases on conventional agriculture, integration, and organic farming as a basis for calculating the rate of energy demand and the carbon emitted. In this study per kg coffee cherry, organic agriculture results in emissions of 0.76 kg CO_{2-eq}, which is better than conventional production at 0.82 kg CO_{2-eq} [87]. Many studies have focused on the difference between organic and conventional production, focusing on the on-farm impacts through crop diversification systems and increase productivity and economic performance [88].

LCA has also been used to measure the environmental impact of processing Aceh Gayo Arabica coffee using wet processing, producing 2.56 CO_{2-eq} for 1 kg of green beans [89]. Using chemical and organic fertilizers affects carbon emissions, 1kg of cherry beans coffee has between 0.26 – 0.67 kg CO_{2-eq} with chemical fertilizers and 0.12 – 0.52 kg CO_{2-eq} with organic fertilizers [90]. The impact of carbon emissions from the coffee roasting process was also assessed for two technologies using different energy sources, solar energy and local electricity, in a case study in Peru. The results indicate that the contribution of carbon emissions when using power from solar panels is 0.318 kg CO_{2-eq} per kg of roasted coffee, while the standard grid electricity was 0.744 kg CO_{2-eq} [35]. Ecological industry-based coffee processing requires the support of farmers in processing coffee with the need to increase the ability of farmers in technical, social, cultural, and economic aspects [91]. Coffee processing should consider the impact on the environment an ecological integration system for coffee processing requires sub-systems combined from coffee plantations and livestock and then the industry as a production unit.

LCA is a systematic methodology focused on identifying and quantifying the environmental impact of products and processes, including the Global Warming Potential (GWP). Through LCA tools, combined with appropriate input data, quantitative GWP can be obtained for evaluating agri-food production process systems [92]. There are four main components of an LCA: goal scope, production inventory, impact assessment analysis, and interpretation. To evaluate the LCA in this study, the authors used data from direct observations and measurements taken at the Andungsari Kopi farmer group in Bondowoso Regency, East Java province in 2021.

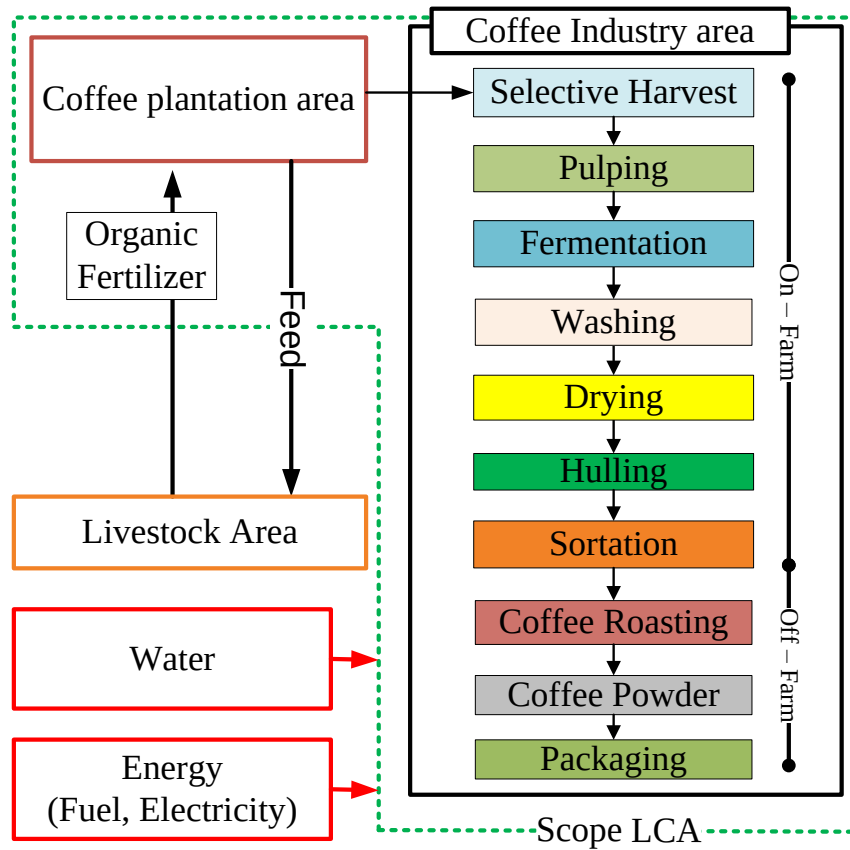


Figure 3.1 Scope of sustainable coffee production for pilot plant improvement

The design of this pilot project is targeted to produce food products and other potential products such as feed, fertilizer, and fuel through industrial-ecology approaches to waste integration, which will be evaluated in future work. In this system, the upstream (*On – Farm*) and downstream (*Off – Farm*) processing processes will be studied to clarify the baseline initial conditions (and options to mitigate potential GWP) before integration. The various configurations will then be evaluated. The initial system boundaries for the current study are shown in Figure 3.1. High coffee quality is categorized as coffee with grading scores above 85 [21]. Premium and commercial grade coffee are considered to be lower quality, with subsequent lower prices [25], [15]. Part of the present research is looking at processes that can enhance the quality of coffee (wet processing) to improve income potential for smallholder farmers. Future work will then look to integrate various waste streams to develop a long-term pilot project as an industrial ecology pilot project by utilizing waste for energy towards SCP (including valorization of by-products for novel food, fuel, feed, and fertilizer). This study primarily aims to evaluate the change in GWP associated with changing to the wet coffee processing method to improve coffee quality. This work adds to the academic knowledge in the field by examining the environmental impacts across multiple downstream processing methods to produce high quality coffee products.

3.2 Methodology

This study uses primary data gathering of waste and energy flows and processes at the case study location . The primary evaluation methodology this study used was LCA (ISO, 2006)[42]. In general, the LCA stages include (i) Goal and Scope definition, (ii) Inventory analysis, (iii) Impact assessment,

and (iv) Interpretation. LCA, as an environmental impact analysis has previously been used to assess the carbon impact of ground coffee production [36], and also the environmental impact of the coffee roasting process with different energy sources [35]. This study uses SimaPro 9.3.0.3 software for LCA analysis. To determine GWP, data was taken from the production processes (farm through to roasting and grinding) and experimental results from the analysis of waste streams and their potential conversion to biogas. Currently, the IPCC emissions factors were used for calculating livestock impacts and COD and BOD (chemical and biological oxygen demand, respectively) were taken for wastewater [93][94] emissions. GWP is used as a measure for comparison of coffee processing between Semi Wash (SW) and Full Wash (FW) processes. IPCC factors are used for calculating wastewater (*Ww*) and livestock (*Lv*) emissions.

Livestock waste is an important source of anthropogenic (GHG): CH₄, N₂O and CO₂ [95][96]. Livestock contributes about 37% of global CH₄ emissions [96]. A previous study in Cluj-Romania showed that the decomposition of 60m³ of dung produced total methane emissions measured at 0.185t CH₄ /year and carbon dioxide emission of 4.7 t CO₂ /year [96]. Based on site observations, one ha average coffee plantation included 2,500 coffee plants, 300 macadamia as shade plants, 110 cinnamon, and 200 lamtoro plants (Table 3.1). In addition to shade plants, grass grown on the farm was used for animal feed for two cows per ha. The cows in the Andungsari group are indeed not sufficient for the amount of organic fertilizer needed for a total of 10ha, however, livestock waste has the potential to be mixed with coffee waste and used as raw material for biogas [97][98][99].

Table 3.1 Average coffee plantation and coffee shade/ha

Coffee Plantation/ha	Quantity	Total	Average Production	Utilization
Mixed Variety				
-Andungsari Variety	1,500			
-Komasti Variety	550	2,500	3,000 cherry beans	Food
-Lini S	450			
Coffee shade tree/ha				
-Macadamia		300		Food
-Cinnamon		110		Food
-Lamtoro		200		Feed

observed data at Andungsari Group.

3.3 Goal and scope of LCA

This study aimed to evaluate the environmental impact of the production of ground coffee (coffee powder) via two alternative processes. The potential for reducing the environmental impacts by substituting renewable energy and integrating industrial ecology solutions that utilise waste streams (cherry skin, husk skin, pulp, and wastewater) across the supply chain or from co-located agricultural activities will be considered in future work, with the LCA and basic mass-energy balance guiding the identification of hotspots and opportunities.

Two alternatives of coffee processing (FW and SW) were considered for analysis [5]. Primary data was obtained via experiments and surveys conducted with the assistance of the Andungsari coffee farmer group, 1048m above sea level in the Bondowoso Regency, on a plot focused on growing

Arabica coffee. 10ha of land area of the Andungsari group were used as a pilot plant aiming to implement Industrial Ecology (IE). The Functional Unit (FU), was based on the pilot plant production of 3,000kg *CB* (*Cherry Beans*) per ha which was then processed to 512kg *CP* (*Coffee Powder*). This land area is part of the total coffee plantation area of the group, which was 66ha according to the Directorate General of Plantations [100]. Results are reported in terms of impacts per kg CP. The GWP produced from the alternative processes (FW and SW) were calculated and compared as the primary indicator. Next, the data on production and processing were used to model and design alternatives for pilot scale implementation of sustainable industrial ecology on the system, with renewable energy being used for increasing production and economic value for the coffee farmers group.

3.4 Inventory analysis

Inventory data was collected during 2021 through surveys and observations at the Andungsari coffee farmers group. Data were collected from the beginning of harvest in April to October. Data collected include: area of the plantation, total shade plants, head of cattle, fertilizer demand, forecast animal feed, water used, energy input, total waste produced, and the potential waste for sustainable industrial ecology to renewable energy. This farmer group produced coffee using two processes: FW and SW including on-farm CB sorting as an initial determinant of quality, selective handpicking (*ripe red coffee cherries*), packing in sacks and delivery to processing sites within 2 - 4km from the plantation. Upstream and downstream technologies have been described in Figure 3.2, as well as the handling of wastewater and coffee hull / skin waste. A number of potential by-products, air emissions, soil pollution, and other aspects were identified through observations during coffee production and processing. Supply chain inputs and outputs of the materials flow, and overall energy input were identified and measured or estimated using available techniques.

Interviews were used to clarify and collect data during all stages of the processing. The survey was conducted in a collaborative approach including discussion groups, and identified a variety of qualitative supportive measures that could help the success of industrial ecology solutions, including the social aspects of the working system of farmer groups; cultural aspects of the processing and methodology of harvest; capacity of technology used, materials supply, waste, fuel consumed, electrical used. Technology was disseminated to the group in 2020 through a community service grant from Ristekdikti so that this research could be undertaken [14]. The major inventory data is reported at the beginning of the results section.

3.5 Impact assessment

Based on the obtained primary data from the coffee production inputs and outputs, as well as supplementary secondary information on emissions factors (for example), the inventory data were compiled and used in the impact assessment in SimaPro software. The ReCipe (2016) midpoint level (ML) method was applied (Table 3.2) [44]. Fuel consumption was calculated using characteristic factors [46]. Figure 3.2 shows the flow of coffee from cherry beans upstream to packaged ground coffee downstream. For each of these stages, the waste generated will be described and evaluated based on the function and benefits of the products. In consequence, engine capacity and fuel consumed or energy input have been identified. Figure 3.2 illustrates FW (black line) and

SW (blue line), showing that the SW involves drying twice and a huller stage used on the beans to take them from 40% moisture after first drying to the target 12% moisture after the second drying.

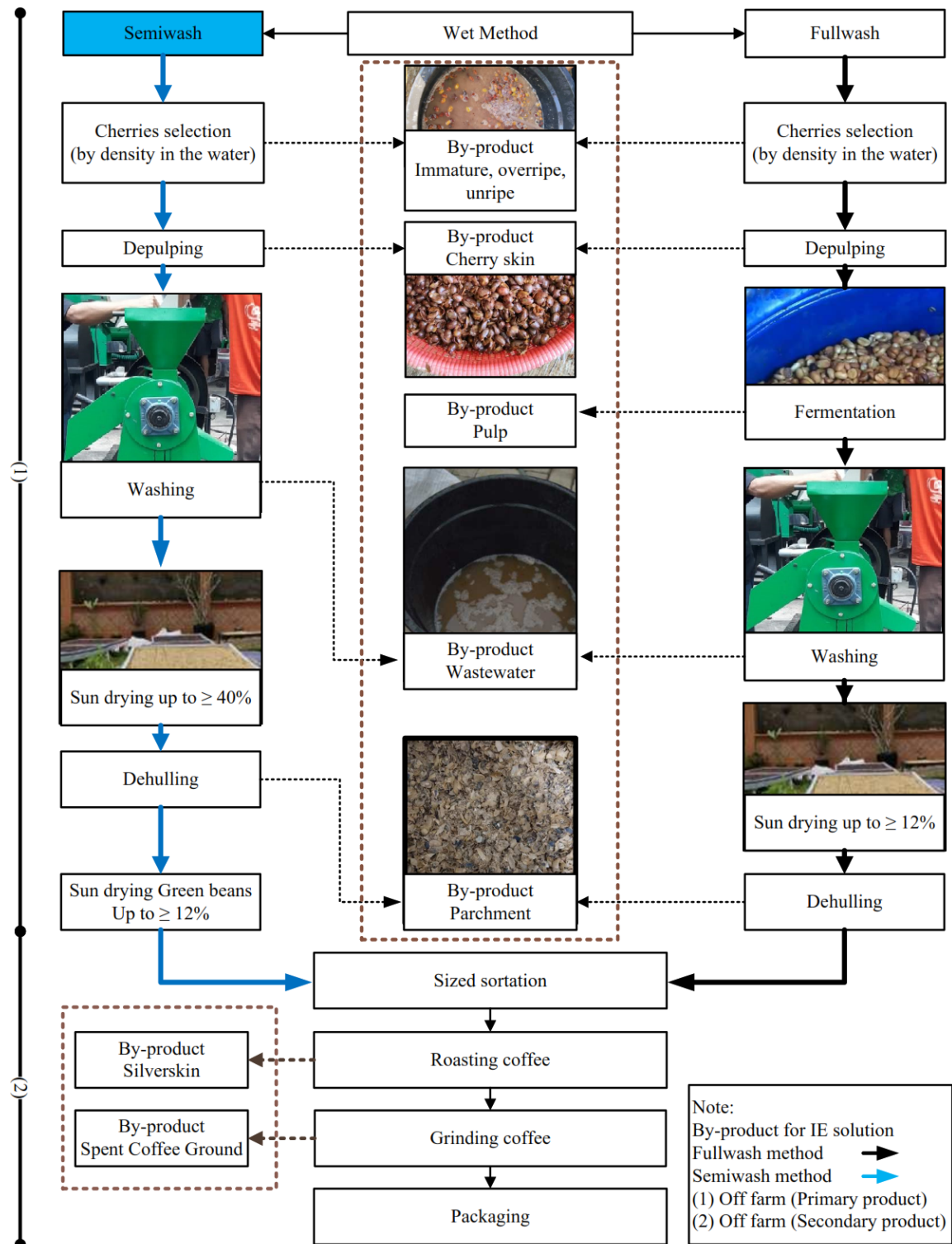


Figure 3.2 Flow processes full wash (FW) and semi wash (SW)

Table 3.2 Environmental impacts considered in the ReCiPe 2016 database at the Midpoint Level (ML)

Impact Category	Unit of the Results
Global warming (GWP)	kg CO ₂ eq
Stratospheric ozone depletion (ODP)	kg CFC ¹¹ eq
Ionizing radiation (IRP)	kBq Co-60 eq
Ozone formation, Human health (HOFp)	kg NO _x eq
Fine particulate matter formation (FPMF)	kg PM _{2.5} eq
Ozone formation, Terrestrial ecosystems (EOFp)	kg NO _x eq
Terrestrial acidification (TAP)	kg SO ₂ eq
Freshwater eutrophication (FEP)	kg P eq
Marine eutrophication (MEP)	kg N eq
Terrestrial ecotoxicity (TETp)	kg 1,4-DCB
Freshwater ecotoxicity (FETp)	kg 1,4-DCB
Marine ecotoxicity (METp)	kg 1,4-DCB
Human carcinogenic toxicity (HTPc)	kg 1,4-DCB
Human non-carcinogenic toxicity (HTPnc)	kg 1,4-DCB
Land use (LOP)	m ² a crop eq
Mineral resource scarcity (SOP)	kg Cu eq
Fossil resource scarcity (FFP)	kg oil eq
Water consumption (WCP)	m ³

3.6 Interpretation

In the interpretation phase, we undertook a comparison of the two processing types - FW and SW. As FW processing tends to produce a more acid-tasting product than SW [101][102] (the less-acid SW coffee product is sold at a lower price than the FW coffee that has more complex characteristic flavors). Processing coffee by fermentation produces a higher acidity (Figure 3.2) and makes the mucilage easier to separate from the parchment; besides which, the microorganism content in mucilage is vital for flavor, and can be related to changes in pH and temperature [103]. During fermentation, the mucilage changes to a sour taste, affecting the coffee's taste. Mucilage will produce various acid compounds, including lactic acid, butyric acid, propionate, and several alcohol compounds, such as ethanol [104]. Moreover, FW and SW coffee production environmental impacts should be identified and compared to clarify the relative merits. In addition, this phase considers the energy supply of each of the stages, and the potential for waste recycling towards IE solutions. We have focused on biogas solutions in this pilot plant [13], with this study providing an initial analysis of utilization of by-product from coffee processing wastewater mixed with cow-dung to produce biogas. In future research we will focus on a biogas digester as part of an IE solution for utilization of by-products, including a consideration of the economics of the process configurations.

3.7 Coffee processing technologies towards lower environmental impact

3.7.1 Inventory data analysis

The material flows of coffee, from the input harvested cherry beans through to green beans, and the flow of water in and waste (or potential by-products) is shown in Table 3.3. The average CB harvest produce 3 tons per ha per year. The waste can potentially be used to produce feed, fuel, and fertilizer. Only about 15-20% of the coffee cherry is used to produce ground coffee for consumption; more than 80% is waste and has the potential to become a valuable product to increase the economic value or reduce the energy used for coffee production [105].

Table 3.3 Materials flow coffee and benefit of waste as a by-product

Coffee Plant ha/year				
Materials (ha/year) Arabica	Input	Output Product	Waste	Benefit
Cherry Beans, kg	3,000			
Water, litres	6,375			
Green Coffee Beans, kg		610		Food (Coffee Drink)
Parchment, kg			150	Feed, Fuel (Briquette)
Cherry Skin, kg			1,320	Food (Cascara)
Pulp, kg			132	Fuel (Biogas)
Wastewater, kg			7,163	Fertilizer

observed data 2021

Table 3.4 Wastewater

Parameter	Average	Quality Std	Unit
TSS	165	150	mg/l
TDS	1,338.8		mg/l
pH	4,2	6-9	-
Density	130.4		NTU
DO	137.36		mg O ₂ /l
BOD _{wut}	37.39	90	mg/l
COD	1,906	200	mg/l

Data taken experimentally; TSS (Total Suspended Solid), TDS (Total Dissolved Solid), DO (Dissolved Oxygen), BOD_{wut} (Biological Oxygen Demand wastewater untreated), COD (Chemical Oxygen Demand), DO (Dissolved Oxygen), NTU (Nephelometric Turbidity Units)

Potential emissions from wastewater and organic fertilizer are calculated from experimental data based on emission factors and correction factors [106][94]. Table 3.4 shows experimental data from the analysis of wastewater, to which the IPCC impact factors and formulae were applied for the LCA.

Table 3.5 illustrates the correction factors calculated for potential emissions from wastewater (pulp and washing wastewater – Figure 3.2) to support the calculation of potential GWP [107].

Table 3.5 Parameter correction factor

Parameter	Factor [107]	Unit
CF_{CO_2}	1,375	mg
MCF_{WW}	0	
CF_s	530	mg
CF_c	375	mg
BG	0.65	
λ	0.65	

To support for solving input database from wastewater calculate [107]:

$$CO_2 = 10^{-6} \times Q_{WW} \times COD \times Eff_{BOD} \times CF_{CO_2} \times [(1 - MCF_{WW} \times BG) \times (1 - \lambda)] \quad eq\ 1.$$

Therefore :

CO_2 = Estimate CO_2 emission rate (mg/ha)

Q_{WW} = Wastewater demand (l/ha)

Eff_{BOD} = Oxygen demand removal efficiency

CF_{CO_2} = Conversion factor for maximum CO_2

MCF_{WW} = Correction factor wastewater treatment

BG = Fraction of carbon

λ = Biomass yield (g C)

3.7.2 Animal husbandry and fertilizer operation

On the case study plantation livestock is also raised, offering potential for onsite production of fertilizer (manure). An IE system for coffee plantations could produce feed for animal husbandry, integrate livestock waste used as raw material for fuel and fertilizer, and coffee skin waste used as feed and fuel. The organic fertilizer was used as much as 37.5 tons/ha/year for around 2,500 coffee plants. The estimated fertilizer used on each coffee plant from livestock was 15kg on average per coffee plant per year. Cows excrete between 20-25kg of manure per day, which means that the 8 cows in the case study area provide a potential 200 kg per day of dung, or an estimated 73 tons per year. Thus, livestock waste is not currently able to supply sufficient fertilizer for the full 10 ha. However, coffee cherry wet skin is also produced at a rate of 1.32 tons per ha, and leaf waste from pruning coffee trees can also be used as fertilizer.

3.7.3 Mass balance for coffee processing

From an input of 3 tons of sorted coffee cherry produces 1.65 tons wet coffee beans and the rest is cherry skin. After drying to a moisture content of 12%, the dry-skinned coffee beans are reduced to a mass of only 25% of the raw coffee cherry beans. While ready-to-drink coffee powder is only about 15 to 20%. Table 3.6 describes the mass balance at each stage of the process, from harvesting to producing CP.

Table 3.6 Mass Balance of Coffee Processing

Stages Process*		SW / FW Specific	Input		Output		
			Material (kg)	Water (l)	Product (kg)	Waste	
						Solid (kg)	Liquid (l) Losses (kg)
Coffee Plant	Organic Fertilizer		37,500				
Harvesting	Selected Cherry		3,000		3,000		
Submerged	Cherry Grading		3,000	6,375	2,970	30	6,375
Depulping	Pulping Coffee Cherry 16-24 hour (Get Flavor)		2,970		1,650	1,320	
Fermentation	Cleaning Pulp		1,650		1,650		
Washing	Cleaning Pulp		1,650	2,475	1,560	132	2,433
Drying (FW)	Dry Beans (FW) 12%	FW	1,560		750		810
Drying (SW)	Dry Beans (SW) 40%	SW	1,560		950		610
Dehulling	Clean Parchment (FW)	FW	750		610	140	
	Clean Parchment (SW)	SW	950		810	140	
Drying	Dry Beans (SW) 12%	SW	810		610		200
Grading	Grading Quality		610		600	10	
Roasting	Coffee Roasted		600		540		60
Grinding	Ground Coffee		540		512		27
Packaging	Ready to sell per kg		512		512		
Total					512	1,632	8,808 897

*observed data 2021

3.7.4 Product system inventory

Table 3.7 displays the supply of energy for FW and SW processes. The SW process requires more fuel due to the de-hulling process because coffee beans have a moisture content of 40%; the de-hulling process requires more energy due to the high water content; this process generally shortens the drying process to produce GB, reduces the acidity level, and makes the GB color more dark-green. Inventory data is obtained during the coffee production process; the limit of production per ha is the basis for calculation. This unit can be used as a practical model for farmer groups regarding the production capability of managed land to produce final products. Data were collected during the early coffee harvest from April to October 2021. The peak of the Andungsari Arabica coffee harvest was in August. Figure 3.3 shows the trend of coffee harvesting from the beginning to the end of harvest from a total of 10ha; the coffee harvest in that year was not optimal compared to the Indonesian coffee and cocoa research institute guidelines [108]. Plantation processing, harvesting, pruning management, and technology are problems farmers need to solve. Improvements in various aspects are needed to increase the productivity of the coffee harvest. electricity in the current study is assumed to come from the Indonesian electricity grid, while in future work, solar panels will be considered for off farm activities (roasting and grinding).

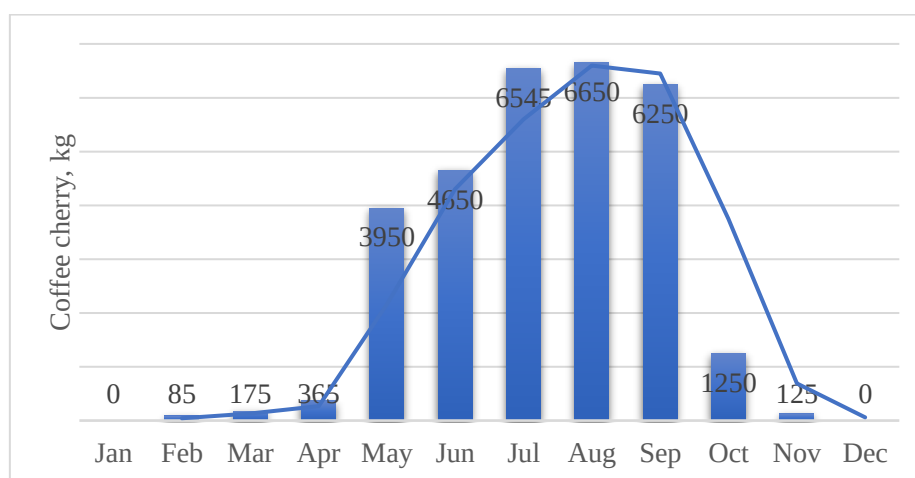
Table 3.7 Coffee processing energy supply processing per ha

Materials Arabica*	Processing	Total (kg)	Tech Used	Energy Input		
				FW	SW	Unit
Harvesting	Transportation	3,000	Motorcycle, 100kg/batch	10.5	10.5	Litre
Cherry Beans, kg	Depulping	3,000	Engine 5hp, 300kg/hr	6	6	Litre
			Electric Light, 0.02kW, 16hr	1.28	1.28	kWh
Fermentation, kg	Fermentation	1,650				
Washing, kg	Cleaning Pulp	1,650	Engine 5hp, 300kg/hr	3.3	3.3	Litre
Coffee Parchment, kg	Dehulling	750	Engine 5hp, 250kg/hr	1.8	3	Litre
Green Beans Coffee, kg	Sorted	610	Electric 0.75kW, 250kg/hr	1.8	1.8	kWh
Green Beans Coffee, kg	Roasting	600	Electric 0.75kW, 50kg/hr	8.1	8.1	kWh
			Gas 0.75 L/hr	8.1	8.1	Litre
Coffee Roasted, kg	Grinding	513	Electric 1kW, 15kg/hr	34.2	34.2	kWh
		512				
Coffee Ground, kg	Packaging	Kg	Electric 0.5kW, 40kg/hr	6.4	6.4	kWh

*observed data

Transport from the plantation to the industrial location is 3.5km, which is transport carry out 100kg of CB, based on calculate the average fuel consumption is 100ml/km. Water demand for the submerged process is 6,375 liters. Description of the specifications of the gasoline engine used for each method is described in Table 3.7.

The plant data in Table 3.6 was used in the process flows input into SimaPro. The correction factor value converts fuel use into emission equivalents [46]. Currently, the system still relies on energy input from fossil fuel, but part of this study is to examine the potential for waste-based biogas and alternative energy integration through IE. The researchers will further examine opportunities for reducing emissions through the use of renewable energy, adding a bio-energy scenario for integrated IE.

**Figure 3.3 Andungsari arabica coffee harvest for farmer groups by month (in 2021)**

3.7.5 Impact assessment for pilot plant incorporating industrial ecology

A simple IE system is being trialed through this pilot for reuse of waste across the operations. Flows of waste that could be used as co-products such as feed, fuel, and fertilizer have been identified. Figure 3.1 shows the scope of the IE model for sustainable coffee production utilizing waste. The integration of waste flows between animal husbandry and coffee production may also lead to improved environmental outcomes. Biomass waste-based renewable energy in coffee plantations was considered to produce energy from CB skin and waste water as raw materials for biogas. These waste streams are available during the coffee harvest and processing period of 6 months, while livestock waste will be used continuously across the year to produce energy. Solar panels are also considered for installation for electricity to support IE and farming households.

The results for supply chain energy usage in each stage are illustrated in Figure 3.4. Potential wastes used as biogas include washing water, pulp, and cherry skin. Meanwhile, the potential for mixed animal feed in the form of parchment and dried cherry skin was also observed. In the SW process, there are two stages of drying, the first drying CB to a moisture content of 40%, producing 950kg of coffee beans. The coffee beans are not completely dry, and this stage is followed by the huller process, producing 810 kilograms of wet coffee beans. The final drying stage produces 610kg of green coffee beans as per the FW process. Table 3.8 shows the total emission results from the SW processing, including the contribution of indirect emissions from the power plant's energy production; there are also emissions generated from each stage of the coffee production process.

The total emissions produced for 512kg coffee powder using SW processing is 391.68 kg CO_{2-eq}; in this case, the following stages contribute most significantly to the emissions (Figure 3.4); production of coffee cherries (3,000kg in the case of both SW and FW) contributed 855 kg CO_{2-eq} emissions. The emissions produced from the FW process from CB to CP is 379.39 kg CO_{2-eq}, or 0.741 kg CO_{2-eq} per kg CP (Table 3.8). The SW process is slightly different from the FW process; there is an increase in fuel input from the use of the de-huller. De-hulling at a moisture content of 40% takes longer in order to ensure the coffee beans remain whole. The carbon footprint total for SW is 391.68 kg CO_{2-eq}; or 0.765 kg CO_{2-eq} per kg CP. Based on Table 6, from 3,000kg cherry beans per ha input both processes yield 512kg coffee powder from 610kg green beans. Furthermore, if we look at coffee powder products from green beans, the potential GWP is 0.26 kg CO_{2-eq} per kg CP. These emissions are predominantly from the roasting, and grinding processes. Total energy used from fuel was 1,244 MJ (FW) and 1,315 MJ (SW).

No fuel energy is added in the drying stage, as the conventional drying process just uses solar drying. Therefore the emission contribution was not able to be calculated, as the only emissions would be from losses of volatiles and water vapors from drying. Direct emissions of these components from roasting are not discussed in detail here. It is essential to emphasize the high environmental impact in categories such as global warming, ionizing radiation, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, and water consumption. For this reason, to compare the GWP of the two coffee processing to achieve IE through the utilization of waste into food, feed, fuel, and fertilizer on an A – to – Z (Added value to Zero Waste) was considered.

Other environmental impacts for ionizing radiation, terrestrial ecotoxicity, human non-carcinogenic toxicity, fossil resource scarcity, water consumption, etc. were predominately caused by the

consumption of fossil fuels such as electricity, gas, and petrol. TETP impact is highest for processing CB to CP in both FW and SW, 4.49 and 4.56 kg-1.4-DCB, respectively. Terrestrial ecotoxicity is largely associated with wastewater emissions [109], utilization of wastewater to biogas is a solution to IE option.

Table 3.8 shows a breakdown of emissions process stage. Even though the farmer groups used organic fertilizer, coffee cherries are transported to processing using a motorcycle. Thus, causing the relatively high contribution of emissions from CB. Transportation from the plantation to the industry using a motorcycle with a petrol consumption of up to 10.5l for the total 3tons across a distance of about 3.5km.

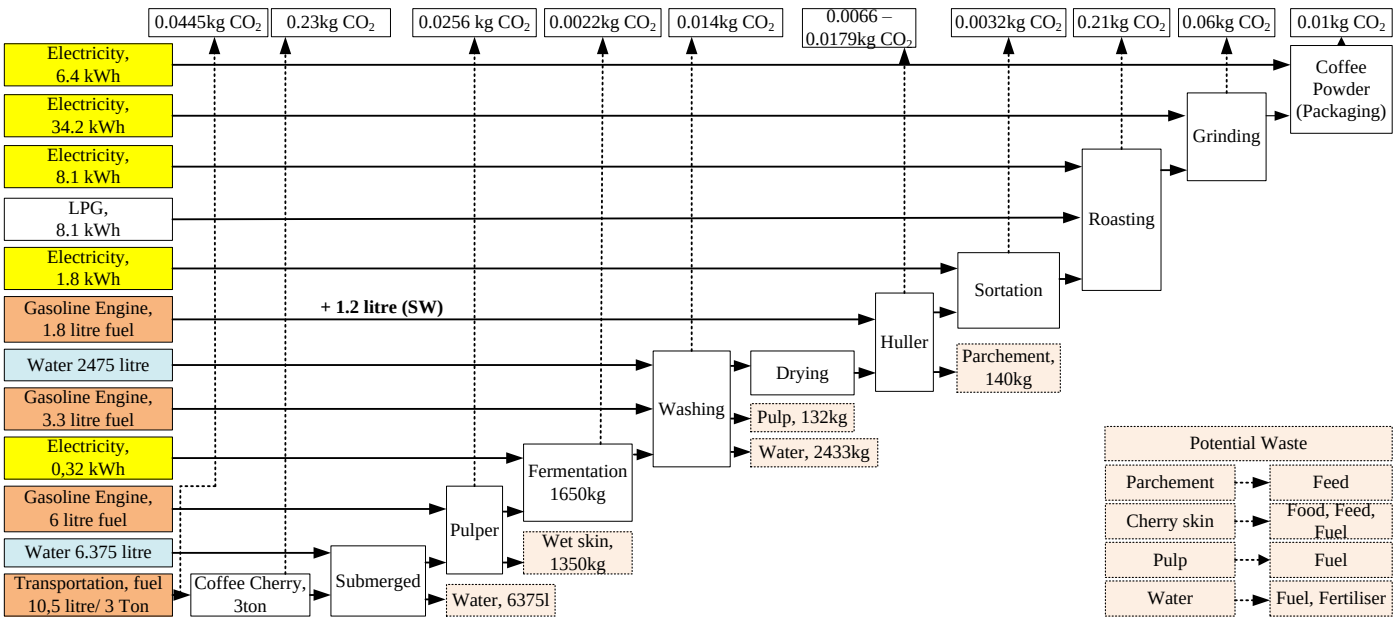


Figure 3.4 The flow of energy inputs, outputs and CO₂-eq emissions by stage and fuel

Other impacts are shown in Figure 3.5 and Figure 3.6. The grinding stage contributes the highest emissions, the electricity requirement per 15kg of CP is 1kWh. Furthermore, at the roasting stage supply gas and electricity is important for this stages. The LCA indicates that much of the impact is associated with the usage of fossil fuels. With the emissions from wastewater also a concern, there is an apparent opportunity to attempt to produce biogas as one substitute energy source.

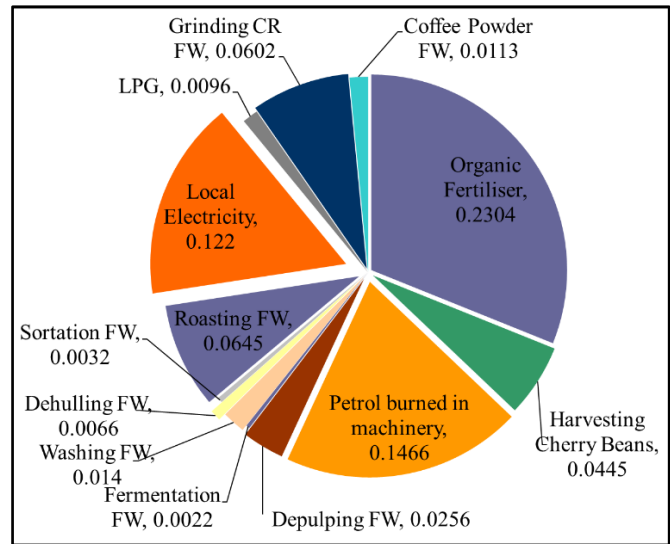


Figure 3.5 Impact contribution by stages of coffee processing - FW

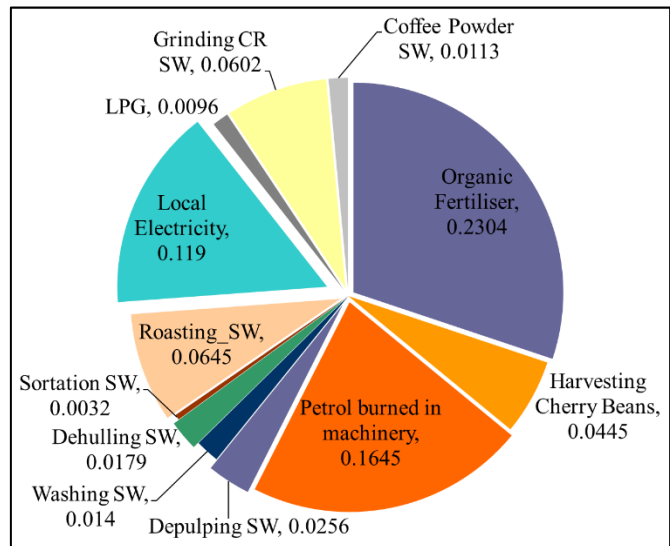


Figure 3.6 Impact contribution by stages of coffee processing - SW

Table 3.8 Life Cycle Impact Assessment (LCIA) of SW and FW processing

Impact category	Unit	OF	Harv-CB	CB to GB		CB to CP		GB to CP
		SW/FW		FW	SW	FW	SW	FW/SW
GWP	kg CO ₂ eq	0.039	0.059	0.41	0.43	0.741	0.765	0.26
ODP	kg CFC ¹¹ eq	1.9 x 10 ⁻⁸	2.6 x 10 ⁻⁸	1.7 x 10 ⁻⁷	1.8 x 10 ⁻⁷	2.46 x 10 ⁻⁷	2.5 x 10 ⁻⁷	3.5 x 10 ⁻⁸
IRP	kBq Co-60 eq	8.5 x 10 ⁻⁴	9.5 x 10 ⁻⁴	0.0053	0.0054	0.00712	0.00727	0.00086
HOFP	kg NO _x eq	2.3 x 10 ⁻⁴	3.1 x 10 ⁻⁴	0.0019	0.00208	0.00267	0.00278	0.00035
FPMF	kg PM2.5 eq	6.1 x 10 ⁻⁵	8.4 x 10 ⁻⁵	6.8 x 10 ⁻⁴	6.5 x 10 ⁻⁴	3.42 x 10 ⁻³	3.38 x 10 ⁻³	2.62 x 10 ⁻³
EOFP	kg NO _x eq	2.4 x 10 ⁻⁴	3.2 x 10 ⁻⁴	2.06x10 ⁻³	2.16x10 ⁻³	2.7 x 10 ⁻³	2.8 x 10 ⁻³	3.5 x 10 ⁻⁴
TAP	kg SO ₂ eq	1.4 x 10 ⁻⁴	1.8 x 10 ⁻⁴	1.14x10 ⁻³	1.18x10 ⁻³	1.8 x 10 ⁻³	1.8 x 10 ⁻³	4.6 x 10 ⁻⁴
FEP	kg P eq	8.52 x 10 ⁻⁶	1.01 x 10 ⁻⁵	2.4 x 10 ⁻⁴	2.4 x 10 ⁻⁴	5.0 x 10 ⁻³	4.9 x 10 ⁻⁴	2.1 x 10 ⁻⁴
MEP		6.43 x 10 ⁻⁷	6.63 x 10 ⁻⁷					
	kg N eq			4.08x10 ⁻⁶	3.8 x 10 ⁻⁶	1.7 x 10 ⁻⁵	1.6 x 10 ⁻⁵	1.2 x 10 ⁻⁵
TETP	kg 1.4-DCB	0.64	0.68	3.7	3.75	4.49	4.56	0.157
FETP	kg 1.4-DCB	8.1 ⁻⁴	8.0 ⁻⁴	0.0047	0.0046	0.0135	0.0134	0.008
METP	kg 1.4-DCB	1.4 x 10 ⁻³	1.5 x 10 ⁻³	0.0082	0.008	0.02	0.02	0.01
HTPc	kg 1.4-DCB	2.3 x10 ⁻³	2.4 x10 ⁻³	0.0132	0.0131	0.026	0.026	0.0106
HTPnc	kg 1.4-DCB	0.027	0.042	0.3	0.31	0.56	0.58	0.21
LOP	m ² a crop eq	0.002	0.003	0.016	0.016	0.019	0.02	0.0008
SOP	kg Cu eq	1.1 x 10 ⁻⁴	1.1 x 10 ⁻⁴	5.7 x 10 ⁻⁴	5.8 x 10 ⁻⁴	7.4 x 10 ⁻⁴	7.4 x 10 ⁻⁴	6.6 x 10 ⁻⁵
FFP	kg oil eq	0.013	0.017	0.106	0.11	0.172	0.177	0.048
WCP	m ³	9.18 x 10 ⁻⁵	9.58 x 10 ⁻⁵	-5.9 x 10 ⁻³	-5.9 x 10 ⁻³	-6.4 x 10 ⁻³	-6.4 x 10 ⁻³	0.0005

OF: Organic Fertiliser

3.8 Conceptual and strategic frameworks

A number of key strategies have been considered in previous studies that can be directly applied to the current case to enhance sustainability performance of production. Through the LCA it was indicated that fossil energy streams produce significant impacts in the pilot plant, and use of biogas produced from the waste streams was identified as a potential option, as per previous studies [110] [97]. In 2020, some coffee processing technology was implemented at the pilot plant to improve the quality of coffee beans [14]. This included a huller, sortation equipment, coffee roaster machine, and a biogas digester as a simple IE solution. Solar panels were also considered as a substitute energy source for fossil gas and electricity. In future research the utilization of waste from coffee processing, including waste water, pulp, husk skin, and parchment as raw material for biogas or animal feed, will be considered, and it is anticipated that a significant proportion of the current waste could be reduced through conversion to useful products. These products include coffee tea (cascara) from cherry skin and husk skin and use of cow dung from cattle farms to produce biogas, with slurry from the reactor to be used as raw material for organic fertilizer. The integration of these solutions will be the focus of future work. Intercropping on plantations is another strategy that has helped farmers to sustainably obtain animal feed, and improve the sustainable use of organic fertilizers, and in LCA this could lead to allocation requirements, which are not currently considered.

Finally, Table 3.9 compares the results of this study with previous research, from which it is apparent that there are a wide variety of estimates of GWP across different functional units from ReCiPe 2016 database at the Midpoint Level (ML). In general there are 3 considered stages, ending in roasted coffee or coffee powder: (Coffee Cherry Bean) CB production; CB to GB (Green Coffee Bean); GB to CR (Roasted Coffee); or GB to CP (Coffee Powder). Sometimes all of these have been examined and specified, sometimes only one or a sub-set of stages have been considered. In this study, we express the GWP at each stage, as well as the overall (CB to CP). These previous studies also highlight some useful alternatives for reduction of emissions.

Firstly, considering the studies that report results for the production from harvest to CB, a coffee Agro-Industry experiment in Costa Rica and Nicaragua identified emissions from two management systems, with the conventional management system 1kg CB contributes emissions of about 0.26 - 0.67kg CO₂ eq while for organic management this is reduced to 0.12 - 0.52kg CO₂ eq [90]. An assessment of emissions from organic management in India 0.16kg CO₂ eq/kg CB [87], compared with 0.5 kg CO₂ eq/kg CB for integrated and 0.74kg CO₂ eq/kg CB for conventional farming. Another study expressed the impact only in terms of the final GB product, with 1.89 – 2.82 kg CO₂ eq/kg GB [36]; using their conversion factors, this would equate to 0.34 – 0.51 kg CO₂ eq/kg CB. Similarly, using the aforementioned study's conversion factors, the 0.05 – 1.04 kg CO₂ eq/kg GB reported for CB growing by [111] would equate to 0.009 – 0.19 kg CO₂ eq/kg CB for sustainable or conventional farming. These were mostly higher than the current study (0.039 kg CO₂ eq/kg CB), which is likely due to the use of onsite organic fertilizers, and a significant manual component in the harvesting, and no consideration of raising seedlings, among other assumptions, with Noponen noting that the emissions factor and assumptions around pruning were important.

The next stage – from CB to GB was reported as 0.482kg CO₂ eq/kg GB [112] and 1.50 - 2.82 kg CO₂ eq/kg GB [36]. The latter of these two studies is a higher outlier in the literature examined. The emissions for on-farm processing reported as “milling” were 0.08 – 0.18 kg CO₂ eq/kg GB in the

study by [111], which is assumed to equate to the CB to GB stage in the current study. This compares to 0.568 CO₂ eq/kg GB from SW and 0.473 CO₂ eq/kg GB from FW processes in this study.

Regarding the next stage, from GB to CR, the carbon impact of roasting coffee 0.318kg CO₂ eq/kg CR with alternative energy from solar panels was reported compared with grid electricity 0.744kg CO₂ eq/kg CR [35]. Most other studies found did not report the GB to CR, but typically ended at CP, while some extended to coffee drinks - e.g. in Finland brewing coffee produces a carbon impact of about 0.7kg CO₂ eq/ L Coffee Drink [113].

A number of strategies have been implemented for reducing emissions and waste. Although a higher impact estimate for emissions, the potential for using waste to produce energy in the Mexican coffee Agro-Industry showed significant potential to reduce emissions [36]. Integrated farming has also been implemented for the sustainable management of coffee plantations when compared with using conventional methods, including integration with other crops. While a number of similar studies were concerned about GWP from coffee processing, there was typically no detail about which process was used (wet or dry method). For future studies, it is recommended that more work be done on LCA on dry methods (Natural, anaerobic, Lactic, Hydro honey, Carbonic Maceration, and so on), which are essential for estimating GWP for SCP of higher value products, and particularly focusing on IE solutions and valorization of by-products.

Table 3.9 Comparison of results of this study with previous research

Reference	Farming	On-Farm	Off-Farm	Distribution	/kg	LCA
	Cultivation/kg CB	Harvesting/kg CB	Primary/kg GB	Secondary	GB	Method
(Noponen et al., 2012)	NA	0,67kg CO ₂ eq	NA	NA	NA	
	Conventional Farming to Harvest CB					
	NA	0,52kg CO ₂ eq	NA	NA	NA	Calculated
	Organic Farming to Harvest CB					
(Rican et al., 2013)		0.102 kg CO ₂ eq	0.482 kg CO ₂ eq	0.305 kg CO ₂ eq/kg CP	0.27 kg CO ₂ eq	
	Harvesting CB		Process CB to GB	Process GB to CP	Export to Europe	Calculated
(Giraldi et al., 2018)		2.82 kg CO ₂ eq	2.82 kg CO ₂ eq	2.90 kg CO ₂ eq/kg CP	NA	
	Conventional Farming to Harvest CB					
		1.89kg CO ₂ eq	1.50 kg CO ₂ eq	1.58 kg CO ₂ eq/kg CP	NA	Calculated
	Organic Farming to Harvest CB					
(Franco & Bartl, 2018)	NA	NA	NA	0,318 kg CO ₂ eq/kg CR	NA	
			Process GB to CP (Solar Panel)			LCA Sima
	NA	NA	NA	0,744 kg CO ₂ eq/kg CR	NA	Pro
			Process GB to CP (Local Hdyro Electricity)			
(Usva et al., 2020)	NA	NA	NA	0,27 to 0,70 kg CO ₂ eq/ l CD		Calculated
(Nab & Maslin, 2020)	NA	NA	16.04 kg CO ₂ eq	NA	NA	
		Conventional Farming in Vietnam Harvest CB to Process GB				
	NA	NA	14.61kg CO ₂ eq	NA	NA	Calculated
	Integrated Farming in Brazil from Harvest CB to Process GB					
Basavalingaiah, et.al (2022)		0.74kg CO ₂ eq	NA	NA	NA	
	Conventional Farming to Harvest CB					
		0.5kg CO ₂ eq	NA	NA	NA	
	Integrated Farming to Harvest CB					Calculated
		0.16kg CO ₂ eq	NA	NA	NA	
Organic Farming to Harvest CB						
This Study	Cultivation/kg CB	Harvest CB/kg CB	Process CB to GB/kg GB	Process CB to CP/kg CP		
SW	0.039 kg kg CO ₂ eq	0.275 kg CO ₂ eq	0.568 kg CO ₂ eq	0.765 kg CO ₂ eq		
FW			0.473 kg CO ₂ eq	0.741 kg CO ₂ eq		
				Process GB to CP		
FW or SW				0.26 kg CO ₂ eq/kg CP		

CB : Cherry Beans; GB : Green Beans; CR : Coffee Roasted; CP : Coffee Powder; CD : Coffee Drink

3.9 Conclusions

In this study, the authors obtained data through experiments and direct observations during the harvest season for Andungsari Arabica coffee in Bondowoso Regency. The stages of the coffee production process using the SW and FW methods were observed from picking CB through to CP. The results of carbon emissions for one kg CP from SW was 0.765 kg of CO₂-eq while for the FW method it was 0.741 kg of CO₂-eq. Based on this study, the author will continue this research project based on IE integration across the production chain through the use of waste to reduce the use of external input energy. In future research we will continue to further-consider valorization of by-products for food (cascara) from cherry skin, husk skin, fuel (mixed or dust husk skin), and some potential for feed, and fertiliser.

4 A comparison of lifecycle assessment for specialty coffee towards sustainable coffee production

4.1 Chapter introduction

Coffee is a globally significant commodity, influencing economies, cultures, and livelihoods. Specialty coffee, which emphasizes quality and sustainability, emerged in the 1960s-70s [114], driving the establishment of specialty coffee shops. Distinguished by its superior quality and limited production, specialty coffee plays a crucial economic role [116]. Producers benefit from higher incomes [117], while specialty coffee establishments stimulate economic activity [118]. Ethical sourcing practices also attract consumers, enhancing the industry's economic value [80][119][120]. 4th wave coffee culture further emphasizes sustainability and ethical practices. Environmental impact and sustainability are key concerns across these coffee movements. In this context, Life Cycle Assessment (LCA) is useful for assessing and monitoring Sustainable Coffee Production (SCP). LCA is a methodology that focuses on identifying and quantifying product impacts through the appropriate combination of input data for analysis. LCA results greatly depend on the location.

Indonesia is the fourth largest coffee producer in the world and plays a significant role in the specialty coffee industry due to its unique coffee varieties, ideal growing conditions, and commitment to quality and sustainability. Coffee plantations in Indonesia have become a significant source of income for farmers [121], owing to the widespread popularity of the beverage worldwide [20]. Despite variations in plantation quality affecting coffee production, the growing demand for coffee remains steadfast [122]. Consequently, emphasis on quality and flavor has become pivotal, especially in specialty coffee produced by smallholders, even though the quantity may be relatively low [123]. The supply of specialty quality coffee plays a crucial role in enabling smallholders to bypass lengthy sales chains, directly selling to customers and augmenting their income despite financial constraints [118]. In regions like Bondowoso, Indonesia, coffee smallholders have adopted approaches such as the Product Life Cycle (PLC) method to bolster their income by shortening the sales chain [124]. Furthermore, innovations in coffee processing offer alternative avenues for smallholders to derive income from Specialty Coffee Grade [6]. However, to align with the requirements of specialty coffee, mindful consideration of environmental impacts is essential. The concept encompasses environmentally friendly and socially responsible coffee cultivation practices that prioritize fair treatment of workers, biodiversity and conservation towards Sustainable Coffee Production (SCP) [125][28].

The primary coffee bean processing configurations include the Wet and Dry Methods (DMs). While the Wet Methods (WMs) are generally used, DMs have become a focus for processors aiming to produce Specialty Coffee with high Cup of Excellence (COE) scores [123]. DMs yield coffee with complex flavors and aromas [126][6]. However, meeting market demands of 4th wave coffee culture [127] poses a challenge for DM coffee production. Investing in technological infrastructure to enhance quality and enable the production of derivative coffee products is a key component of SCP. Additionally, there is the option of implementing Industrial Ecology Coffee (IEC), an approach to coffee production that integrates principles of industrial ecology to optimize sustainability by minimizing waste and environmental impacts. To tailor these investments effectively, LCA is

necessary. It analyzes environmental impacts, identifies improvement areas, aids decision-making, fosters continuous improvement, helps in market positioning, and guides policy development. Thus, this study delves into the environmental impact assessment of DMs: Natural, Hydro honey, Anaerobic, Lactic, and Carbonic Maceration, an aspect not previously explored in the literature.

The most relevant previous works in environmental impact analyses of coffee production discuss separate processing chains to evaluate GWP. For instance, a study conducted in Vietnam compared Fine-Robusta or “Robusta Specialty” coffee production, from planting, plant care, and fertilizer to products through natural processes. It revealed a GWP impact of 0.64 kg CO₂-eq per kg of Green Beans (GB) for organic treatment, and 0.93 kg CO₂-eq for non-organic [128]. Chemical fertilizers, especially as a source of N₂O, were identified as major contributors to emissions [89]. In another study in Jember-Indonesia, the use of organic fertilizer in full-washed coffee processing resulted in 1.2 kg CO₂-eq per kg of Arabica Coffee Powder (CP) [27]. However, the impact of wastewater contribution was not addressed. Similarly, Gayo Arabica coffee processing using the full-wash method produced a GWP impact of about 1.48kg CO₂-eq [129]. Other studies explored GWP impact of cherries production per kg of 0.76kg CO₂-eq [87] and 0.26kg CO₂-eq [90]. While most studies focus on specific processing chains for GWP measurement, integrating organic practices into Industrial Ecology (IE) for SCP proves challenging. The authors previously conducted LCA on coffee roasting, comparing biogas and fossil use, resulting in GWP impacts of 0.68kg CO₂-eq and 0.82kg CO₂-eq per kg Coffee Roasted (CR) respectively [13].

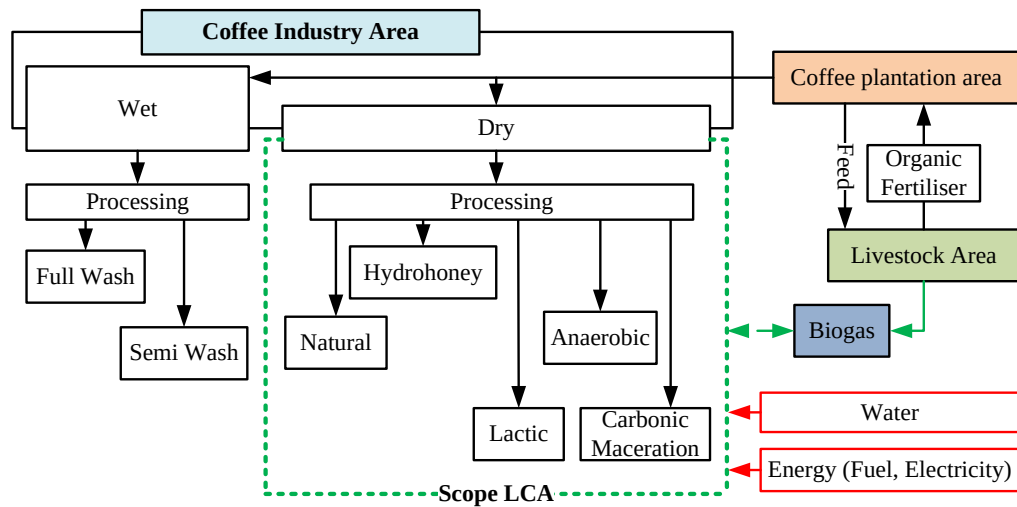


Figure 4.1 Limitations of the LCA study for the IEC pilot plant improvement

To evaluate the LCA in this study, the authors used data from direct observations and measurements taken at a smallholder coffee farm at the Andungsari Kopi in Bondowoso Regency, East Java province, in 2022. Since 1992, this smallholder coffee farmers` group has implemented organic fertilizer use on a 10-ha plantation as a Pilot Plant towards IEC. This study aims to evaluate the changes in GWP and in other impact categories such as Stratospheric ozone depletion (ODP), Ionizing radiation (IRP), Ozone formation, Human health (HOFP) etc., related to the DM to improve coffee quality [15][21]. First, it compares input, output, and yields, along with gas produced during fermentation across the different DMs. GWP can be obtained quantitatively to evaluate agri-food production systems [92]. In this system, the upstream (On – Farm) and downstream (Off – Farm) processes are studied to clarify the baseline initial conditions in the DMs, and the options for

potential GWP mitigation before integration of IEC. The various parameters are then evaluated. The initial system boundaries for the current study are illustrated in Figure 4.1. Future work will integrate all waste streams to develop a long-term pilot plan IEC towards SCP (including utilizing by-products for novel food, feed, fertilizer, and fuel). This work adds to academic knowledge in the field by mitigating the environmental impacts of On – Off Farm for “Specialty Coffee” products.

4.2 Boundary and methodologies

4.2.1 Study area and boundary system

This research was conducted within the Andungsari Bondowoso coffee farming collective, situated in the East Java Province of Indonesia. The coffee plantations of 10ha span across 3 locations in Pakis Village, ranging in elevation from 1,048 to 1,400m above sea level (with coordinates Latitude: -7.9231361, Longitude: 113.708889). Coffee production in 2022 averaged 580kg of GB/ha per year, a decrease compared to 2021. Smallholders implemented both wet and dry processing methods to cater to the demands of the local coffee market. However, this paper specifically delves into the DMs, with wet processing discussed elsewhere [130]. This study used a mixed variety (Komasti, Andungsari, and Lini S) to compare the different DMs.

4.2.2 Coffee processing through dry methods

Dry processing methods are often used in countries with arid climates, such as Ethiopia, Brazil, and some parts of Indonesia, providing unique coffee flavors depending on the environmental conditions of the drying location and the coffee variety used [32]. DMs offer the advantage of requiring less water. This paper studies the following DMs: Natural, Hydro honey, Lactic, Anaerobic, and Carbonic Maceration (CM). Figure 4.2 shows the flowchart of coffee processing using the DMs. Red-picked CB that were carefully selected during harvest were transported to the production site by a motorcycle over a distance of approximately 3.5km.

After harvesting, the processing methods differed depending on of the selected processing route. The Natural method did not require fermentation, while the other methods did. The differences in fermentation procedures for each DM are detailed in their respective descriptions.

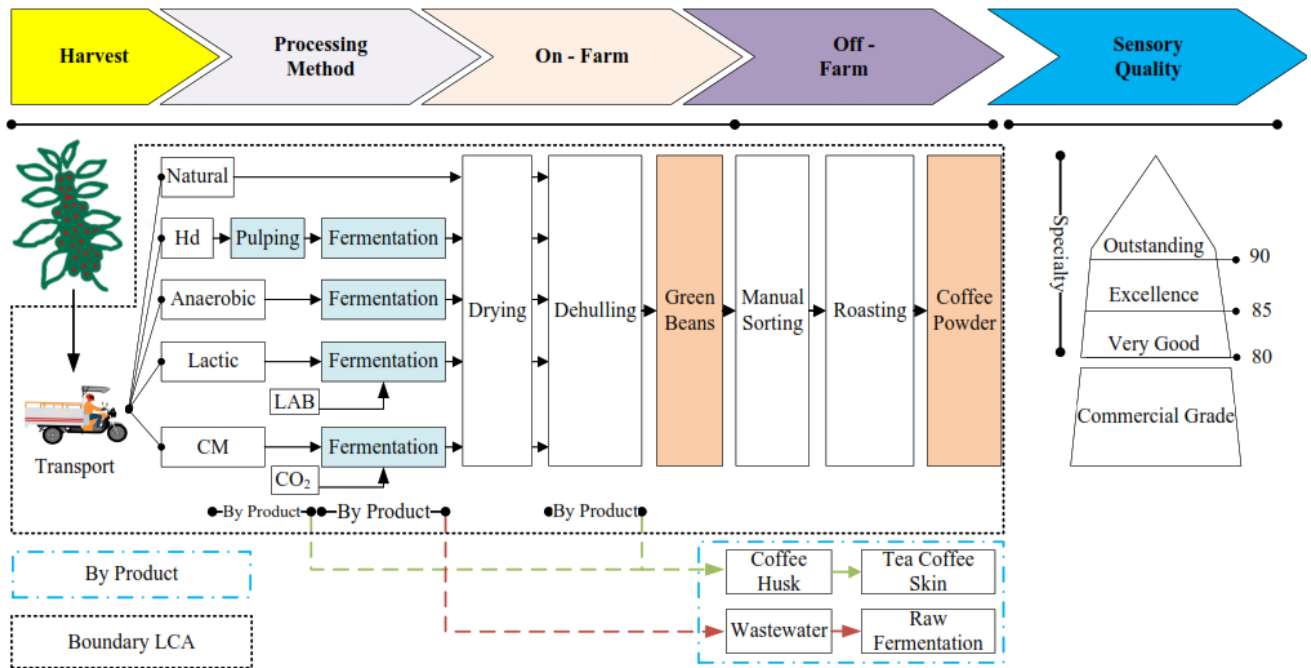


Figure 4.2 Coffee flow process and LCA scope

Figure 4.3 illustrates the anatomy of coffee with detailed processing steps and the corresponding product and by-products. When CB are picked red, and left unprocessed, they will become coffee seedlings. When the CBs were treated, they first go through on-farm processing. The Hd process differed from the other DMs as it required depulping, which involved separation of the cherry skin and pulp (CB-p) from the coffee beans. Afterward, the coffee beans which still have mucilage and parchment skin were dried and dehulled to produce GB and parchment skin. However, in the case of the other DMs, the CB were directly dried, and dehulled to produce GB and coffee husks as by-products. The GB, then went through off farms process where they were roasted. From that step, roasted coffee and silver skin were obtained.

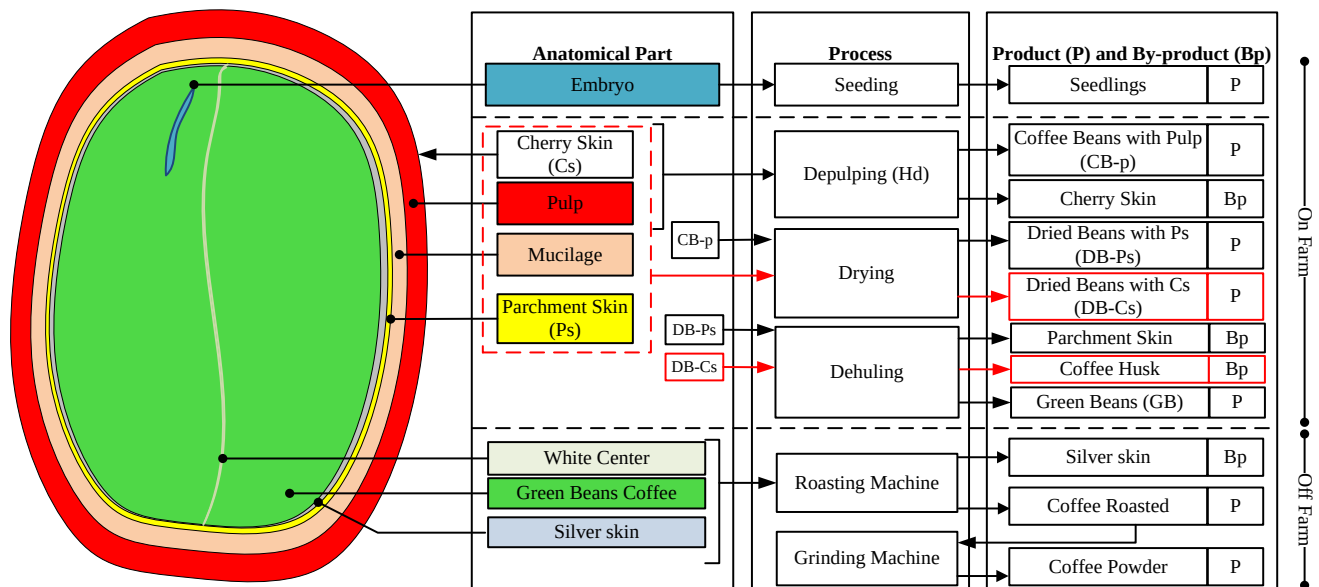


Figure 4.3 Anatomy of CB, processing steps and corresponding product as well as by-product

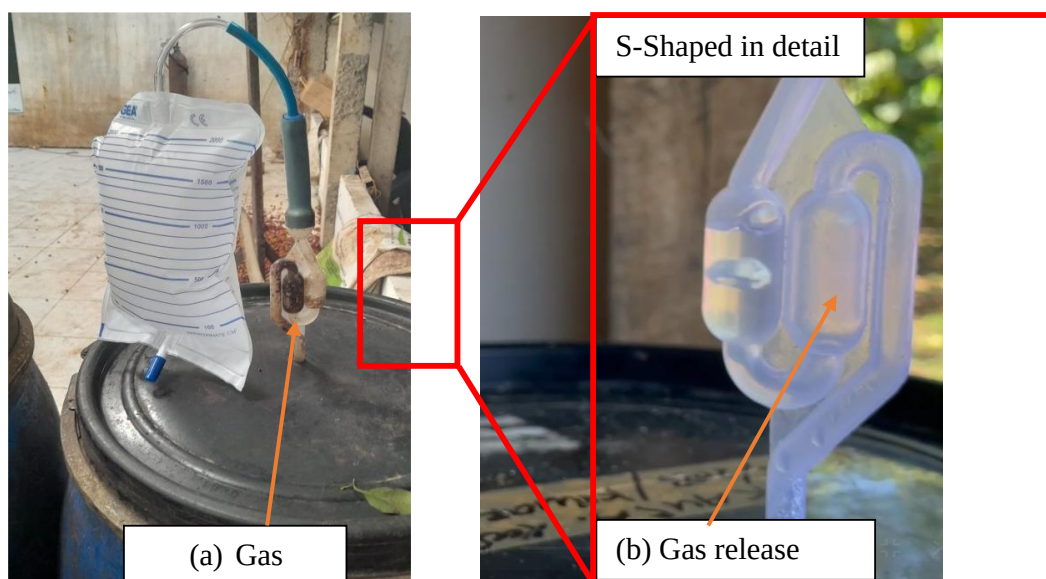


Figure 4.4 (a) Reactor tank with gas capture observation, (b) gas produced during fermentation

In more detail about the processing steps, fermentation was performed in a one-batch process configuration inside full reactor tanks for three days [120][131] at room temperature, without stirring. A plastic reactor with a CB capacity of 150kg/batch was used under oxygen-deprived conditions [132]. The reactor had dimensions of 60 cm in diameter and 115 cm in height, with a capacity to hold 150 kg of CB. Figure 4.4 shows the production of gas coming out of the reactor. As additional parameters for the input data in the LCA, we collected the gas during fermentation and tested for the CO₂, CH₄ and N₂O content Figure 4.4 (a). To capture the gas, the plastic sample bag (capacity 2 Litres) is replaced every 24 hours and sample measurements were carried out daily. For this purpose, we installed an S-shaped airlock Figure 4.4 (b). Additionally, the pH, Brix, Total Dissolve Solid (TDS), and Total Suspended Solid (TSS) were measured in the fermentation wastewater [133].

After fermentation, the CBs went through the drying process. Smallholders rely on sun drying, while larger operations may use mechanical drying. According to SNI, proper drying is crucial for consistent quality, with a variety of mechanical dryers offering efficiency improvements [134]. If it rains, sun drying may take longer. Drying untreated coffee takes longer than drying fermented cherry beans because the cherry skin on the untreated coffee is still fresh and the pulp has not decomposed yet, making it harder for the surface of the fruit to release water vapor. Even though it is relatively easy, drying is an important step. Mold can develop if the drying process takes too long. In this case study, the GBs were sun-dried for 9 to 12 days. The drying bed had dimensions of 1m x 6m, and a capacity to hold 150 kg cherries in layers between 2 and 4cm thick. The target moisture content was 12%, which is within the standard target range between 11 to 14% [131][135][136].

Then, On-Farm DMs continued with the dehulling stage to separate the husk skin or parchment skin, followed by sorting to ensure good quality GBs. Defects in the coffee beans were manually sorted to remove cracked beans, black beans, beans with holes, and others [15], Cracks can be caused by technology or raw materials [137], and optical detection technology is one option for sorting defective coffee [138], although not employed here.

Next, the beans were roasted using a rotary roaster with heating from an LPG burner, for 10-12 minutes to reach a medium roasting temperature between 205 and 210° C. This roasting machine had a vacuum blower to separate the Silver skin and the CR [13]. Finally, the coffee was ground to a coffee powder state, ready to produce coffee drinks at the Off-farm stage.

Two types of products are described based on On-Off farm processing. On-farm processing transforms the CB to the GB, while Off-farm is the processing from the GB to the Coffee Powder (CP). The quality sensor shall determine the coffee product category. Specialty coffees have grades over 80.

4.3 Environmental impact analysis

For impact analysis, this work used SimaPro v9.3.0.3, and the ReciPe 2016 midpoint level (ML) method was applied [44][13]. Through direct observation and measurement, coffee production and fuel consumption data were obtained and used for LCA. The study considered contributions of $\geq 1\%$, outlining the sources from each stage of the process, in accordance with typical cut-off requirements [139]. The following steps were then performed to complete the LCA.

1. Goal and Scope

In this study, we have meticulously collected and analyzed harvest data from 2022. The average yield per hectare reached 2,950 kg/ha/year of cherry beans, resulting in an average of 580 kg/ha/year of GB. For dry processing, this group uses a 150 kg/batch capacity reactor for fermentation. The DM was chosen as the harvest capacity increased and in response to market demand. The functional unit (FU) is based on a 10-hectare pilot plant. Results were reported on the impacts per kilogram of CP. The GWP from the DMs was calculated and compared as the primary indicator. Production and processing data were used to model and design alternatives for the pilot-scale implementation of sustainable specialty coffee bean production.

2. Inventory analysis

The harvest data inventory for the year 2022 was conducted through observation and experimentation in the Andungsari Coffee Group, Bondowoso, East Java, Indonesia. Harvest data from March to September were utilized. The average number of coffee plants and coffee shade trees was the same as in the previous year's study [130]. However, this research focused on dry processing, considering CB transportation handling, fermentation, dehulling, roasting, and grinding. Fuel consumption during coffee processing was measured as part of the inventory process. Table 4.1 displays petrol, LPG, and electricity consumption at each stage.

Table 4.1 Parameters to quantity fuel consumption at each stage

Stages Process	Tools Specification	N	HD	A	L	CM
Harvesting	Motorcycle (100kg/batch), MJ	31.40	31.40	31.40	31.40	31.40
Pulping	Petrol Engine 5Hp, 200kg/h, MJ		20.41			
Fermentation	CO ₂ injection, kg					1.5
Dehulling	Petrol Engine 5Hp, 200kg/h, MJ	14.13	7.20	14.24	14.26	14.44
Grading Size	Electric 0.5kW, 50kg/h, kWh	0.28	0.28	0.28	0.28	0.29
Roasting Coffee	Electric 1kW, 10kg/h, kWh	1.17	1.18	1.18	1.19	1.26
	LPG 0.75 kg/h	1.96	1.97	1.96	1.98	2.10
Grinder Coffee	Electric 0.5kW, 40kg/h, kWh	0.33	0.33	0.33	0.33	0.35

N=Natural; HD=Hydro honey; A=Anaerobic; L=Lactic; CM=Carbonic Maceration
Data measured

3. Impact assessment

Based on primary data on coffee production inputs and outputs, and with the application of emission factors (for example) where necessary, and secondary data for impact analysis, the data inventory was compiled and used for impact assessment in the SimaPro software. The ReCipe (2016) midpoint level (ML) method was applied. Fuel consumption was calculated with characteristic factors. Furthermore, fermentation was carried out for dry processing, during which fermentation gas products such as CO₂, CH₄, and N₂O is captured. Gas captured during fermentation was stored in plastic gas storage and tested at the Agricultural Laboratory, Pati Agricultural Laboratory Centre, Central Java, Indonesia. Fermentation is carried out for three days, and every day, the gas is collected to assess gas production for impact analysis considerations. Wastewater from fermentation was also tested for Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), TSS, and pH at the Agricultural Technology Laboratory, Jember University. While many other studies do not consider wastewater in their impact assessments, this work found a significant impact of biogenic CO₂ from wastewater with the following correction factors in Table 4.2.

Table 4.2 Factor correction to calculate CO₂ from wastewater

Parameter	Factor [107]	Unit
MCF _{ww}	0	
λ	0.65	
CF _{CO2}	1375	mg
BG	0.65	

To support for solving input database from wastewater calculate [107]:

$$CO_2 = 10^{-6} \times Q_{ww} \times COD \times Eff_{BOD} \times CF_{co2} \times [(1 - MCF_{ww} \times BG) \times (1 - \lambda)] \quad (1)$$

Therefore:

$$CO_2 = \text{Estimated } CO_2 \text{ emission rate (mg/batch)}$$

$$Q_{ww} = \text{Wastewater produce (mg/batch)}$$

Eff_{BOD}	= Oxygen demand removal efficiency
CF_{CO_2}	= Conversion factor for maximum CO_2
MCF_{ww}	= Correction factor wastewater treatment
BG	= Fraction of carbon
λ	= Biomass yield

4. Interpretation

In this phase, we compared five processes: Natural, Hd, Anaerobic, Lactic, and CM. The fermentation stage contributes to wastewater and gas. Although the fermentation stage is categorized as biogenic waste [140], the threshold for wastewater needs to be considered. Therefore, as a part of coffee production, dry processing methods need to identify their environmental impact. Through this study, we also consider the valorization of waste skin that can be utilized to add-value to waste as a by-product and potential step towards zero-waste [8].

4.4 Comparison mass balance from dry methods coffee processing

4.4.1 Yield from different dry processing

Yields from various DM processing are important for input-output in the LCA data inventory. The mass balance is used for the GWP analysis of each of the treatment stages. Table 4.3 compares the input and output during the different coffee processing. In terms of input, Hd differs from the other DMs because 50L of water were added during fermentation.

In terms of efficiency and by-products, the Natural method appears to be efficient with high yields of dried beans (67.5 kg) and fewer process steps involving less water and chemicals. It produces a significant amount of coffee husk (39.8 kg) during dehulling.

The Hd method involves significant water use during fermentation, producing considerable wastewater (47.0 kg). It has the lowest output of dried beans (34.4 kg) but results in a substantial amount of de-pulped coffee (70.2 kg) and cherry skin (79.8 kg).

Anaerobic and Lactic methods are similar in outputs, producing high amounts of wet fermented coffee (137.5 kg and 136.5 kg, respectively) and significant amounts of coffee husk (40.1 kg and 40.4 kg). The Lactic method uses lactic acid bacteria, introducing an additional biological component, which may explain the fact that wastewater from the Lactic method (15.5 kg) is higher than that from the Anaerobic method (12.5 kg).

CM involves CO_2 and has a slightly higher output of grade beans (28.0 kg) and roasted beans (22.9 kg) compared to others. It generates the least defective beans (0.8 kg) and the highest yield of dried beans (69.0 kg), making it efficient but slightly more complex due to the use of CO_2 . Overall, the outputs for the studied DMs differed up until the drying step due to variations in fermentation conditions and inputs across the different DM processes. However, after drying and sorting, the outputs of final CP were similar across all methods, ranging between 22.4 and 22.8kg.

Table 4.3 Comparison of the dry methods in input and output during coffee processing

Steps	Input - Output	Amount (kg)				
		N	Hd	A	L	CM
Handpicking	Input					
	Cherry Coffee	150.0	150.0	150.0	150.0	150.0
	CO ₂	-	-	-	-	1.5
	Lactic Acid Bacteria	-	-	-	2.0	-
	Water					
Pulping	(Fermentation)	-	50.0	-	-	-
	Output					
	De-pulping	-	70.2	-	-	-
	Cherry skin	-	79.8			
	Wet Fermented	-	73.2	137.5	136.5	134
Fermentation	Wastewater		47.0	12.5	15.5	16.0
	Dried beans	67.5	34.4	68.0	68.1	69.0
Dehulling	Dehulled beans	27.8	27.8	27.9	27.8	28.8
	Coffee skin	-	31.0	-	-	-
	Coffee husk	39.8	-	40.1	40.4	40.2
	Parchment	-	6.6	-	-	-
	Grade beans	26.1	26.2	26.2	26.4	28.0
Sortation	Defect GB	1.6	1.5	1.1	1.4	0.8
	Roasted beans	22.8	22.8	22.8	23.4	22.9
Roasting	Silver skin	1.0	1.1	1.1	1.1	1.2
	Coffee powder	22.7	22.7	22.7	22.8	22.4
Grinding						

N=Natural; Hd=Hydro honey; A=Anaerobic; L=Lactic; CM=Carbonic Maceration

*Data were measured

4.5 Coffee fermentation, gas release and wastewater

Quantifying gas release during fermentation is essential to evaluate the environmental impact of the processes. The natural processing method, which does not involve fermentation, was not included in this section. Table 4.4 shows the total gas produced during three days of fermentation for the different coffee processing methods that required fermentation, focusing on CO₂, CH₄, and N₂O emissions. The Anaerobic method produced the least CO₂ at 8.6 mg, while Hd, Lactic, and CM methods produced 150.3 mg, 566.2 mg, and 934.5 mg of CO₂, respectively.

Methane emissions were fairly consistent among the methods, except for Lactic, which emitted 0.0155 mg. For the other DMs, Anaerobic released 0.0087 mg, Hd emitted 0.0083 mg and CM emitted 0.0090 mg. In contrast, nitrous oxide emissions varied more significantly. Anaerobic emitted 5.7 mg, Hd emitted 6.4 mg, Lactic emitted 13.9 mg, and CM emitted 28.6 mg.

Table 4.4 Total gas produce during fermentation

Process	Gas released (mg)		
	CO ₂	CH ₄	N ₂ O
Anaerobic	8.6	0.0087	5.7
Hd	150.3	0.0083	6.4
Lactic	566.2	0.0155	13.9
CM	934.5	0.0090	28.6

*Data measured

To undertake the LCA, the gas concentrations were converted to mass of emissions. To do this, the gas pressure was assumed to be atmospheric pressure (unfortunately the gas pressure was not measured in all processes for this specific experiment, but the pressure of CM was taken as indicative, with a range of 50-100 mbar (gauge), and it was therefore estimated to be a reasonable assumption). In terms of environmental impact, the CM method has the highest emissions of both CO₂ and N₂O, indicating a considerable environmental impact. The Lactic method also shows high emissions, particularly of CO₂ and N₂O. The Hd method produces moderate CO₂ and N₂O emissions with low CH₄ emissions. The Anaerobic method is the most environmentally friendly, with the lowest levels of all gases.

In more detail, Figure 4.5 illustrates the release of (a) CO₂, (b) CH₄ and (c) N₂O gases during fermentation across different coffee processing methods: Anaerobic, Hd, Lactic, and Carbonic Maceration (CM).

In the (a) CO₂ graph, the CM method exhibits the highest emissions, followed by the Lactic method, the Hd, and the Anaerobic method. This indicates that CM and Lactic methods, which were more intensive in terms of fermentation, resulted in significantly higher CO₂ emissions. The Anaerobic method, with the lowest CO₂ emissions, suggests a more controlled and less oxidative fermentation process.

For CH₄ emissions (b), the differences among the methods are less pronounced compared to CO₂. The Lactic method shows slightly higher CH₄ emissions than the other methods, while the Hd and CM methods have similar lower levels, and the Anaerobic method is slightly higher than Hd and CM but lower than Lactic. This suggests that methane production is not as heavily influenced by the type of fermentation process as CO₂.

In the N₂O graph (c), the CM method again shows the highest emissions, followed by the Lactic, Hd, and Anaerobic methods. This pattern highlights the intensive nature of CM and Lactic fermentations, which produce significantly more nitrous oxide. The relatively low N₂O emissions from the Anaerobic method further reinforce its environmental advantages.

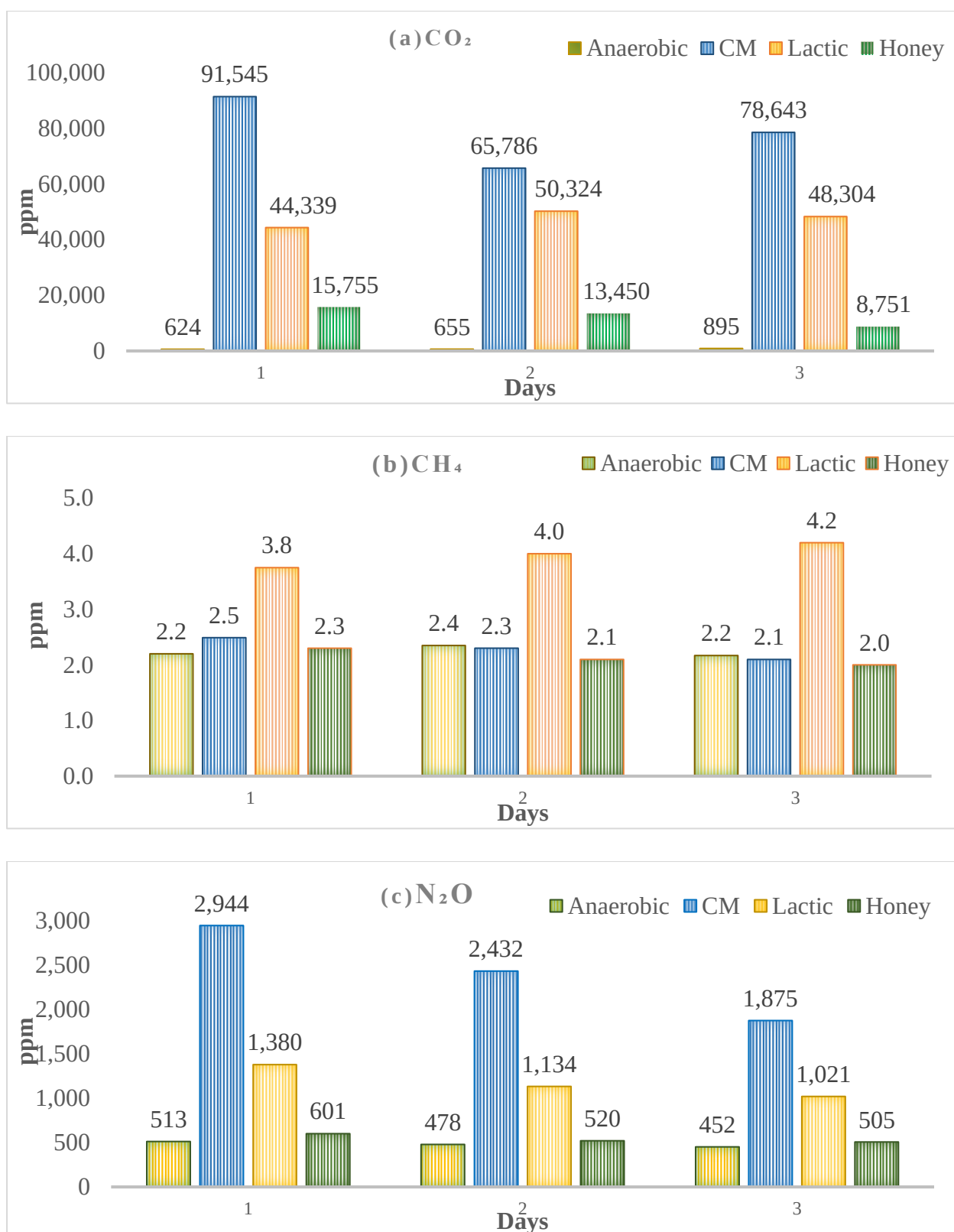


Figure 4.5 (a) CO₂, (b) CH₄, and (c) N₂O gas released during fermentation

Table 4.5 compares the properties of wastewater produced during the fermentation stage of different dry coffee processing methods: Anaerobic, CM, Lactic, and Hd. The Lactic method produces wastewater with the highest levels of COD, BOD, and TSS, indicating significant environmental

impact due to the high organic load and particulate matter. Its low pH further suggests a more acidic wastewater, which can be harmful to aquatic life.

Table 4.5 Comparison of wastewater properties during fermentation in dry methods

Properties*	Units	A	CM	L	Hd
Chemical Oxygen Demand (COD)	mg/L	9,850	10,400	11,950	6,700
Biological Oxygen Demand (BOD)	mg/L	5,642	6,444	7,248	4,844
Total Suspended Solid (TSS)	mg/L	145	151	257	134
pH		4.1	3.9	3.8	4.2

N=Natural; Hd=Hydro honey; A=Anaerobic; L=Lactic; CM=Carbonic Maceration

*Data measured

The CM method, while slightly better than Lactic in terms of COD and BOD, still produces high levels of organic pollutants and suspended solids, and also results in acidic wastewater. The Anaerobic method shows moderate levels of COD, BOD, and TSS, with a slightly acidic pH. This suggests a relatively lower environmental impact compared to CM and Lactic methods.

The Hd method has the lowest levels of COD, BOD, and TSS, and the highest pH, making it the most environmentally friendly option among the methods studied. Its wastewater is less polluted with organic matter and particulates and is less acidic, posing a lower risk to the environment.

Overall, the Hd method has the lowest levels of COD, BOD, and TSS, and the highest pH, making it the most environmentally friendly option among the DMs involving fermentation. Its wastewater is less polluted with organic matter and particulates and is less acidic, posing a lower risk to the environment.

4.6 Life cycle impact characterization

Table 4.6 provides a comparative analysis of the environmental impact categories for different dry coffee processing methods, from CB to CP. The methods assessed are Natural, Anaerobic, Lactic, Hd, and CM. Each method's impact is measured across several categories, including GWP, ODP, and other key environmental indicators. (Values indicated per kilogram of CP).

Global Warming Potential (GWP)

The GWP measures the potential of greenhouse gases to trap heat in the atmosphere. The Lactic method has the highest GWP at 1.168 kg CO₂-eq, indicating a significant contribution to climate change. The Natural method has the lowest GWP at 0.676 kg CO₂-eq, making it the most climate-friendly option.

Stratospheric Ozone Depletion Potential (ODP)

ODP indicates the potential for substances to deplete the ozone layer. The Lactic method shows the highest ODP at 3.34 x 10⁻⁷ kg CFC¹¹-eq, while the Natural method has the lowest ODP at 2.1 x 10⁻⁷ kg CFC¹¹-eq. The differences among the methods are relatively small but still noteworthy.

Ionizing Radiation Potential (IRP)

IRP measures the potential impact of ionizing radiation on human health and the environment. The Lactic method has the highest IRP at 0.027 kBq Co-60_{eq}, whereas the Natural, Anaerobic, and Hd methods all have an IRP of 0.008 kBq Co-60_{eq}, showing less impact.

Ozone Formation, Human Health (HOFP) and Terrestrial Ecosystems (EOFP)

Both HOFP and EOFP assess the potential of precursor emissions to form ground-level ozone, which affects human health and ecosystems. The Lactic and Hd methods have higher values (0.002 kg NO_x_{eq}) for HOFP and EOFP compared to Natural and Anaerobic methods, indicating more significant impacts on human health and terrestrial ecosystems.

Fine Particulate Matter Formation (FPMF)

FPMF measures the impact of fine particulate matter on air quality and human health. The Lactic method shows the highest FPMF at 0.002 kg PM_{2.5}_{eq}, while other methods are at 0.001 kg PM_{2.5}_{eq}, indicating less pollution.

Terrestrial Acidification Potential (TAP)

TAP evaluates the potential of acidifying pollutants to affect soil and water bodies. The Lactic method has the highest TAP at 0.002 kg SO₂_{eq}, while other methods have a TAP of 0.001 kg SO₂_{eq}, indicating a lower impact.

Eutrophication Potentials (FEP and MEP)

Eutrophication potentials assess nutrient enrichment in freshwater (FEP) and marine environments (MEP). The Lactic method has the highest FEP (5.3×10^{-4} kg P_{eq}) and MEP (1.9×10^{-5} kg N_{eq}), suggesting significant contributions to water pollution.

Ecotoxicity Potentials (TETP, FETP, METP)

Ecotoxicity potentials measure the impact of toxic substances on terrestrial (TETP), freshwater (FETP), and marine environments (METP). The Lactic method exhibits the highest values in all three categories, indicating greater potential for environmental harm.

Human Toxicity Potentials (HTPc and HTPnc)

Human toxicity potentials evaluate the potential impact of toxic substances on human health, both carcinogenic (HTPc) and non-carcinogenic (HTPnc). The Lactic method again shows the highest impacts, particularly for HTPnc at 0.562 kg 1,4-DCB.

Land Use (LOP)

LOP measures the potential impact on land use. The Lactic method has the highest LOP at 0.014 m² a crop eq, indicating a higher impact on land resources.

Mineral and Fossil Resource Scarcity (SOP and FFP)

SOP assesses the scarcity of mineral resources, and FFP measures fossil resource depletion. The Lactic method has the highest SOP (5.6×10^{-4} kg Cu_{eq}) and FFP (0.344 kg oil_{eq}), showing greater resource consumption.

Water Consumption Potential (WCP)

WCP evaluates the amount of water used in the process. The Lactic method has the highest water consumption at 0.0063 m³, indicating a significant use of water resources.

Altogether, the Lactic method consistently showed higher environmental impacts across almost all categories, indicating that it is the least sustainable option among the methods assessed. Its high values in GWP, ODP, and other categories highlight significant contributions to climate change, ozone depletion, and resource depletion. In contrast, the Natural method generally shows the lowest impacts, making it the most environmentally friendly option. The Anaerobic and CM methods fall in between, with moderate impacts across most categories.

Table 4.6 Impact category through dry method for CB to CP

Impact category	Unit	Processing CB to CP				
		Natural	Anaerobic	Lactic	Hd	CM
GWP	kg CO ₂ eq	0.676	0.702	1.168	0.788	0.713
ODP	kg CFC ¹¹ eq	2.1 x 10 ⁻⁷	2.19 x 10 ⁻⁷	3.34 x 10 ⁻⁷	2.4 x 10 ⁻⁷	2.2 x 10 ⁻⁷
	kBq Co-					
IRP	60 _{eq}	0.008	0.008	0.027	0.008	0.009
HOFP	kg NO _x eq	0.001	0.001	0.002	0.002	0.001
FPMF	kg PM _{2.5} eq	0.001	0.001	0.002	0.001	0.001
EOFP	kg NO _x eq	0.001	0.002	0.002	0.002	0.002
TAP	kg SO ₂ eq	0.001	0.001	0.002	0.001	0.001
FEP	kg P _{eq}	1.1 x 10 ⁻⁴	3.1 x 10 ⁻⁴	5.3 x 10 ⁻⁴	4.6 x 10 ⁻⁴	3.9 x 10 ⁻⁴
MEO	kg N _{eq}	3.5 x 10 ⁻⁶	3.7 x 10 ⁻⁶	1.9 x 10 ⁻⁵	3.6 x 10 ⁻⁶	3.8 x 10 ⁻⁶
TETP	kg 1,4-DCB	0.952	1.004	2.570	1.161	0.988
FETP	kg 1,4-DCB	0.003	0.003	0.015	0.003	0.003
METP	kg 1,4-DCB	0.005	0.005	0.021	0.005	0.005
HTPc	kg 1,4-DCB	0.003	0.003	0.018	0.003	0.003
HTPnc	kg 1,4-DCB	0.284	0.296	0.562	0.348	0.294
LOP	m ² a crop _{eq}	0.008	0.009	0.014	0.009	0.009
SOP	kg Cu _{eq}	2.3 x 10 ⁻⁴	2.5 x 10 ⁻⁴	5.6 x 10 ⁻⁴	2.6 x 10 ⁻⁴	2.4 x 10 ⁻⁴
FFP	kg oil _{eq}	0.176	0.182	0.344	0.192	0.187
WCP	m ³	0.0003	0.0003	0.0063	0.0025	0.0003

GWP=Global warming potential; ODP=Stratospheric ozone depletion; IRP=Ionizing radiation; HOFP=Ozone formation, Human health; FPMF=Fine particulate matter formation; EOFP=Ozone formation, Terrestrial ecosystems; TAP=Terrestrial acidification; FEP=Freshwater eutrophication; MEP=Marine eutrophication TETP=Terrestrial ecotoxicity; FETP=Freshwater ecotoxicity; METP=Marine ecotoxicity; HTPc=Human carcinogenic toxicity; HTPnc=Human non-carcinogenic toxicity; LOP=Land use; SOP=Mineral resource scarcity; FFP=Fossil resource scarcity; WCP=Water consumption.

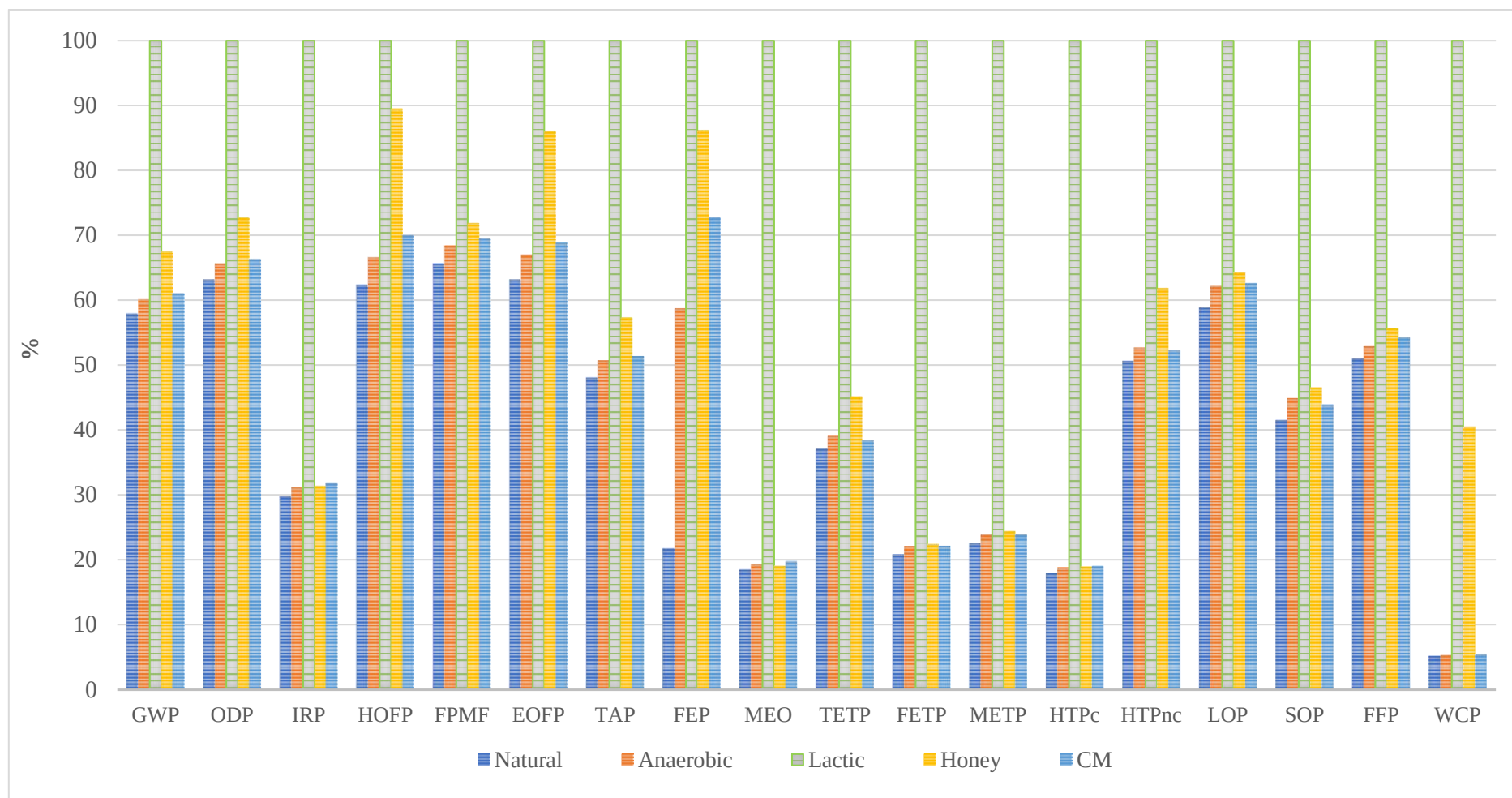


Figure 4.6 Impact categories dry method coffee process

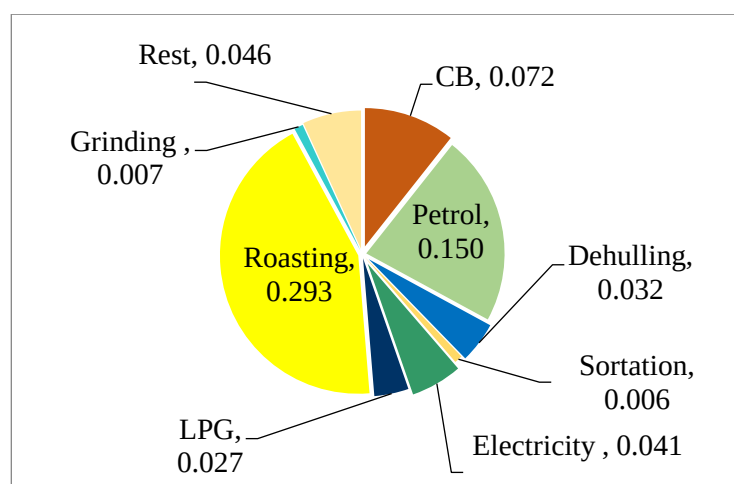


Figure 4.7 Impact characterization of natural in terms of GWP

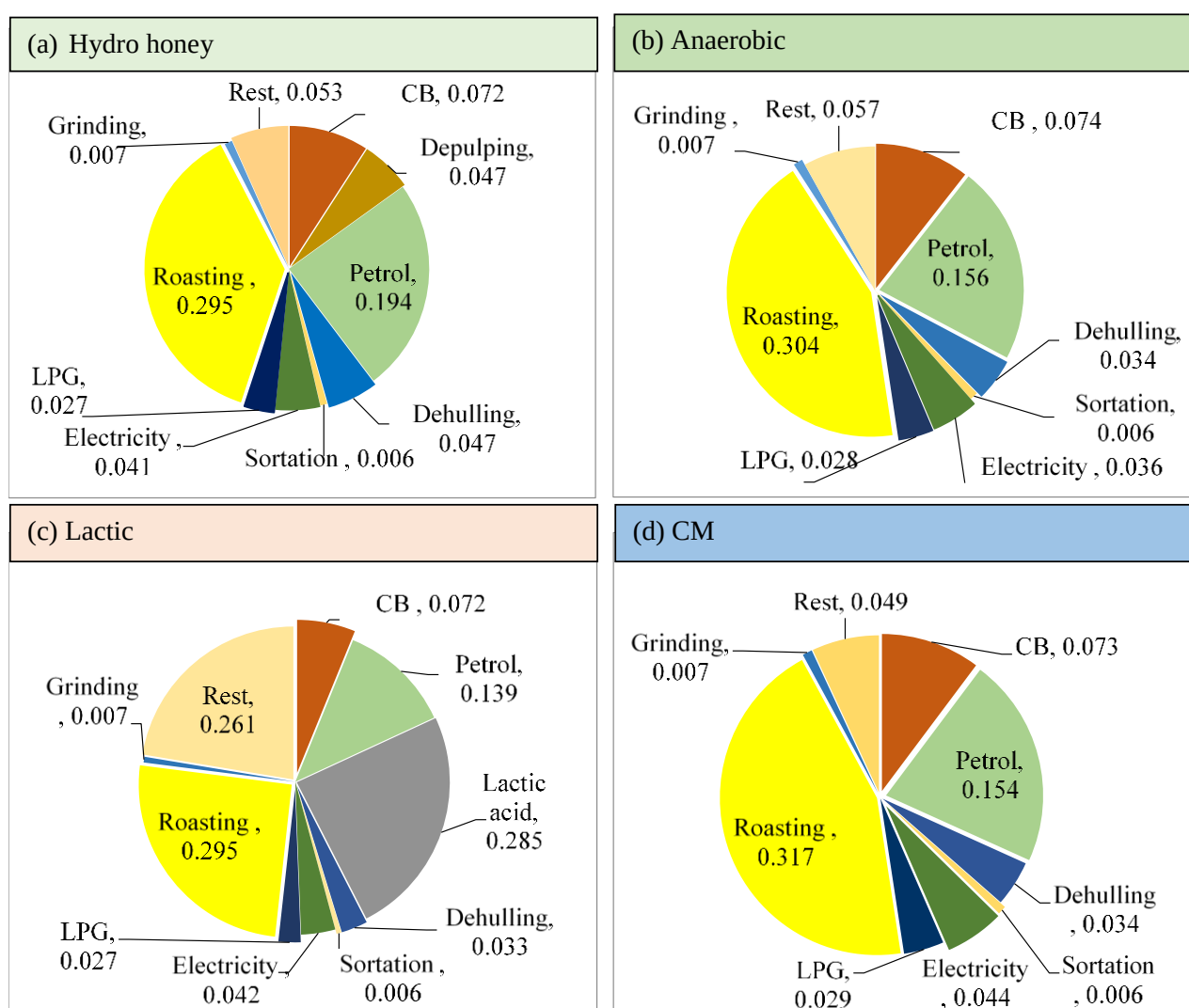


Figure 4.8 Impact characterization of Hydro honey (a), Anaerobic (b), Lactic (c) and (d) CM Processing in terms of GWP

Figure 4.6 shows the impact categories in percentage of the highest impact. It confirms that Lactic contributes with the highest impact in all categories. Aside from the Lactic method, the other dry coffee processing methods—Natural, Anaerobic, Hd, and CM—show varying degrees of environmental impact across different categories. Comparatively, the Natural method consistently presents the lowest values across many environmental impact categories. This suggests that the Natural method has the least environmental impact among the dry coffee processing methods assessed. For example, in categories like GWP, HOFp and EOFp, the Natural method typically exhibits the lowest values, indicating lower emissions of greenhouse gases and reduced potential for ground-level ozone formation compared to other methods.

The Anaerobic and CM methods generally fall in between the Natural and Lactic methods, displaying moderate environmental impacts across most categories. While they may not have as low an environmental impact as the Natural method, they also do not exhibit the consistently high values seen with the Lactic method. The Hd method often shows values closer to the Natural method, indicating relatively lower environmental impacts compared to Lactic, Anaerobic, and CM methods, but not as low as the Natural method.

These findings suggest that while the Lactic method tends to have the highest environmental impact among the dry coffee processing methods assessed, the Natural method tends to be the lowest impact, while the other methods—Anaerobic, Hd, and CM—offer varying degrees of environmental friendliness. Producers can use this information to make informed decisions about which processing methods to adopt, considering factors such as environmental sustainability, flavor profile, and processing efficiency.

For further details on the impact source, the pie chart in Figure 4.7 illustrates the Global Warming Potential (GWP) impact of various steps in Natural process. Roasting has the highest impact at 0.293kg CO₂-eq/kg, followed by petrol usage at 0.015kg CO₂-eq/kg. CB, a specific material or chemical, contributes 0.072kg CO₂-eq/kg, while electricity usage accounts for 0.041kg CO₂-eq/kg. The "Rest" category, including minor steps, contributes 0.046kg CO₂-eq/kg. Dehulling and LPG use contribute 0.032kg CO₂-eq/kg and 0.027kg CO₂-eq/kg, respectively. Grinding and sortation have minimal impacts at 0.007kg CO₂-eq/kg and 0.006 kg CO₂-eq/kg. The main contributors to GWP are roasting and petrol usage, indicating a focus area for reducing the environmental footprint of Natural.

Figure 4.8 illustrates the GWP impact of various steps in four processes: Hydro honey (a), Anaerobic (b), Lactic (c), and CM Processing (d). The Hd, Anaerobic, and CM showed similar tendency than for Natural, with roasting contributions the most and varying from 0.293 – 0.317 kg CO₂-eq/kg CP. The second area of contributions for Hd, Anaerobic, and CM was petrol varying from 0.139 – 0.195 kg CO₂-eq/kg CP. The following areas of contribution for all methods were CB and electricity, and their value were comparable thought the DMs. The pattern for Lactic is different from the other process as the lactic acid produce during fermentation contributes to 0.285 kg CO₂-eq/kg CP. This might be another reason why overall environmental impact from lactic was so high.

4.7 Comparison between GWP and total energy consumption

The energy resources used by this group of smallholders were fuel (petrol and LPG), and local electricity. Table 4.7 compares various dry coffee processing methods in terms of their GWP On – Off Farm, as well as their total energy consumption from CB to CP. The methods evaluated include Natural, Anaerobic, Hydro honey, Lactic, and CM processing.

For the Natural process, the on-farm GWP is 0.302 kg CO_{2-eq}/kg GB, the off-farm GWP is 0.676 kg CO_{2-eq}/kg CP, and the total energy consumption is 147.79 MJ. This process has a relatively low on-farm GWP and moderate off-farm GWP, with the lowest total energy consumption among the methods.

For the Anaerobic process, the on-farm GWP is 0.306 kg CO_{2-eq}/kg GB, but it has a slightly higher off-farm GWP than Natural, at 0.702 kg CO_{2-eq}/kg CP, and similar total energy consumption at 148.23 MJ. The Hydro honey process shows an increase in both on-farm and off-farm GWP, with values of 0.407 kg CO_{2-eq}/kg GB and 0.788 kg CO_{2-eq}/kg CP, respectively. It also has the highest total energy consumption at 161.81 MJ, indicating more energy-intensive processing steps. The Lactic process has the highest GWP with 0.577 kg CO_{2-eq}/kg GB on-farm and 1.168 kg CO_{2-eq}/kg CP off-farm, but its total energy consumption is 149.00 MJ. This suggests that the fermentation process produces significant greenhouse gases. The CM process, with an on-farm GWP of 0.310 kg CO_{2-eq}/kg GB, and off-farm GWP is 0.713 kg CO_{2-eq}/kg CP, and its total energy consumption is 155.58 MJ, indicating that later stages of processing or transportation are more emission-intensive.

Overall, the Natural, Anaerobic and CM processes have the lowest on-farm GWP, indicating less energy-intensive initial processing. The Hd process has higher GWP and energy consumption, likely due to more intensive processing. The Lactic process, despite moderate energy usage, has the highest GWP due to significant emissions and by-products from fermentation. The CM process, while efficient on-farm, shows higher off-farm emissions. Optimizing these methods should focus on reducing emissions and energy use, especially in the more impactful stages.

Table 4.7 Comparison of the dry methods in their Global Warming Potential (GWP) On- and off-farm, as well as in their total energy consumption

No	Coffee Process	On-farm (kg CO _{2-eq} /kg GB)	Off-farm (kg CO _{2-eq} /kg CP)	Total Energy CB to CP (MJ)
		CB to GB	CB to CP	
1	Natural	0.302	0.676	147.79
2	Anaerobic	0.306	0.702	148.23
3	Hydro honey	0.407	0.788	161.81
4	Lactic	0.577	1.168	149.00
5	CM	0.310	0.713	155.58

CB=Cherry Beans, GB=Green Beans, CP=Coffee Powder, MJ=Mega Joule.

*Data calculation

4.8 Conceptual frameworks

This study has identified several key elements that can be directly applied to enhance the sustainability performance of specialty coffee production. The LCA findings presented in Table 4.68 reveal that the Lactic method had the highest environmental impact among the assessed dry coffee processing methods. In contrast, the Natural, Anaerobic, Hd, and CM methods offer varying degrees of environmental friendliness. While the Lactic method may offer certain benefits in terms of flavor or processing efficiency, it comes with a trade-off of higher environmental costs. This highlights the importance of considering sustainability factors when selecting coffee processing methods and

emphasizes the need for producers to strike a balance between quality, flavor enhancement, and environmental responsibility.

The visual in Figure 4.6 visually represents the environmental trade-offs inherent in different coffee processing methods. While certain methods may offer unique flavors, their environmental costs must be carefully considered. The Natural method emerged as a more sustainable choice for coffee production due to its lower environmental footprint.

In terms of gas produced during fermentation, Anaerobic method is the most sustainable, with significantly lower emissions compared to the other methods. In contrast, the CM and Lactic methods, while producing unique flavors, resulted in higher greenhouse gas emissions, confirming the need for balancing quality and environmental impact in coffee processing. While previous studies did not measure and account in the LCA the gas produced during fermentation [40], this work considers these parameters to be part of the LCA analysis. This increases the novelty as well as the reliability of the results from this work.

The environmental impact of wastewater from fermentation varies significantly across coffee processing methods. The Lactic method has the most considerable impact, while the Hd method is the least harmful. These differences underscore the importance of selecting appropriate processing methods to minimize environmental damage, particularly in terms of wastewater management. When wastewater is discharged into the environment, it can potentially reduce water availability and generate groundwater pollution [94], due to COD and BOD content in wastewater [141], TSS and pH. The limitation standard in Indonesia for COD, BOD, TSS and pH of wastewater from coffee processing are 200mg/L, 90mg/L, 150mg/L, and 6 – 9, respectively [142]. The values obtained for Anaerobic, CM, Lactic and Hd did not fall into these standards, and thus, their wastewater shall be diluted and corrected in pH before being discarded. Interestingly, wastewater from coffee by-products can be used as raw material for biogas [13], although gas can also be released in the fermentation stages. Therefore, instead of throwing away the wastewater, it can be reused for energy production. Another opportunity is to produce alcoholic beverage or bioethanol from the wastewater.

Each processing method varies in its environmental impact. The Natural and Anaerobic processes demonstrated the lowest on-farm Global Warming Potential (GWP), indicating less energy-intensive initial processing. In contrast, the Hd process exhibits higher GWP and energy consumption, likely due to more intensive processing. Despite moderate energy usage, the Lactic process has the highest GWP, primarily due to significant emissions from fermentation, and by-production of lactic acid. The CM process, while efficient on-farm, shows higher off-farm emissions. Optimizing these methods should focus on reducing emissions and energy use, especially in the more impactful stages identified.

All methods considered, the processing elements with the most significant impact on GWP are roasting and petrol usage, indicating that energy-intensive processes and fossil fuel consumption are major contributors to the environmental footprint. Efforts to reduce GWP could focus on improving energy efficiency, utilizing renewable energy sources, and optimizing processes to minimize fossil fuel dependence. The use of biogas produced from waste streams was identified as a potential option, according to previous research [97]. In 2020, several coffee processing technologies were applied in pilot plants to improve the quality of coffee beans [13]. These include skin peeling machines, sorting equipment, coffee roasting machines, and biogas digesters as simple IE solutions. Solar

panels are also considered as a substitute energy source for fossil gas and electricity. The waste product of coffee skin has been applied into coffee tea (cascara) from cherry skin and husk skin, the remaining waste (husk powder) potentially as briquettes [8]. In future studies, the utilization of wastewater from wet and dry methods for raw material to produce biogas, with slurry from reactors to be used for organic fertilizer, solid waste as fertilizer or animal feed, will be considered, and it is anticipated that most of the waste that exists today can be reduced through conversion into useful products. The integration of these solutions will be the focus of future work. Intercropping in plantations is another strategy that has helped farmers to increase the use of organic fertilizers sustainably, obtain animal feed sustainably, and in LCA this can lead to allocation requirements, which are not currently considered. Another solution to reduce the total annual emissions would be to rotate the DM procedures throughout the year.

Finally, Table 4.8 compares the results of this study with previous studies, where it appears that there are various GWP estimates in various functional units that are different from the ReCiPe (2016) database at the Midpoint Level (ML) level. In general, there are 3 stages considered, which end in roasted coffee or coffee powder: CB production; CB to GB; GB to CR to CP. Sometimes all these stages have been examined and determined, sometimes only one or a few stages are considered. In this study, we reveal GWP at each stage, as well as overall (CB to CP). Previous studies have also highlighted some useful alternatives to reducing emissions, revealing various GWP estimates across different functional units, diverging from the ReCiPe (2016) database at the ML.

In a previous investigation on coffee production [143], emissions from CB harvest in an experimental agro-industrial coffee in Jember were analyzed. Organic Arabica plantations were found to emit 0.29 kg CO_{2-eq}/kg CB during CB harvest, approximately 0.336 kg CO_{2-eq}/kg GB during CB to GB conversion, and about 2.794 kg CO_{2-eq}/kg CP during CB processing to CP [143]. Conversely, conventional plantations in Ijen were found to emit 1.8 kg CO_{2-eq}/kg GB during CB to GB conversion [16]. Comparison two different energy source in coffee processed from GB to CP was reported as 0.318 kg CO_{2-eq}/kg CP with solar panel energy source, 0.744 kg CO_{2-eq}/kg CP Using local hydro energy sources [35]. Similarly, coffee processing from CB to GB in Vietnam resulted in emissions ranging from 16.04 to 14.1 kg CO_{2-eq}/kg GB in conventional and integrated farming, respectively [111], higher than the findings in the current study (0.302 – 0.670 kg CO_{2-eq}/kg GB) using the dry methods, and previous study between 0.473 and 0.568 kg CO_{2-eq}/kg GB using wet methods [130].

Comparison with previous research highlights disparities in methodologies, geographical locations, and farming practices, impacting reported carbon emission values. Variability in data collection methods, boundary definitions, and the inclusion of different life cycle stages further contribute to discrepancies.

The use of different LCA methodologies, including calculated values and software like SimaPro, introduces further variability in reported results. Understanding these variations is crucial for accurately assessing and addressing the environmental impact of coffee production. Geographical and farming practice variations significantly influence carbon emissions, with factors such as climate, soil conditions, agricultural inputs, and regional regulations shaping the environmental impact of coffee production across different regions and farming systems.

Various approaches have been proposed to reduce emissions and waste in coffee production, including using processing wastewater as biogas and repurposing by-products like coffee tea (cascara). Future research should consider integration (Coffee Plantation-Industry-Livestock) as an IEC solution for smallholders in coffee production. This integrated approach could utilize waste streams for food products, wastewater fermentation, and biogas production, offering long-term sustainability solutions. Additionally, future studies should evaluate the potential of IEC for wet and dry methods through solar panels and biogas energy, turning by-products into novel food and fuel.

Table 4.8 Comparison of the results of this study with previous research

Reference	Farming	On-Farm	Off-Farm		LCA Method
	Cultivation/kg CB	Harvesting/kg CB	Primary/kg GB	Secondary	
[36]	Conventional Farming to Harvest CB	2.82 kg CO ₂ -eq/kg CB	2.82 kg CO ₂ -eq/kg GB	2.9 kg CO ₂ -eq/kg CP	Calculated
			Process CB to GB	Process GB to CP	
	Organic Farming to Harvest CB	1.89 kg CO ₂ -eq/kg CB	1.5 kg CO ₂ -eq/kg GB	1.58 kg CO ₂ -eq/kg CP	
			Process CB to GB	Process GB to CP	
[35]	NA	NA	NA	0.318 kg CO ₂ -eq/kg CR	LCA Sima Pro
	NA	NA	Process GB to CP (Solar Panel)		
			NA	0.744 kg CO ₂ -eq/kg CR	
[113]	NA	NA	NA	Process GB to CP (Local Hydro Electricity)	Calculated
				0.27 to 0.70 kg CO ₂ -eq/ l CD Coffee Consumed in Finland	
[111]	NA	NA	16.04 kg CO ₂ -eq	NA	Calculated
	NA	Conventional Farming in Vietnam Harvest CB to Process GB			
		NA	14.61kg CO ₂ -eq	NA	
[16]	NA	NA	1.8 kg CO ₂ -eq /kg GB	NA	Calculated
[144]	NA	NA	NA	1.31 kg CO ₂ -eq /kg CP	Calculated
	Conventional Farming in Lampung		Process CB to CP (Fossil Fuel and Local Electricity)/kg CP		
[143]	NA	0.29 kg CO ₂ -eq	0.336 kg CO	2.794 kg CO ₂ -eq /kg CP	Calculated
	Semi Organic Farming in Sukorambi, Jember		Process CB to CP (Fossil Fuel and Local Electricity)/kg CP		
[145]	Conventional Farming to Harvest CB	0.74 kg CO ₂ -eq	NA	NA	Calculated
	Integrated Farming to Harvest CB	0.5 kg CO ₂ -eq	NA	NA	
	Organic Farming to Harvest CB	0.16 kg CO ₂ -eq	NA	NA	
[130]	SW	0.039 kg kg CO ₂ -eq	0.275 kg CO ₂ -eq	0.568 kg CO ₂ -eq	LCA Sima Pro

FW			0.473 kg CO ₂ -eq	0.741 kg CO ₂ -eq	
	Cultivation/kg CB	Harvest CB/kg CB	Process CB to GB/kg GB	Process CB to CP/kg CP	
This Study	Cultivation/kg CB	Harvest CB/kg CB	Process CB to GB/kg GB	Process CB to CP/kg CP	
Nat			0.302 kg CO ₂ -eq	0.676 kg CO ₂ -eq	
An			0.306 kg CO ₂ -eq	0.702 kg CO ₂ -eq	
Hd	0.072 kg kg CO ₂ -eq	0.276 kg CO ₂ -eq	0.407 kg CO ₂ -eq	0.788 kg CO ₂ -eq	LCA Sima Pro
L			0.577 kg CO ₂ -eq	1.168 kg CO ₂ -eq	
CM			0.310 kg CO ₂ -eq	0.713 kg CO ₂ -eq	

CB : Cherry Beans; GB : Green Beans; CR : Coffee Roasted; CP : Coffee Powder; CD : Coffee Drink

4.9 Conclusions

The author collected data through experimentation and direct observation during Arabica coffee processing in Bondowoso Regency as basis of the life cycle assessment. This study stands out for its comprehensive examination of the three critical stages in coffee production: CB production, CB to GB conversion, and GB to CP processing. While previous studies often focus on select stages, this research delves into each phase, disclosing the GWP at every step and providing an overall assessment from CB to CP. Five DM procedures were investigated: Natural, Hd, Anaerobic, Lactic, and CM. The Lactic process had the highest environmental impact, with a GWP contribution of 1.170 kg CO₂-eq/kg CP. In contrast, the natural process had the lowest environmental impact, approximately 0.676 kg CO₂-eq/kg CP. Furthermore, Anaerobic, Hd, and CM emitted approximately 0.702 kg CO₂-eq, 0.788 kg CO₂-eq, and 0.713 kg CO₂-eq, respectively, per kg CP. Among the DMs that involved fermentation, the Anaerobic process released the least gas, while the Hd process showed to be the most environmentally friendly in terms of wastewater. The findings of this study highlight the importance of valorizing coffee by-products, not only for financial reasons, but also to lower environmental impacts. These points will be addressed in future studies where wastewater and by-products will be explored for fuel, potential feed, and fertilizer through IEC integration.

5 Biogas as a path towards industrial ecology coffee

5.1 Chapter introduction

Sustainable Development Goal (SDG) 17 focuses on strengthening partnerships for sustainable development, aiming to revitalize and implement global partnerships to support the fulfillment of the other sixteen goals. Coffee may not be the most obvious target for such partnerships, but as one of the most traded commodities globally, and a product that is heavily dependent on smallholder producers, the advancement of sustainable practices make it highly relevant.

The move towards sustainability standards in various sectors, including coffee, requires producers to direct their business strategies towards sustainable production [146]. There are a number of voluntary mechanisms or frameworks for reporting, recognizing, evaluating and rewarding sustainable coffee production practices, which producers from major coffee producing countries such as Indonesia are implementing. For example, the Common Code for the Coffee Community (4C) [147] or organic coffee practices [147]. Such initiatives encourage farmers to cultivate coffee sustainably through coffee farmer groups, ultimately contributing to supporting SDG 17. World coffee consumption is predicted to continue to increase [148] but the production process currently leads to a variety of waste streams that impact on the environment – notably wastewater [141]. On the other hand, there is increasing competition and consumer demand for high quality coffee. Quality coffee is defined on the basis of a variety of desired characteristics such as clean coffee beans, showing an attractive roast, distinctive aroma, and good taste, which are also determined by the type of seed, processing, and handling on the plantation [149]. Three broad grades of coffee are defined: commercial, premium and specialty coffee; typically increasing in the price that can be obtained by the seller. Specialty coffee can be determined by various conditions such as plantation location, primary defects, processing, and taste [150], while there is also increasing demand for coffee that is produced in ways that are environmentally lower impact and socially responsible.

This study aimed to obtain data experimentally from alternative processing methods to produce higher grade specialty coffee, and to evaluate the economic potential, as well as the specific opportunity for the production of biogas from waste, and its integration in the process.

5.2 Coffee production process

Broadly, there are two stages of coffee processing: on-farm and off-farm [151][152][120]. About 48% of coffee products in Indonesia are processed on-farm, which is exported, while the remaining 52% is processed off-farm to become ground coffee [100]. 99.3% of production capacity is from smallholder plantations, and the rest are government and private [100]. The quality of the coffee is critical as a determinant of price and taste, with various coffee processing methods used by the industry, generally categorized as wet processing and dry processing [153][154]. Dry processing can potentially be used to upgrade coffee to specialty coffee grade. Wet processing produce wastewater more than dry processing, wastewater for pulping and washing, and this wastewater is categorized as Coffee Washing Waste (CWW), Coffee Pulp Waste (CPW), Coffee Mucilage Waste (CMW), and Coffee Fermentation Waste (CFW) [154]. If coffee wastewater is released, it becomes a pollutant with high COD and BOD concentrations [155][156]. Mitigation of coffee waste and wastewater disposal is important for reducing the environmental impact, but can also be an

opportunity to generate additional income for farmers as a food, pharmaceutical or cosmetic ingredients, or potential energy recovery [154]. This potential for energy recovery has been demonstrated elsewhere [110][157], with the use of coffee pulp (skin and mesocarp cherry beans) and dairy cow dung has been demonstrated across various mixes for the production of biogas [158]. This integrated utilization of the waste streams of a number of industries (dairy farming and coffee production) is a small-scale example of industrial ecology, which is the focus of the current study. The coffee supply chain lends itself to such waste-recovery and integration efforts, because the primary product (extracted coffee) is a relatively small flow comparative to the primary coffee cherry.

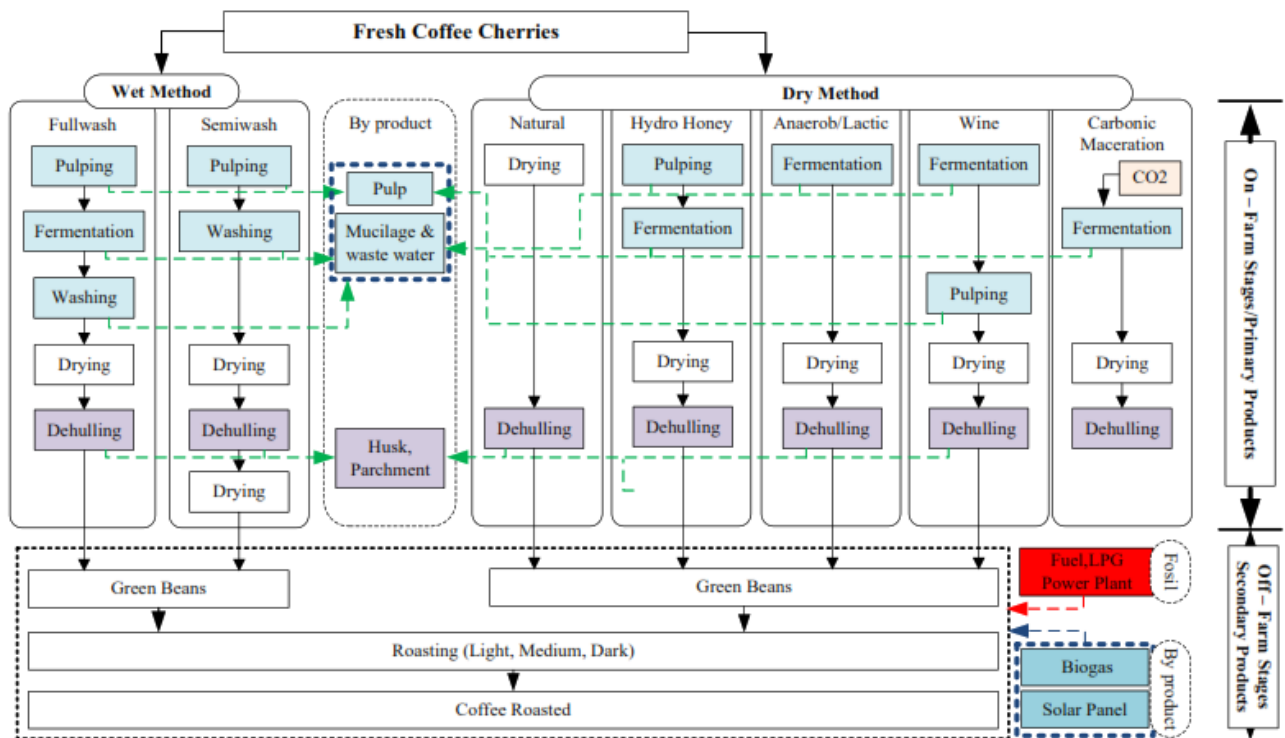


Figure 5.1 Coffee processing in Andungsari-Bondowoso

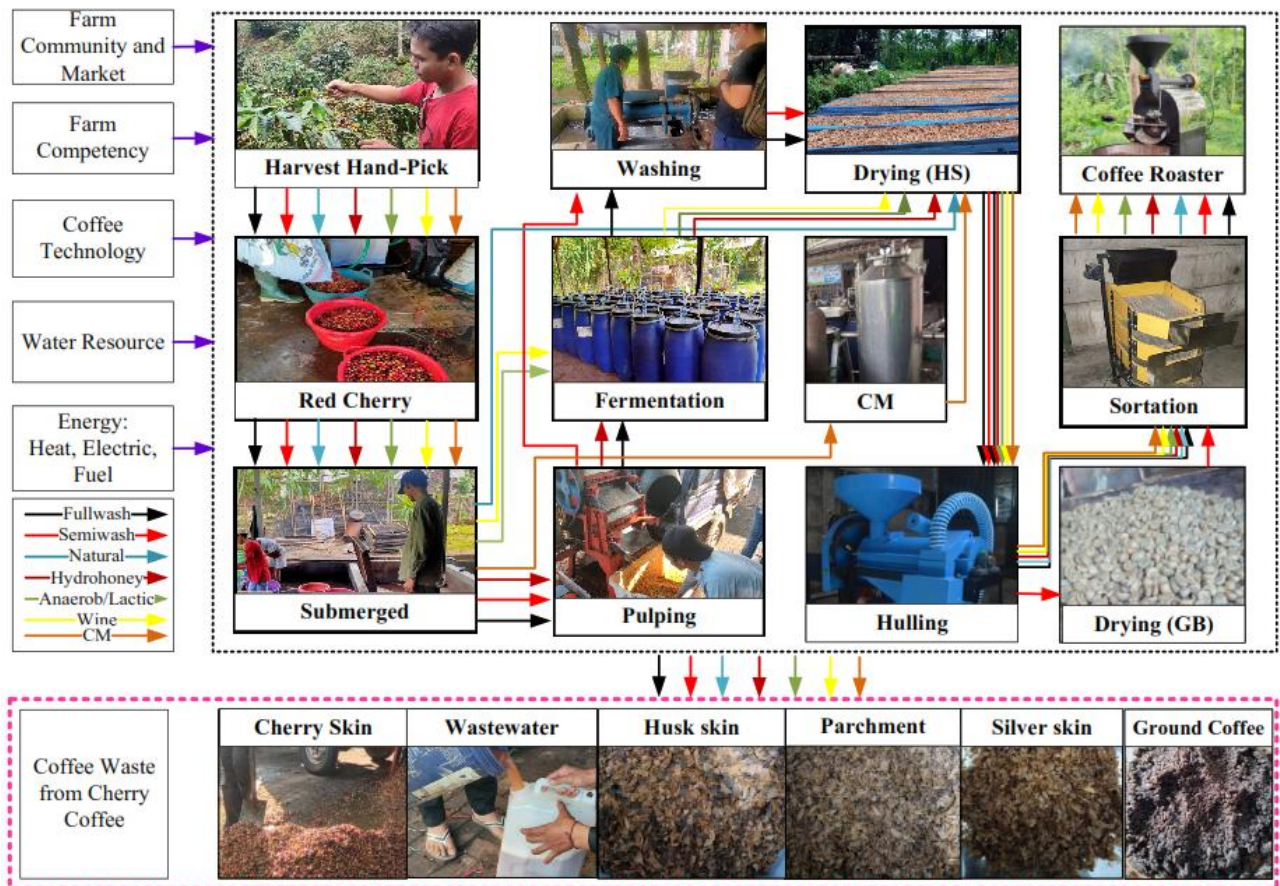


Figure 5.2 Coffee processing routes and coffee by-products

5.3 Case study

A pilot operation towards Coffee Industrial Ecology in the Andungsari coffee farmer group, Bondowoso Regency, East Java Province, Indonesia, is the basis for primary data collection and experiment in the current study. The research location is at 7°55'16.9"S 113°42'32.0" E. The head of the group has experience processing coffee since 1992. The total area of the group's land is 10ha, with an average of 2500 trees per ha and an average cherry production capacity of 3t/ha. The Andungsari coffee group also collaborates with Argopuro Walida in raw materials and coffee processing; the Argopuro Walida group, based on direct interview observations in 2021 and 2022, produced 450 and 507 tons of coffee cherry (respectively) with a plantation area of around 140-150ha.

Coffee cherries are harvested at the farm, then the pilot plant processes coffee via a number of alternative routes (as shown in Figure 5.1): wet (Full wash and Semi wash); and dry processing (Natural, hydro honey, Anaerobic/Lactic, Wine¹ and Carbonic Maceration). The processing flow for the On-farm and Off-farm categories is also defined in Figure 5.1, with on-farm processing leading to green bean coffee product, which then enters the roasting stage to produce the desired taste and

¹ The "wine" process is a method of fermentation of coffee.

aroma off-farm [26]. Coffee processing wastewater and other by-products can potentially be used for producing biogas. Currently, the Andungsari farmer group has been using biodigesters for farmers' cookstoves, but only to a small extent, while biogas has been tested here as fuel for coffee roasting. Figure 5.2 shows the overall flow for coffee production, as well as images of each stage and the main waste products. The biogas is then used as a fuel to provide heat for several operations, such as roasting machines, and also for residential use by the farmers' group in their cooking stoves.

In the present study, biogas was experimentally produced from different waste and wastewater streams arising from different processing routes. The biogas production volume and main gaseous components were analyzed, and a balance of the main mass and energy flows for the coffee production chains was developed. These were then used for economic analysis.

5.4 Materials and methodologies

The research consists of a number of distinct parts. Experimental work was undertaken to produce biogas from various waste flows from the coffee production process and from cow dung produced at or near the coffee plantation. Biogas was produced using a small batch reactor system [110] to estimate biogas potential, with analysis of the CO₂, CH₄, and N₂ content using Gas chromatography. Solar panels were also installed for testing as a source of electrical energy in coffee production [159], mainly in 5kg/batch roasting machines. The entire material balance, energy consumption, were measured or calculated, along with economic value for two scenarios, on the basis of the derived biogas and solar potential: (1) the use of biogas energy and (2) the continued use of fossil energy. The comparison of these scenarios will provide initial recommendations for further development of a sustainable coffee pilot project towards industrial ecology in the coffee production group.

In both cases the functional unit under consideration was the processing of 1000kg of Arabica coffee cherries to green bean coffee. The economic aspects of: Net Present Value (NPV), Benefit Cost Ratio (BCR), and Pay Back Period (PBP) were calculated based on the conditions and production capacity of the Andungsari farmer group. For consideration of practical scale plants, biogas reactors with a capacity of around 16m³ were evaluated.

5.5 Preliminary studies on biogas sampling

To gain indicative data for modelling of scaled-up biogas generation, small-scale batch reactors were used. Biogas was made using a 20L capacity reactor, with 15L gas storage containers. The alternative waste material mixtures used for biogas production are provided in Table 5.1. The categories of wastewater used correspond to different methods of processing coffee: coffee wastewater from fermentation (CWwf), coffee wastewater from anaerobic fermentation (CwwAf), coffee wastewater from hydro honey fermentation (CWwh), coffee wastewater from wine fermentation (CWw), coffee wastewater from carbonic maceration fermentation (CWcm), and initial base condition water (Wt). The wastewater is mixed with Cow dung (CD) as in previous studies, to enhance biogas production and utilise an available waste material [160][161].



Figure 5.3 (a) Small 20L reactor, (b) 15L gas storage containers, (c) gas pressure gauge on storage, (d) biogas burning

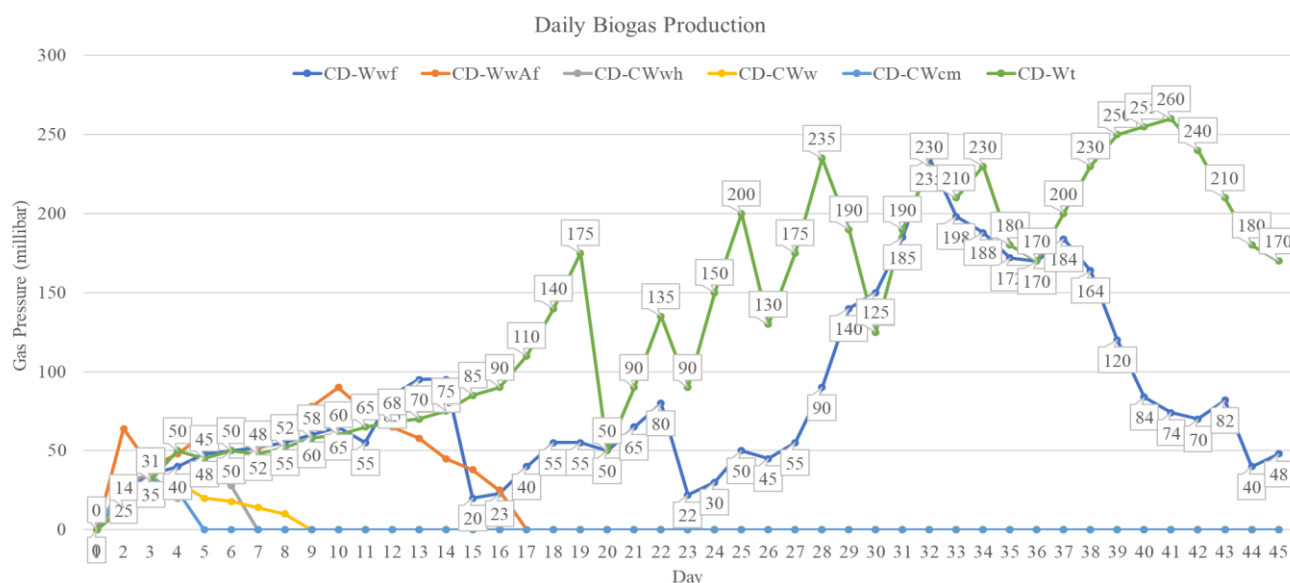


Figure 5.4 Biogas production during the 45 day test period

The biogas was produced in a batch reactor, with measurements taken daily for 45 days. Figure 5.3 shows the primary experimental equipment. No additional materials were added after the initial feedstock mixture. The biogas reactor pressure was measured daily, with the gas collected and stored in 15L vessels as shown in Figure 5.3 (b), to be analyzed later, notably for the content of CH₄, CO₂, and N₂O [97]. The biogas production volume was calculated from the gas pressure. The composition of the gas was expected to vary based on the type of raw feedstock materials and the type of reactor used, with a range of the major gas contributions from approximately 50% CH₄ and 50% CO₂, up to 75% CH₄ and 25% CO₂, as well as a variety of other possible other elements such as water vapor (H₂O), hydrogen sulfide (H₂S), and ammonia (NH₃) [97][162]. As shown in Figure 5.4, the CD-Wt reactor resulted in increased production from day 2 (14mbar) until day 42 (260mbar), but with unstable pressure from day 18 to 37. CD-Wwf, CD-Wwh, CD-CWw, and CD-CWcm resulted in pressure between 20-30mbar, while CD-WwAf was 60mbar on day 2.

By comparison, the use of CWW from coffee processing in Minas Gerais-Brazil was used in the manufacture of biogas on a sample scale to estimate the biomethane potential (BMP), with measurements carried out for 40 days, and the average methane gas measured on days 10, 17, 31 and the 38 producing a pressure of 92 – 94 pa (0.92-0.94 mbar) [110].

Table 5.1 Biogas materials

Sample	Materials	Quantity	Unit	Variables	Measured	Ref
CD-CWwf	Cow Dung	1.5	kg	Untreated cow dung	na	pH: 4.2-4.4
	Coffee wastewater fermentation (Washing)	6	L	Untreated Wwf	pH : 5.2	
	Effective microorganisms-4 (em-4)	0.2	L		na	
CD-CwwAf	Cow Dung	1.5	kg	Untreated cow dung	na	pH: 4.6
	Coffee wastewater (Anaerobic Fermentation)	6	L	Untreated WwAf	pH : 4.3	
	Effective microorganisms-4 (em-4)	0.2	L		na	
CD-CWwh	Cow Dung	1.5	kg	Untreated cow dung	na	pH: 3.8-4.0
	Coffee wastewater (Hydro honey Fermentation)	6	L	Untreated Wwh	pH : 4.2	
	Effective microorganisms-4 (em-4)	0.2	L		na	
CD-CWw	Cow Dung	1.5	kg	Untreated cow dung	na	
	Coffee wastewater (Wine Fermentation)	6	L	Untreated Ww	pH : 4.1	
	Effective microorganisms-4 (em-4)	0.2	L		na	
CD-CWcm	Cow Dung	1.5	kg	Untreated cow dung	na	
	Coffee wastewater (Carbonic Maceration Fermentation)	6	L	Untreated Wcm	pH : 4.1	
	Effective microorganisms-4 (em-4)	0.2	L		na	
CD-Wt	Cow Dung	1.5	kg	Untreated cow dung	na	pH: 6-7.9
	Water	6	L	Dug well water	pH : 6	
	Effective microorganisms-4 (em-4)	0.2	L		na	

untreated, na= undefined, [97][163][164]

5.6 Preliminary study on the solar electricity generation

While biogas could potentially be utilized for generating electricity, it was expected that the generated quantity of biogas would be more appropriately used for thermal purposes such as coffee roasting and domestic cooking. In the case study location, solar photovoltaic (PV) electricity generation was considered a potential option for producing zero-carbon electricity (unlike the highly coal-based electricity of the Indonesian electricity grid). A small-scale test plant was therefore implemented at the case study site. The solar system applied in this study included 400Wp PV panels, with series and parallel circuit arrangements considered. Measurements were not carried out continuously at the study location; the tests were only carried out from 7 am to 5 pm on both configurations (series and parallel) for a week in Mid-August 2022. The measured temperature at the study location was between 21 – 28° C, and clouds shaded the panels for an average 1 to 2 hours each day.

Table 5.2 Parameters of the solar system

Table 5.2 shows the system characteristics. Figure 5.5 shows potential power from measurements of voltage and current, the voltage range over seven days was between 57.6 volts to 82.3 volts, and the current ranged between 0.1 – 4.3 Ampere. In this case, a 100A battery with a 1000W cosine wave-type inverter was used as energy storage. This system was too small to provide electricity for the farmers' houses, but provided power for some tools used in coffee processing, such as coffee roasters and packaging equipment.

Table 5.2 Parameters of the solar system

PV System Power-plant*	Voltage (V)	Current (I)
Series @100Wp x 4	57.6 – 82.3	0.1 – 4.3
Parallel @100Wp x 4	15.9 – 20.8	0.3 – 13
Battery (Pb)	12	100
Inverter (DC-AC) Cosine wave	1000 W	

*Data were taken from equipment specifications

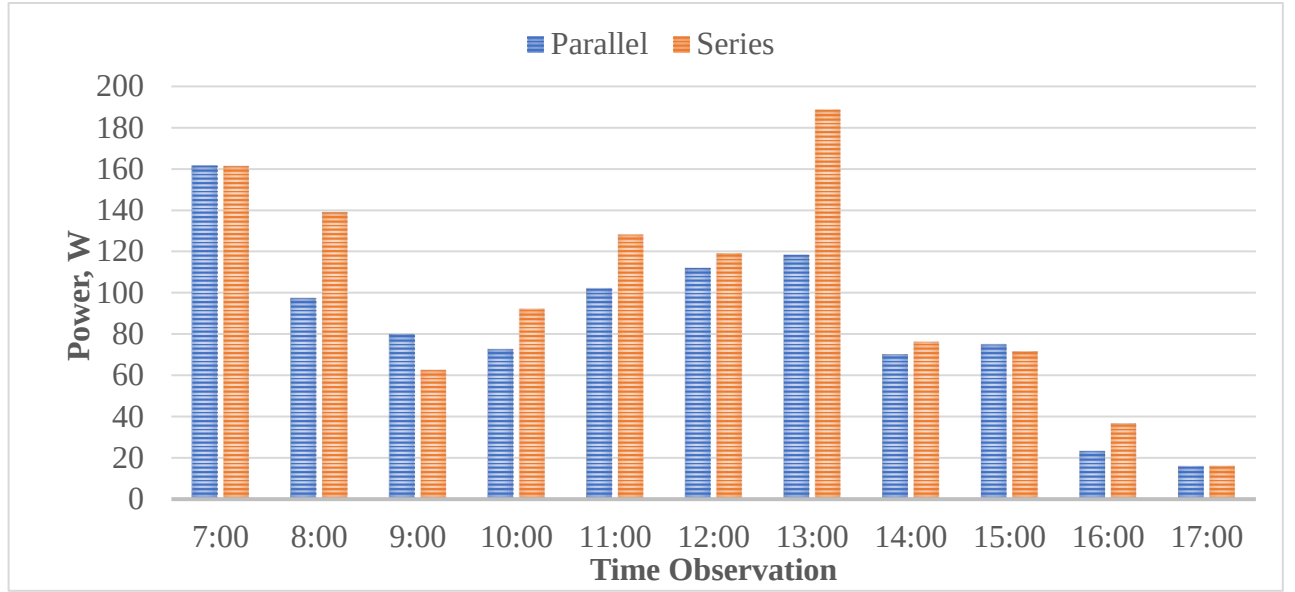


Figure 5.5 Observation of average power at each hour taken across one week (Mid-August 2022), for series and parallel configurations

While the observed power generation in Figure 5.5 cannot be considered strictly representative of a whole year, the conditions are considered to be representative of the harvest season, allowing a rough empirical estimation of the potential power from such as system for the critical time of the year.

5.7 Economic analysis

This study's approach to the economic analysis of coffee production differentiates between the two scenarios. In order to implement the industrial ecology solutions, there is a required technological investment for alternative processing technology, the biodigester, and solar panel installation. This is incorporated in the first scenario. The second scenario of the economic analysis uses fossil energy sources in coffee production (without digester investment). When on-farm coffee production is not operating the liquid waste biogas must be substituted with alternatives. Hence, in this case cow dung is utilized as biogas material for farmers' houses outside of on-farm production periods.

Economic analysis is calculated based on cash flow, the net present value (NPV) equation (1), benefit-cost ratio (BCR), and payback period (PBP) criteria were used to evaluate both scenarios for the financial viability of the investment. This study uses a discount rate of 6% per year [165], and assumes that the technology implementation is for 15 years.

$$NPV = \sum_{t=1}^N \frac{R_t}{(1+i)^t} - C_o \quad (1)$$

Where C_o is the total cost of investment, R_t of cash flows over a period of time, i discount rate or return on investment and t time. The criterion, if the NPV is positive is said to be economically feasible in the scenario, whereas if NPV is negative the business is typically not feasible. The benefit-cost ratio (BCR) is the ratio between the relative costs and benefits in the second scenario applied in the industrial ecology pilot project; if the BCR is significantly above 1.0 the project is expected to have a positive impact. The PBP refers to the years an investment takes to recover its

initial costs through an annual net return of cash income generated. The detailed NPV assumptions on cash flows are given by:

$$NPV = -I + AB \times (P/A, i, n) + S \times (P/F, i, n) - AC \times (P/A, i, n) - Oh \times (P/F, i, n) \quad (2)$$

$$PWB = AB \times (P/A, i, n) + S \times (P/F, i, n) \quad (3)$$

$$PWC = AC \times (P/A, i, n) - Oh \times (P/F, i, n) \quad (4)$$

$$BCR = PWB/PWC \quad (5)$$

Where:

PWB	= Present Worth Benefit (Revenue)
PWC	= Present Worth Cost (Expenditure)
AB	= Annual Benefit (Income)
AC	= Annual Cost (Fixed and variable costs)
S	= Salvage Value (Residual value of technology)
Oh	= Overhaul (Technology service operation)
P/A, i, n	= Present worth (Uniform series)
P/F, i, n	= Present worth (Single payment)

In the NPV calculation, the discrete compounding calculation of *Uniform Present worth* ($P/A, i, n$) was 9.71, assuming a project lifetime of 15 years and an interest rate of 6%. Likewise, the *Single Payment Present worth* ($P/F, i, n$) for calculating the *Salvage Value* at $n=15$ is 0.42; while it is assumed that there is extensive overhaul (Oh) maintenance on the technology in year 8, where $n=8$ is 0.63. AB income comes from two products (GB and CP), while AC is the operational cost from electricity, gas, raw materials, and labor.

5.8 Biogas frameworks and economic analysis

5.8.1 Biogas concentration

Table 5.3 shows the biogas testing data according to the type of waste water material used to produce biogas. Testing of biogas samples using gas chromatography (GC) was carried out at the Agricultural Environmental Research Center, PATI – Agricultural Environmental Research Center Laboratory in Central Java, Indonesia. Cow dung and wastewater mixture ratio of 1:4 was applied in this study [166], some GC results were not available for CD-CWwh, CD-CWw, and CD-CWcm because biogas production decreased from the fifth day. The CH₄, CO₂, and N₂O of the biogas from the CD-Wt mixture produced the highest concentrations compared to the others, followed by CD-

CWwf and CD-CwwAf. However, the CO₂ value for CD-CwwAf was even higher than CD-CWwf. GC testing helped to estimate the impact of liquid waste producing gaseous emissions if it was directly released, in addition to the potential for biogas. This biogas capacity can potentially be expanded to match with the total waste flows or total demand, but effectiveness and efficiency need to be considered in conjunction with the economic factors. Currently, the Andungsari farmer group has used liquid waste to produce biogas for the heating system in coffee roasters; the Andungsari farmer group has established a model for this system by piloting the integration with livestock, plantation, and coffee processing. This system can enable sustainable utilization of coffee production waste and reducing the use of energy from outside the system to mitigate emissions from waste and reduce the use of fossil energy sources.

Table 5.3 Gas chromatography results for biogas from wastewater

Sample Code*	Ratio	Parameters	Method of Analysis	Limit of Detection (LoD)	Result of Analysis (ppm)
CD-CWwf					65,951
CD-CwwAf					16,465
CD-CWwh	1 : 4	CH ₄	IKM LAB.BALINGTAN 7.2.2.2.36 (GC-2014)	0.1	NA
CD-CWw					NA
CD-CWcm					NA
CD-Wt					352,674
CD-CWwf					2,710
CD-CwwAf					9,406
CD-CWwh	1 : 4	CO ₂	IKM LAB.BALINGTAN 7.2.2.2.38 (GC-2014)	48.58	NA
CD-CWw					NA
CD-CWcm					NA
CD-Wt					98,779
CD-CWwf					348
CD-CwwAf					363
CD-CWwh	1 : 4	N ₂ O	IKM LAB.BALINGTAN 7.2.2.2.37 (GC-2014)	36.72	NA
CD-CWw					NA
CD-CWcm					NA
CD-Wt					786

*data were measured

5.8.2 Coffee production

Processing coffee with different forms of fermentation aims to improve the taste of coffee [25]. For example, coffee processing using carbonic maceration fermentation with different fermentation times was demonstrated to affect the coffee flavor score for Robusta with a fermentation time of 120h scoring 83.25 points, while 24h was only 78.64 points [167]. Very long (up to 20 days) fermentation times have also been tested [168]. Coffee processing in this study consisted of two groups: wet and dry processing. Wet processing was further divided into two processes: full wash (Fw) and semi wash (Sw). While dry processing was done by the following five processes: natural (N), hydro honey (Hd), anaerobic/lactic (A/L), wine (W), and carbonic maceration (CM). Fw, Sw, and N processes are the coffee processes most commonly carried out by coffee producers and

farmers [153]. The seven processes all involved selecting cherry beans and flotation / submersion before being used to produce specialty coffee.

Typically, coffee cherries are picked when ripe and red in color, but the use of specialty coffee processing has potential to use non-red cherries for producing quality coffee. The condition of the red picks in the Andungsari Group was adjusted for the level of ripeness of the cherry with the estimated harvest schedule shown in Figure 5.6.

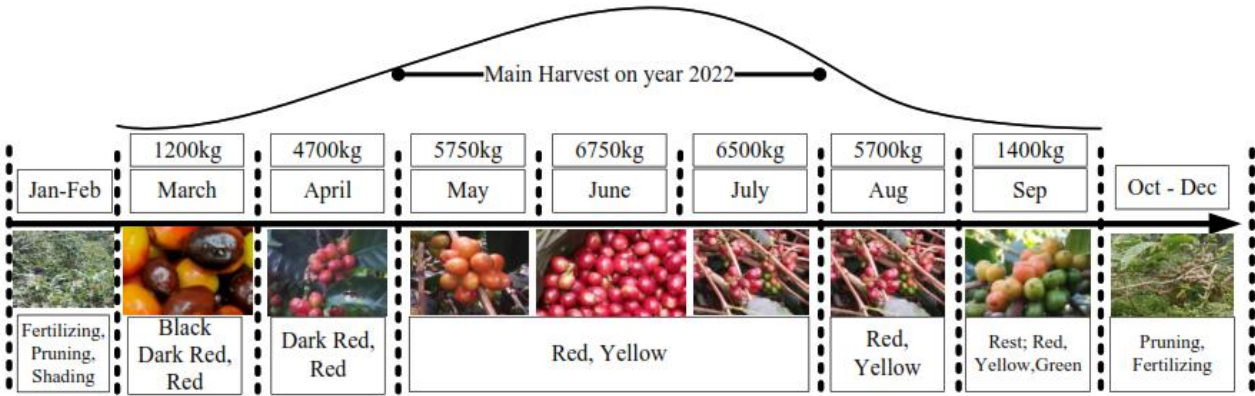


Figure 5.6 Timetable of coffee harvest for Andungsari group

Table 5.4 illustrates the data and timetable of the coffee harvest in this farmers group, in March-April some cherries are ready to be picked and overripe but still predominantly orange, yellow, and dark green. So, black cherries (overripe) and red (ripe) cherries are selected and picked. The months of May-August are the peak of the harvest; when production capacity increases, so coffee farmer groups use the dry processing method to process coffee by fermentation without pulping, with less time consumed in processing. While in September-October for the rest of the harvest generally, the farmers take all of the remaining cherries, then undertake pruning, fertilization and maintenance during flowering periods. Based on the harvest pattern, this group produces three green bean products: Specialty, Premium, and Commercial. Advanced stages of processing require submersion / flotation of cherries to be made into a premium or commercial products. Cherry coffee is pulped in Fw, Sw, and Hd processing. The natural processing goes directly to the drying process while the remaining three processes go through the cherry fermentation stage (Figure 5.1 and Figure 5.2) before the drying stage. For Sw, a second drying phase occurs after hulling, whereas for other processes there is only one drying stage. All processed green beans are sorted by size, then roasted to color and flavor profiles. Every coffee processing route produces waste (Figure 5.2), starting from cherry skin waste which is waste from the pulping process, wastewater from washing and fermentation, husk skin (HS) waste from dry processing from the hulling stages; parchment, which is also waste from the hulling stages in the full wash process, silver skin is waste from the coffee roasting stages, and the last is Spent Coffee Grounds that comes from coffee brewing.

Table 5.4 Coffee harvest at Andungsari Group 2022

Month	Harvesting*		Production (kg)		
	%	kg	Specialty	Premium	Commercial
January	-	-	-	-	-
February	-	-	-	-	-
March	3.8	1,200	50	280	870
April	14.7	4,700	770	2,950	980
May	18	5,750	2,850	2,305	595
June	21	6,750	3,100	3,650	-
July	20.3	6,500	5,120	1,380	-
August	17.8	5,700	4,050	365	1,285
September	4.4	1,400	60	270	1,070
October	-	-	-	-	-
November	-	-	-	-	-
December	-	-	-	-	-
Total	100	32,000	16,000	11,200	4,800

*data were measured

Table 5.5 Mass balance for coffee processing (Part 1 – Wet processes)

Stages process*		Input		Output			Waste Benefit
		Material (kg)	Water (L)	Product (kg)	Waste Solid (kg)	Liquid (L)	
Full wash	Selective Pickling	1000					
	Submerged	-	2500	970	30	2500	Fuel
	Pulping	970	-	534	437	-	Feed, Fuel
	Fermentation	534	-	512	-	21	
	Washing	512	750	502	-	760	Fuel, Fert
	Drying (HS)	502	-	246	-	-	256
	Dehulling	246	-	202	44	-	Fuel, Feed
	Grading Size	202	-	192	10	-	
	Roasting Coffee	192	-	172	5	-	14 Fuel
Semi-wash	Selective Pickling	1000					
	Submerged	-	2500	960	40	2500	Fuel
	Pulping	960	-	528	432	-	Feed, Fuel
	Washing	528	750	517	-	761	Fuel, Fert
	Drying (Parch)	517	-	414	-	-	103
	Dehulling	414	-	298	116	-	Feed, Fuel
	Drying (GB)	298	-	203	-	-	95
	Grading Size	203	-	191	12	-	
	Roasting Coffee	191	-	171	4.5	-	15 Fuel

Table 5.5 Mass balance for coffee processing (Part 2 – Dry processes)

Stages process*		Input		Output			Waste Benefit	
		Material (kg)	Water (L)	Product (kg)	Waste			Losses (kg)
					Solid (kg)	Liquid (L)		
Natural	Selective Pickling	1000						
	Submerged	-	2500	965	35	2500	Fuel	
	Drying (HS)	965	-	483	-	-	483	
	Dehulling	483	-	207	275		Feed, Fuel	
	Grading Size	207	-	191	17			
	Roasting Coffee	191	-	172	5		14 Fuel	
Hydro-honey	Selective Pickling	1000						
	Submerged	-	2500	968	32	2500	Fuel	
	Pulping	968	-	532	436	-	Feed, Fuel	
	Fermentation	532	-	506	-	27	Fuel	
	Drying (Parc)	506	-	248	-	-	258	
	Dehulling	248	-	203	45	-	Feed, Fuel	
	Grading Size	203	-	195	8	-		
	Roasting Coffee	195	-	176	6	-	14 Fuel	
Anaerobic/Lactic	Selective Pickling	1000						
	Submerged	-	2500	976	24	2500	Fuel	
	Fermentation	976	-	927	-	49	Fuel	
	Drying (HS)	927	-	482	-	-	445	
	Dehulling	482	-	207	275	-	Feed, Fuel	
	Grading Size	207	-	199	8	-		
	Roasting Coffee	199	-	179	5	-	15 Fuel	
Wine	Selective Pickling	1000						
	Submerged	-	2500	970	30	2500		
	Fermentation	970	-	931	-	39	Fuel	
	Pulping	931	-	512	419	-	Feed, Fuel	
	Drying (Parchment)	512	-	251	-	-	261	
	Dehulling	251	-	211	40	-	Feed, Fuel	
	Grading Size	211	-	200	11	-		
	Roasting Coffee	200	-	180	4.5	-	16 Fuel	
Carbonic Maceration	Selective Pickling	1000						
	Submerged	-	2500	975	25	2500	Fuel	
	Fermentation + CO ₂	975	-	917	-	59	Fuel	
	Drying (HS)	917	-	477	-	-	440	
	Dehulling	477	-	219	257	-	Feed, Fuel	
	Grading Size	219	-	208	11	-		
	Roasting Coffee	208	-	187	5	-	16 Fuel	

Sol = Solid; Liq = Liquid; Fert = Fertilizer; HS = Husk Skin; GB = Green Beans; Parch = Parchment.
 *data were measured harvest 2022.

Figure 5.5 describes the technology used and the material balance of the entire coffee production process based on 1000kg of cherry coffee, with data taken from processing in the 2022 harvest season. The lower quality coffee products are premium or commercial products. Andungsari coffee processing in 2022 increased compared to 2021, ranging from 32 tons of cherry coffee producing 50% (3.2 tons) of specialty green beans, 35% (2.24 tons) of premium and 15% (0.96 tons) of commercial coffee.

5.8.3 Energetic application

Coffee processing water waste was used as the main substrate mixture in the digester unit (Figure 7). Cow dung is used in some mixtures at a ratio of 1:2 (0.5t of cow manure with 1t of water). The material filling system continues when the biogas pressure decreases below 60 mbar, the stable pressure on the gas collector in this digester is between 55 and 65 mbar and can be used for the coffee roasting process for 3 hours without stopping from the initial gas pressure of 65 to 50 mbar. Below this pressure of 50 mbar, the gas can be used for cooking for around 1-2 hours until reaching a final lower pressure of 30 mbar: Figure 5.7 digester application, pressure measurement, and unit design. The capacity of the substrate digester is around 16m³, with a range of 1-1.5 tons of substrate.



Figure 5.7 (a) Unit digester, (b) gas pressure, and (c) sketch of unit

Table 5.6 Waste type basis 1000kg cherry beans on processing

Stages Process*	Fw	Sw	N	Hd	A/L	W	CM
Wastewater, l	3,250	3,250	2,500	2,500	2,500	2,500	2,500
Mucilage/Pulp, l	32	11	-	27	49	39	59
Cherry Skin, kg	437	432	-	436	-	419	-
Husk Skin, kg	-	-	275	-	275	-	257
Parchment Skin, kg	44	116	-	45	-	40	-
Silver Skin, kg	5	4,5	5	6	5	4,5	16
Total Wastewater, l	3,282	3,261	2,500	2,527	2,549	2,539	2,559
Total Solid Waste, kg	486	552	280	486	280	464	273

*Data measured.

Biogas is produced to pressures ranging from 60 to 65 mbar for 15 days from 1.5t batches. This group adds about one cubic meter of incoming material up to 4 times per month. Assuming that 1t equals 1000 liters, the liquid waste produced on a 1000kg basis of cherry for processing from Fw to CM ranges from 2.5t to 3.2t, while solid waste is 0.27t to 0.48t (Table 5.6).

Table 5.7 Outputs from production of 1000kg cherry beans (wet basis)

Output Product, 1000kg wet basis*	Fw	Sw	N	Hd	A/L	W	CM
Green Beans	20%	20%	21%	20%	21%	21%	22%
Mucilage/Pulp	3%	1%	-	3%	5%	4%	6%
Cherry Skin	44%	43%		44%	-	42%	-
Husk Skin	-	-	28%	-	27%	-	26%
Parchment Skin	4%	12%	-	4%	-	4%	-
Silver skin	1%	1%	1%	1%	1%	1%	2%
Water vapor	28%	23%	51%	28%	46%	28%	45%

*data measured

The total waste for one year of production, from 32t of input cherry material, reaches 96t of liquid waste and 14t of solid waste (Table 5.10). However, the production processes are not all undertaken at the same time, and the waste is currently anticipated to be partly disposed of in plantations and partially used as raw material for biogas.

Table 5.8 Process stages and the energy consumed

Stages Process*	Equipment Specification	Units	Fw	Sw	N	Hd	A/L	W	CM
Harvesting	Motorcycle (100kg/trip)	l	3.5	3.5	3.5	3.5	3.5	3.5	3.5
Pulping	Gas Engine 5Hp, 300kg/h	l	2	2	-	2	-	2	-
Washing	Gas Engine 5Hp, 300kg/h	l	1	1	-	-	-	-	-
Dehulling	Gas Engine 5Hp, 250kg/h	l	0.6	1	1.2	0.6	1.2	0.6	1.1
Grading Size	Electric 0.75Kw, 250kg/h	l	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Roasting Coffee	Electric 1Kw, 20kg/h	kWh	6.8	6.8	7	6.9	7	7.1	7.4
	Gas 0.75 kg/h	Kg	6.8	6.8	7	6.9	7	7.1	7.4
Total, 1000kg/batch process CB-GB	Gasoline Fuel	l	7.1	7.5	4.7	6.1	4.7	6.1	4.6
	Electricity Consumption	kWh	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Total, 1000kg/batch process CB-CP	Gasoline Fuel	l	7.1	7.5	4.7	6.1	4.7	6.1	4.6
	Electricity Consumption	kWh	7.4	7.4	7.6	7.5	7.6	7.7	8.0
	Gas Consumption	Kg	6.8	6.8	7	6.9	7	7.1	7.4

*data measured

The Andungsari coffee group produces specialty coffee from around 16t of cherry beans, of which 40% is processed via the Fw method, 20% Sw, and the remaining 40% N. Premium and commercial products are produced from around 11.2t and 4.8t of cherry beans respectively, through Fw, Sw, and N routes. The potential for more waste is successively generated from specialty, premium, and commercial products (liquid and solid waste). Table 5.7 shows the product and waste potential on a 1000kg basis of wet cherries. For specialty products green bean yields range from 20-22% by weight. Cherry skin waste is 42-44%, and HS 26-28%. 1000kg of cherry coffee requires between 8-10 fermentation drums, with each drum containing 100-120kg of coffee. During the fermentation, the reaction produces wastewater (Table 5.6). Fermentation time depends on the type of processing, Fw 24-36hr, Hd 36-48hr, A/L 48-96hr, W 48-96hr, CM 24-36hr. This liquid waste has the potential to

be used as biogas material and can also be used for bioethanol feedstock material [169] and drinks [170]. Energy use during the production process on a 1000kg of cherry basis is described in Table 5.8, with estimates of the use of fuel, electricity, and gas in various processing methods. The location of the plantation from the production house is around 3.5km which can be reached by motorbike to transport the cherries at a rate of 100kg per trip, fossil fuel consumption was calculated round trip (Table 5.8). Gasoline is used in the motors of the pulper, huller, and washer engines, while electricity is used in sorting and roasting machines.

5.9 Economic aspect

Coffee production carried out at Andungsari coffee production in 2022 produced several products, including specialty, premium, and commercial grade coffee. Specialty products are sold in the Jakarta, West Java, and Medan areas, while premium products are sold in the island of Java and commercial are only for the local market. Table 5.10 describes the raw materials for cherry coffee, with each type of processing and product. The Specialty GB produced from 16t of cherry is 3,289kg, while Premium GB from 11.2t of cherry is 2,275kg, and Commercial grade GB from the remainder is 983kg. The selling price of green beans varies according to grade and processing type, as shown in Table 5.12. Note that, aside from Specialty grade coffee, there are only three types of processing: Fw, Sw, and N, found in premium and commercial varieties.

Total revenue is calculated from the total production of GB in each category:

$$\text{Total Income (IDR)} = \sum \text{Total production by grade and route} \times \text{Price per grade and route} \quad (6)$$

Labor operational costs are divided into two categories lower skill and high skill, 80,000 IDR, and 100,000 IDR respectively, depending on the position of stages processing. Mostly, high skills are required for processing stages with specialized skills, such as fermentation, and roasting. Gasoline and electricity operating costs are allocated by process. Table 5.12 shows the selling price of GB and other estimated operational costs. 32t of Cherry coffee is assumed to be purchased from farmers, at approximately 10,000 IDR /kg. Investment in processing technology and other equipment in both scenarios is determined based on the use of technology in the production process. Not all production routes require all pieces of equipment, as shown in Table 5.11. Equipment prices are described in Table 5.9 based on the results of direct observation and interviews. The total investment in other processing is also calculated based on the price and use of technology from the Indonesian Coffee and Cocoa Research Institute (ICCRI)[171], products sold are green beans or coffee powder. The Andungsari group currently sells specialty coffee as green beans, premium coffee (half green beans, the rest is powder), and commercial coffee powder.

Table 5.9 Equipment investment cost

No	Equipment specifications*	Quantity	Investment cost, IDR
1	De-pulping, 300kg/batch	1 Unit	25,000,000
2	Washing, 300kg/batch	1 Unit	24,500,000
3	Drum Fermentation, 120kg/batch	20 Pcs	3,500,000
4	Coffee Drying Beds, 50kg/tray	100 Pcs	32,500,000
5	Hulling, 250kg/batch	1 Unit	24,500,000
6	Sortation, 250kg/batch	1 Unit	20,000,000
7	Other Tools, Coffee sack, etc,	Set	15,000,000
8	Reactor CM, 2000kg/batch	1 Unit	35,500,000
9	Coffee Roaster, 20kg/h	1 Unit	20,000,000
10	Sealer Packaging, 10kg/h	1 Unit	1,250,000
11	Grinder, 15kg/h	1 Unit	12,000,000
12	Reactor Digester 16m ³	Set	17,500,000
13	PV, 4panel @100WP	Set	7,500,000
Total Investment Cost (Excluding Digester), IDR			213,750,000
Total Investment Cost (Including Digester), IDR			238,750,000

*Observed ICCRI

Table 5.10 Process mass flows in Andungsari group (harvest year 2022)

Inputs (wet basis) *			Process Route						
Product	Processed Cherry Beans	Total	Fw	Sw	Nat	Hd	A/L	Wine	CM
	Specialty (kg)	16,000	6,400	3,200	1,600	320	1,600	1,280	1,600
	Premium (kg)	11,200	5,600	3,360	2,240	-	-	-	-
	Commercial (kg)	4,800	1,200	1,200	2,400	-	-	-	-
Total Processed Cherry Beans (kg)			13,200	7,760	6,240	320	1,600	1,280	1,600
Waste	Waste Streams								
	Wastewater, liter	96,450	43,317	25,302	15,600	809	4,078	3,250	4,094
	Solid waste (kg)	14,080	6,412	4,287	1,747	156	448	594	437
Products									
Product	Output (dry basis)								
	Specialty (kg)	3,289	1,291	649	332	65	332	270	351
	Premium (kg)	2,275	1,129	681	465	-	-	-	-
	Commercial (kg)	983	242	243	498	-	-	-	-

*Data were measured

The three raw material streams (cherry beans) converted into green beans in each product grade are described in Table 5.10, as well as the potential for wastewater and solid waste. But not all

processing routes require every piece of equipment – for example, to produce green beans with Fw, investment needs only up to point 7 (Table 5.9). As for other processing routes, the equipment used is described in Table 5.11, which is used as a model for calculating the NPV amount based on the investment value and the type of processing.

Table 5.11 Equipment used in coffee processing

Equipment for coffee processing	Fw	Sw	N	Hd	A/L	Wine	CM
Depulping, 300kg/batch	✓	✓		✓		✓	
Washing, 300kg/batch	✓	✓					
Drum Fermentation, 120kg/batch	✓			✓		✓	
Coffee Drying Beds, 50kg/tray	✓	✓	✓	✓	✓	✓	✓
Hulling, 250kg/batch	✓	✓	✓	✓	✓	✓	✓
Sortation, 250kg/batch	✓	✓	✓	✓	✓	✓	✓
Other Tools, Coffee Bag, etc.	✓	✓	✓	✓	✓	✓	✓
Reactor CM, 2000kg/batch					✓		✓
Coffee Roaster, 20kg/h*	✓	✓	✓	✓	✓	✓	✓
Sealer Packaging, 10kg/h*	✓	✓	✓	✓	✓	✓	✓
Grinder, 15kg/h*	✓	✓	✓	✓	✓	✓	✓
Digester Biogas, 7m ³	✓	✓	✓	✓	✓	✓	✓
PV, 4panel @100WP	✓	✓	✓	✓	✓	✓	✓
Inv CB to GB, IDR (x 1000)	145,00 0	141,50 0	92,000	120,50 0	127,50 0	120,50 0	127,50 0
Inv CB to CP, IDR (x 1000)	178,25 0	174,75 0	125,25 0	153,75 0	160,75 0	153,75 0	160,75 0
Inv CB to CP, Digester IDR (x 1000)	203,25 0	199,75 0	150,25 0	178,75 0	185,75 0	178,75 0	185,75 0

*This equipment is considered in the NPV calculations to produce CB to CP.

Table 5.12 Coffee price for green beans or coffee powder, cost of production, and coffee income by grade and processing route

Coffee Price in GB per kg*							
Specialty, IDR	115,000	105,000	110,000	120,000	125,000	135,000	145,000
Premium, IDR	95,000	90,000	95,000	-	-	-	-
Commercial, IDR	65,000	60,000	65,000	-	-	-	-
Coffee Price in CP per kg							
Premium, IDR	140,000	135,000	140,000	-	-	-	-
Commercial, IDR	95,000	90,000	95,000	-	-	-	-
Income in GB (x 1000), (AB for GB)							
Specialty, IDR	148,672	68,208	36,608	7,795	41,400	36,461	50,808
Premium, IDR	53,732	30,694	22,131				
Total Income in GB, IDR	496,509	202,404	98,902	58,739	7,795	41,400	36,461
Income in CP (x 1000), (AB for CP)							
Premium, IDR	71,266	41,436	29,353	-	-	-	-
Commercial, IDR	20,725	19,732	42,682	-	-	-	-
Total Income in CP, IDR	225,193	91,991	61,168	72,035			
Energy Cost in GB (x1000), (AC for Energy GB production)							
Specialty, IDR	661.5	347.0	119.0	29.5	119.9	118	120.5
Premium, IDR	239.5	151.5	62.5	-	-	-	-
Total Energy Cost in GB, IDR	1,968.9	901.0	498.5	181.5	29.5	119.9	118
Energy Cost in CP (x1000), (AC Energy CP production)							
Premium, IDR	1,089.5	664.5	412.6	-	-	-	-
Commercial, IDR	467.5	474.5	884.5	-	-	-	-
Total Energy Cost in CP, IDR	3,993.1	1,557	1,139	1,297.1			
Variable Cost in GB (x1000), (AC Labor for GB)							
Specialty, IDR	80,640	38,656	19,712	4,045	20,672	16,179	20,480
Premium, IDR	35,280	20,294	13,798	-	-	-	-
Total Variable Cost in GB, AC	269,757	115,920	58,950	33,510	4,045	20,672	16,179
Variable Cost in CP (x1000), (AC Labor for CP)							
Premium, IDR	36,120	20,798	14,134	-	-	-	-
Commercial, IDR	15,480	14,856	30,288	-	-	-	-
Total Variable Cost in GB, AC	131,677	51,600	35,654	44,422			

*Data were calculated

The NPV, BCR, and PBP values of the Andungsari farmer group are evaluated for a total coffee cherry production capacity of 32 tons per year of specialty, premium, and commercial production, comparing two energy provision scenarios and two economic cases. The first energy scenario uses biogas in production, and the second uses fossil fuels only. The production mix of specialty, premium and commercial for the base case follows the existing practices of the farming group, while the alternative economic case seeks to enhance income for the group.

Table 5.13 shows the price, cost, and energy costs of the current conditions based on the two scenarios according to the current product output with the condition that 50% of coffee is sold as specialty products in the form of GB, 35% are Premium GB and CP, while the remaining 15% was commercial CP. The calculation of the NPV for each process route, scenario and output used the following NPV estimates based on the amount of production capacity per processing route:

$$TICp = \frac{CPp}{Tp} \times Total\ Investment\ Cost \quad (7)$$

TICp = Total Investment Cost per process route (IDR)

CPp = Capacity of processing route (kg)

Tp = Total processing (kg)

e.g. to find the allocated investment Scenario 1 calculated by:

For Fw processing except equipment no 8 (Table 5.9) to produce from CB to CP, taking the data from $\left(\frac{13,200kg}{32,000kg}\right) \times 203,250,000\ IDR$. The investment for Fw to process CB 13,200kg was 83,849,625 IDR.

Hence, the NPV is calculated from Table 5.12 following this estimation

NPV for Fw processing CB to GB, and CB to CP: $(-83,849,625) + (294,394,800 \times 9.71) + (18,382,031 \times 0.42) - (167,520,000 \times 9.71) - (7,352,813 \times 0.63) = 1,151,201,864\ IDR$

Table 5.13 Economic assessment – current production case

Potential in CB (kg)		Total Process	Fw	Sw	N	Hd	A/L	Wine	CM
50%, Specialty		16,000	6,400	3,200	1,600	320	1,600	1,280	1,600
35%, Premium		11,200	5,600	3,360	2,240	-	-	-	-
15%, Commercial		4,800	1,200	1,200	2,400	-	-	-	-
Total Processing (TP)		32,000	13,200	7,760	6,240	320	1,600	1,280	1,600
Economic Assessment									
Indicator	Scenario	All Products	Fw	Sw	N	Hd	A/L	Wine	CM
NPV	1. Biogas	2,877,949	1,151,202	589,003	484,813	34,693	192,319	190,043	285,535
(x1000 IDR)	2. Fossil fuel	2,845,058	1,137,647	579,166	475,331	34,657	192,405	189,897	285,615
Benefit Cost- Ratio (BCR)	1. Biogas	1.80	1.76	1.69	1.68	1.93	2.00	2.25	2.48
	2. Fossil fuel	1.77	1.73	1.66	1.65	1.91	1.99	2.24	2.46
Payback Period (PBP)	1. Biogas	0.33	0.28	0.30	0.22	0.23	0.22	0.20	0.18
	2. Fossil fuel	0.30	0.25	0.26	0.19	0.20	0.19	0.17	0.16

*Data were calculated

Table 5.14 Simulation of Andungsari Coffee's processing model

Potential in CB, kg		Total Process	Fw	Sw	N	Hd	A/L	Wine	CM
75%, Specialty		24,000	7,200	4,800	2,400	2,400	2,400	2,400	2,400
12.5%, Premium		4,000	2,000	1,200	800	-	-	-	-
12.5%, Commercial		4,000	400	400	3,200	-	-	-	-
Total Processing (TP), kg		32,000	9,600	6,400	6,400	2,400	2,400	2,400	2,400
Economic Assessment									
Indicator	Scenario	All Products	Fw	Sw	N	Hd	A/L	Wine	CM
NPV	1. Biogas	3,142,070	887,281	515,356	459,221	260,201	288,478	356,330	428,302
(x1000 IDR)	2. Fossil fuel	3,109,179	870,914	504,456	449,864	261,789	289,189	357,059	429,007
Benefit Cost Ratio (BCR)	1. Biogas	1.87	1.80	1.73	1.63	1.93	2.00	2.25	2.48
	2. Fossil fuel	1.84	1.77	1.70	1.60	1.92	1.99	2.24	2.47
Payback Period (PBP)	1. Biogas	0.32	0.28	0.30	0.23	0.23	0.22	0.20	0.18
	2. Fossil fuel	0.29	0.24	0.26	0.19	0.20	0.19	0.17	0.16

*Data were calculated

To improve the income of the group, the fraction of coffee sent to specialty processing was assumed to increase, and the use of biogas has been applied to both the coffee roasting process, and cooking stoves for the group. The coffee processing assumption was modeled as 3:1, which means 3 for the specialty type, and the rest for premium-commercial, or 75% specialty and 25% the rest (Table 5.14). This condition is determined based on observations and surveys; some of the CB from handpicking can be selectively processed into specialty types (Fw and Sw) after submersion for selecting premium types. Premium and commercial grade beans were chosen for processing using the natural method optimum. The economic assessment is shown in Table 5.13, along with the assumed processing routes. Table 5.14 shows the NPV values are more feasible than the current conditions.

Finally, this simulation model encourages farmers to consider processing coffee on the basis of the raw material potential and product quality using specialty processing. The sustainability of coffee processing is determined by the balance of selection of specialty, premium and commercial processing methods.

5.10 Conclusions

This study conducted biogas experiments from different wastewater and sources from different processing routes at Andungsari Coffee Group, Bondowoso, Indonesia. This coffee group processes coffee into specialty, premium, and commercial grades. Mass-balances for coffee processing and energy flows were used as parameters for economic analysis. Two scenarios were applied to compare economic feasibility: the biogas scenario investing in biogas utilization as a renewable energy source and the fossil fuel scenario as a comparison. Through these two scenarios, the biogas scenario was concluded to have a greater impact on economic feasibility than the fossil fuel scenario. We simulated and modelled the optimization of coffee processing by increasing specialty production higher than premium or commercial processing. Finally, simulation modelling showed that increasing specialty processing coffee production was more economically feasible compared to the premium-commercial and fossil fuel scenarios at the Andungsari Coffee Group, Bondowoso. Through this study, the application of digesters was determined to be a useful tool for the future of Industrial Ecology Coffee (IEC), certainly, with the management of coffee production, and using renewable energy including biogas for coffee farmer group households.

6 Exploring the unique approach of evaluating the physical and sensory quality of coffee

6.1 Chapter introduction

Coffee plantations are vital for coffee farmers, particularly smallholders, and are the primary choice for producing high-quality export goods [6]. There are at least 25 types of Indonesian Arabica coffee; some can be grown as low as 700 meters above sea level (masl), including the Andungsari variety [172]. In Indonesia, approximately 28.5% of coffee plantations are Arabica, while the remaining majority is Robusta [173][174]. Robusta coffee is prevalent in commercial products, while high-quality Arabica varieties are sought after in specialty items and are recognized by the Specialty Coffee Association (SCA) as a standard for Cup of Excellence (COE) export opportunities [175]. The challenge smallholder coffee farms face is producing coffee quality that is of COE quality as a form of sustainable coffee production (SCP) [176][177].

The specialty coffee market is constantly expanding. Currently, smallholder coffee farms can only produce nano lots, which refers to the minimum quantity for export, approximately 100 kg of green beans (GB), through a small-scale process. These quantities are mainly produced for international contests, resulting in high profits, but the quantity is small compared to micro lots (600 kg) or commodity-scale production (above 20,000 kg). The benefit of improving the quality of coffee for smallholders is that it allows them to access the global coffee market [178]. In the coffee processing stages, fermentation is a key step that enhances the flavor of the coffee [132], such as the anaerobic method, which applies fermentation to cherry beans (CB). In the food industry, bioreactors are mainly used for producing alcoholic beverages, vinegar, yeast biomass, enzymes, yoghurt, aroma compounds, other lactic beverages, and pigments [179]. Changes in the aroma and flavor of coffee occur during the fermentation period, which is typically up to 96 hours. Beyond that, it will result in defective flavors, similar to wine [167]. Improving the quality of coffee beans is crucial for smallholder supply chains, particularly when coffee with different sensory profiles is in high demand.

Even as coffee quality is improved, the risk of environmental impact needs to be mitigated. In the fermentation stages, wastewater is generated. So it is essential to consider the impact of wastewater-based emissions and environmental risks [5], by utilizing wastewater as an alternative feed into the fermentation stages [104], and final wastewater can be used for biogas [180]. Wastewater, if not properly reused or recycled, contributes to the impact of Global Warming Potential (GWP) [53]. In the previous research, fermentation was monitored for the temperature, time, and stirring [168], without any gas monitoring.

This work conducted coffee processing to improve quality using anaerobic, inoculant, and mossto methods. The fermentation stages are applied in these methods to evaluate the quality, flavors, and GWP impact. This work designed a novel stainless steel fermentation, with measurement and monitoring of the following parameters: gas release during fermentation, pH, Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and Total Suspended Solid (TSS). Wastewater parameter content was considered for GWP [181]. The small reactor was used to observe performance during fermentation in order to assess the quality of GB and compare the GWP. For

the assessment of GWP, Life Cycle Assessment (LCA) was used to evaluate the environmental impact.

In our experiment, we developed a small reactor with a 25kg capacity to assess the Anaerobic, Inoculant, and Mossto processes. In a previous study, we produced cascara from coffee skin and coffee husk as a by-products of fermentation [8]. This study evaluates coffee flavors, bean quality, and the use of by-products (Cascara) in Industrial Ecology Coffee (IEC) for SCP, including GWP impact.

Figure 6.1 illustrates the classification of CB from the coffee tree and by-product options for improve bean quality, and valorization of by-products respectively. Harvesting with selective picking is a key factor determining the quality of specialty coffee. The IEC approach was used to implement the reactor fermentation concept, starting from smallholder coffee production and extending to the pilot plant at Andungsari Coffee Group. This study aimed to evaluate the quality of coffee and assessthe environmental impact due the implementation of fermentation methods. This serves as a model for other coffee farmers to adopt the Added Value to Zero Waste (A to Z) approach, aiming to move towards SCP.

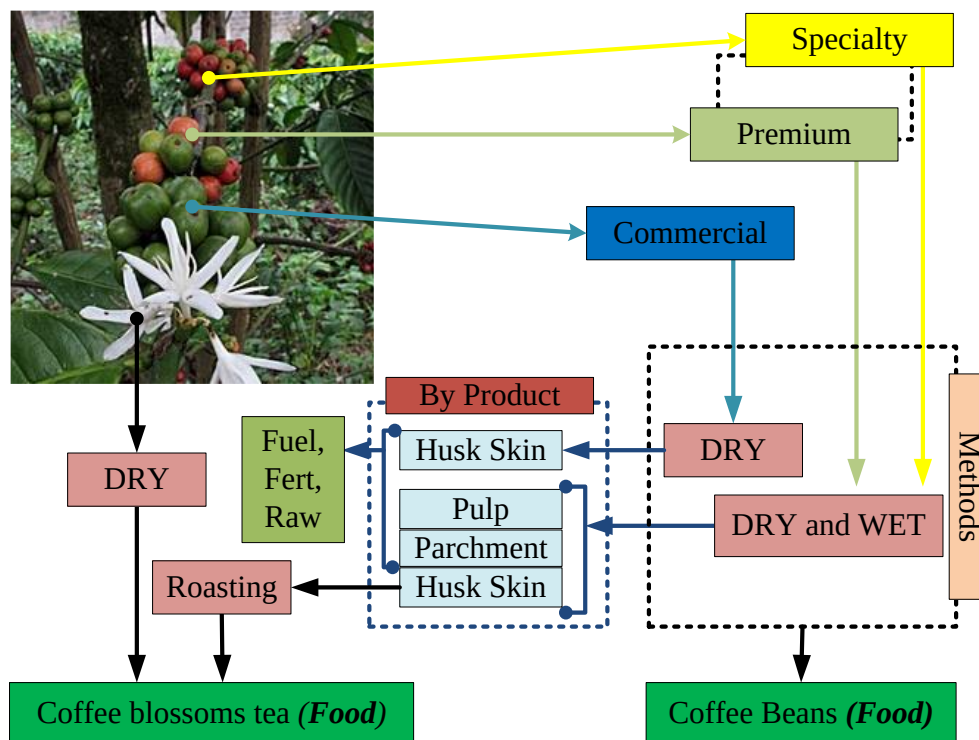


Figure 6.1 Classification of materials CB in coffee tree and options by-product

6.2 Material and methodology

6.2.1 Study area and boundary of coffee processing

The study was conducted at the Pilot Plant Andungsari Coffee Group, Bondowoso Regency, Pakis Village, East Java Province, Indonesia. Andungsari variety coffee (single variety) was chosen for specialty coffee from the plantation between 1,048 and 1,400 meter above sea level (masl) (Latitude: -7.9231361, Longitude: 113.708889). Coffee processing routes chosen were anaerobic (An),

inoculant (In), and mossto (Mos). The anaerobic method was simple: cherry beans (CB) were fermented in a reactor for four days. For the inoculant method, we added pineapple fruit, sugar, yeast, and coffee blossom to change the flavors. In mossto processing, CB were de-pulped to separate the Cherry skin (Cs) from GB. The GB were then fermented without the skin, and the wastewater from inoculant was added to the reactor tank. Figure 6.2 demonstrates the type of coffee processing methods applied in this study. This work also considered the conversion of by-products to novel food (cascara) by roasting. Cascara is a fruit-tea product that is typically produced from cherry skin (CS) dried without roasting [28].

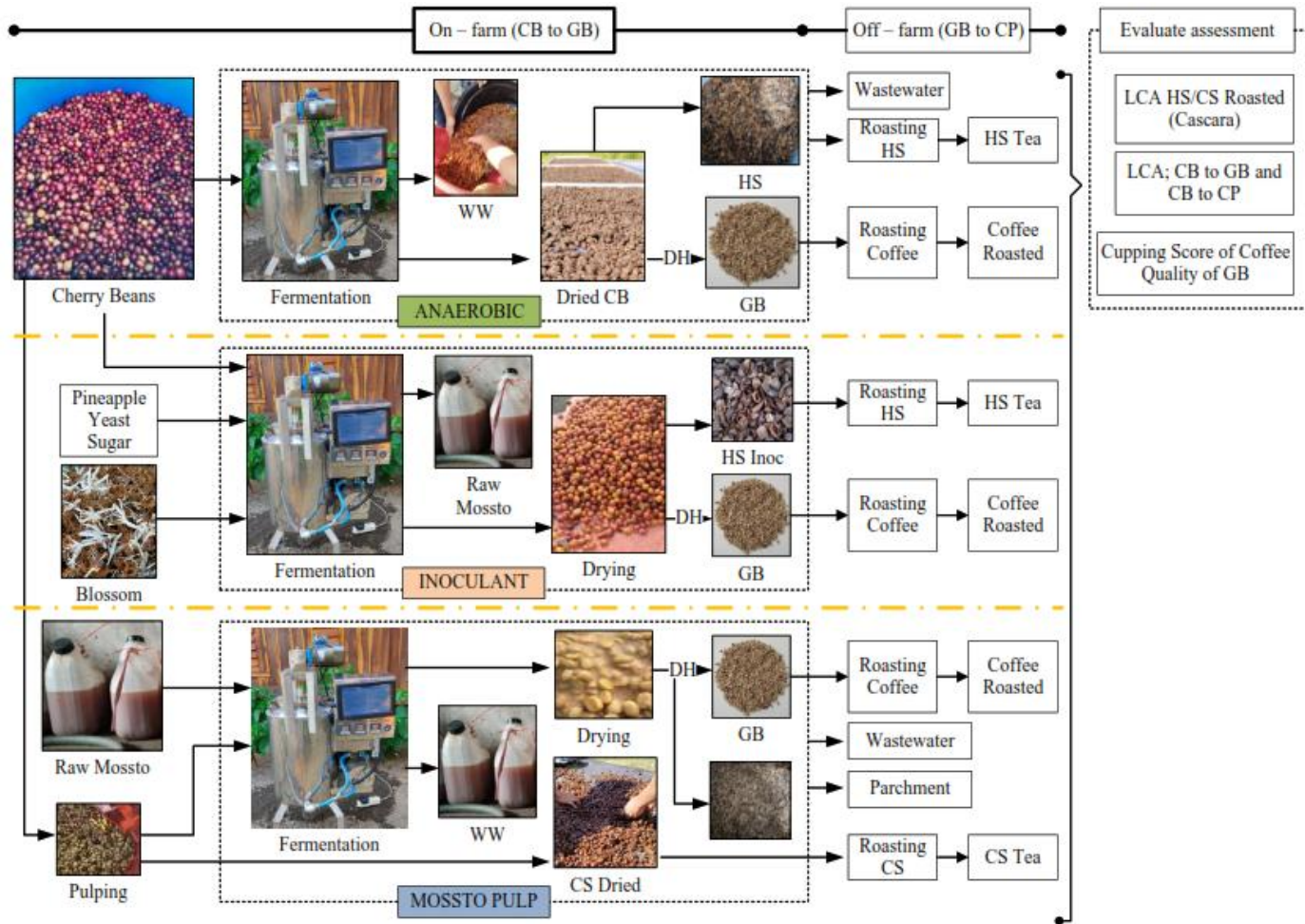


Figure 6.2 Scope of processing and assessment

6.3 Biological material

Red cherries were chosen to identify the quality and flavor. CB were taken during the Arabica coffee harvest season from April to July 2023. From observation, the CB sugar concentration was between 11% and 17% Brix. This was measured with an ATC optical refractometer. Figure 6.3 shows the appearance of CB when it was overripe, ripe, unripe, and raw CB. For Arabica coffee varieties, we needed to harvest according to the ripeness, selectively; unripe harvesting would reduce productivity in the next harvest season. Most of the Robusta did not follow the schedule. The harvested Robusta was usually mixed and chosen for producing commercial grade coffee. Even though there were also types of Robusta coffee processed as fine Robusta (Premium Grade), Robusta could not be said to be a specialty product under the COE classifications [182].

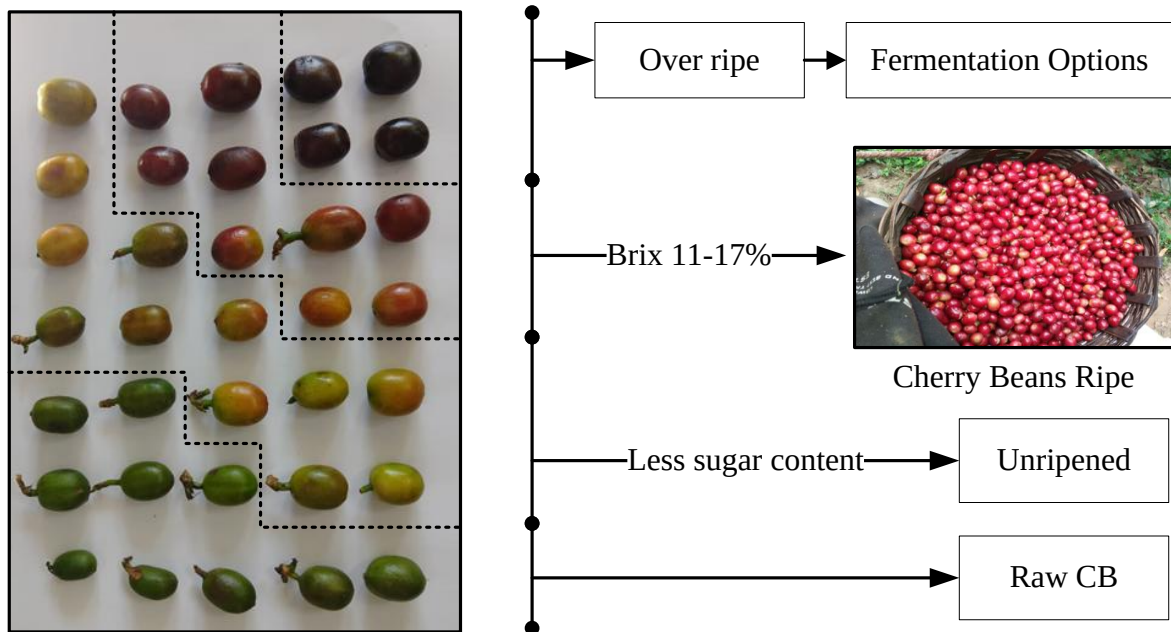


Figure 6.3 Classification of raw material selection

6.4 Physical and sensory quality

Standard National Indonesian (SNI) was chosen as the method for determining the grade of coffee. SNI has six standards based on defect scores [15]. Table 6.1 shows the grade reference for GB. The score assessment was based on the quantity of seeds with various defect score parameters. For example, first grade (highest quality) has a maximum defect value of 11. The quantity of sampled beans in the SNI test was approximately 300g, taken after the bean sorting stage. Next, the samples were tested at the Coffee Science Institute (CSI) laboratory and Indonesian Coffee and Cocoa Research Institute (ICCRI), Jember, East Java, Indonesia. The laboratory provided flavor scores as a comparative control [172]. Using the SCA method, they tested the coffee flavor using panelists who were certified Q Arabica Graders [182]. The cup taste was evaluated under the international Coffee Quality Institute (CQI) certificate, which considered 10 attributes (fragrance, flavor, aftertaste, acidity, body, uniformity, balance, clean cup, sweetness, overall, taint/defect) and the total score.

Table 6.1 Defect parameter score SNI

Grade Quality	Defect Parameters Score
Grade 1	11
Grade 2	12 - 25
Grade 3	26 - 44
Grade 4	45 - 80
Grade 5	81 - 150
Grade 6	151 - 225

The Q-Graders from the ICCRI and CSI provided assessment on bean quality. Then, we combined the scores for comparison of the results. Under these tests they serve the coffee in 8 minutes for scoring, the first score was fragrance to evaluate freshly ground coffee powder, then hot water was

poured over it with the water temperature from 95°C to 98°C. The extraction time was about 3 minutes, flavors and aftertaste were checked on the liquid coffee over approximate intervals of 1-2 minutes. Next, scoring on the attributes of aftertaste, acidity, body, uniformity, balance sweetness was made during 2-6 minutes. Lastly, scoring at around 6-8 minutes was done for clean cup, overall, taint or defect scores.

6.5 Design and description of the stainless steel reactor

The bioreactor has a volume of 0.0626 m³ and was made of stainless steel to ensure hygienic conditions for food production. Figure 6.4 provides a detailed explanation of the bioreactor. The stainless steel tank was designed in a cylindrical shape with a total capacity of 25 kg CB. The bioreactor has an inner diameter (d_0) of 400 mm, an outer diameter (d_1) of 480 mm, an outlet diameter (d_2) of 100 mm, and a height (h_d) of 600 mm.

This reactor was equipped with a hot water tank, with diameter (d_w) of 150 mm, and height (h_w) of 350 mm. Hot water was supplied to the water jacket when the temperature in the water jacket was below the set temperature of 30°C to 35°C to maintain the desired temperature. The gate valve opens automatically when the temperature increases or decreases. Cold water or hot water circulated through the inner and outer flow channels, and the radiator fan motor ran when hot water flow circulated. Digital temperature indicators on fermentation drums, hot water tanks, and water jackets were displayed during fermentation. The reactor had a stirrer motor to mix (25 Rpm) the CB, and an anchor motor for the final process.

The monitors in this fermentation reactor were used to measure gas release every two hours during fermentation (only CO₂, CH₄ auto monitoring), and N₂O by test using Gas Chromatography (GC). Meanwhile, in wastewater, measurements of Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD). Both gas and wastewater were considered for Life Cycle Assessment (LCA) analysis. Figure 6.5 shows the hourly power usage of the reactor for the heater, motor, stirrer, fan, pump, and module controller.

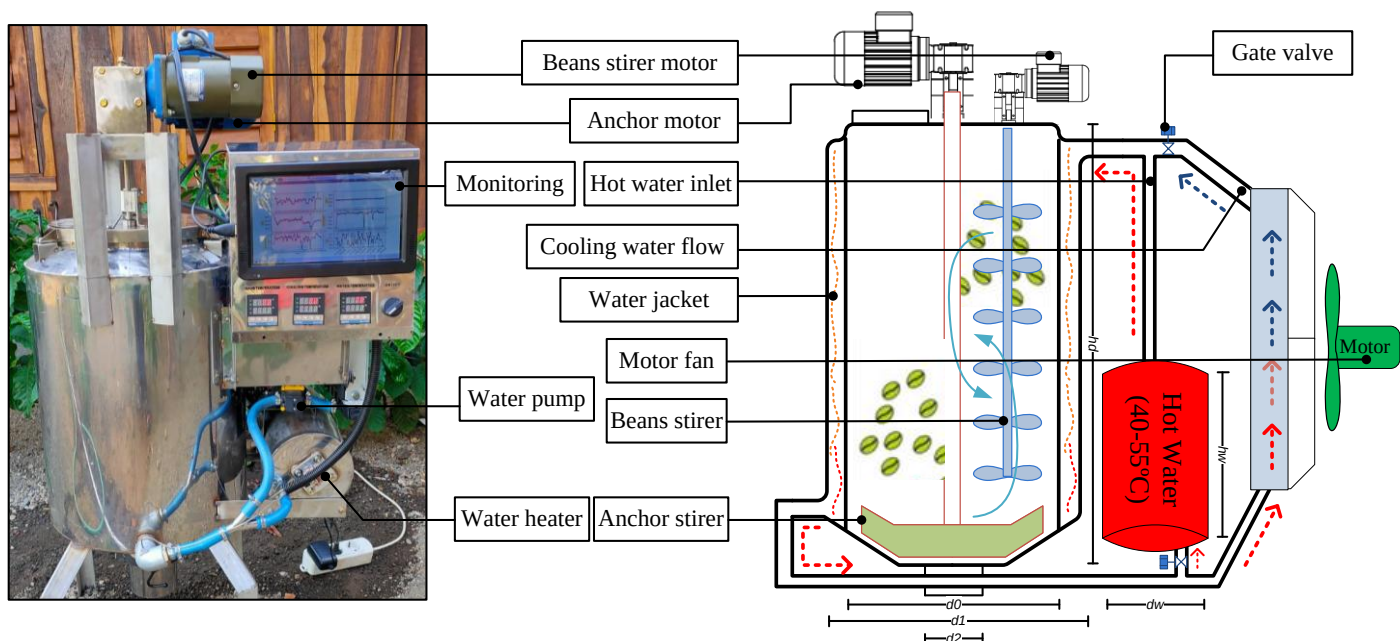


Figure 6.4 Sketch of the fermentation reactor

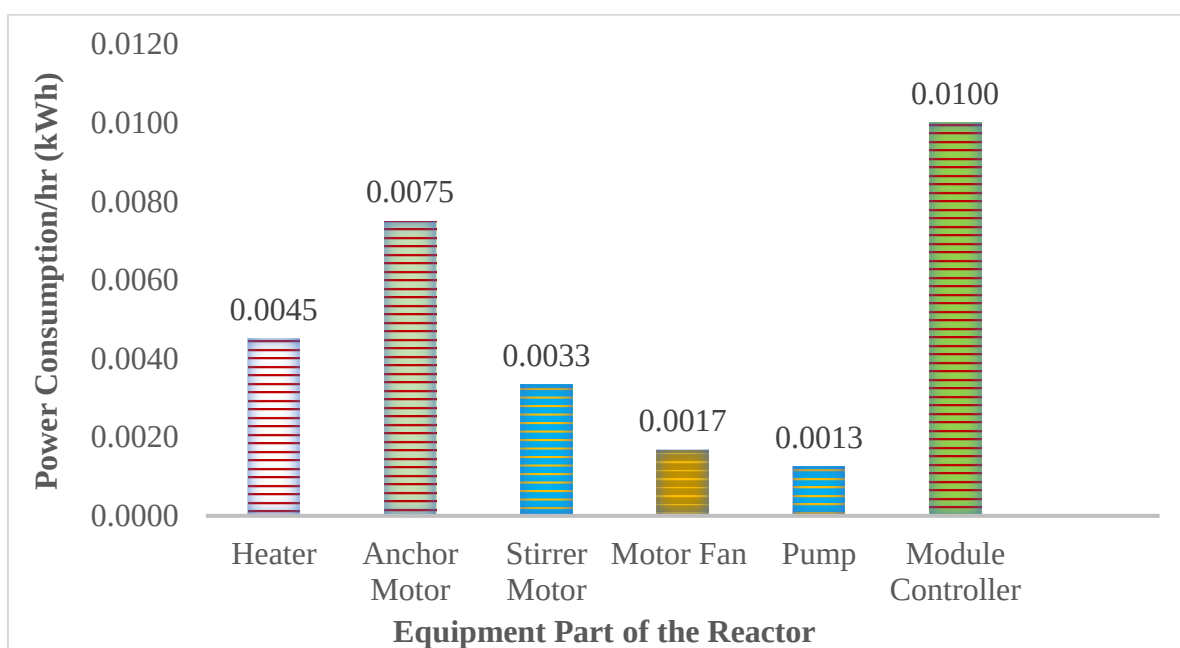


Figure 6.5 The consumption of electricity per hour in the reactor

6.6 Environmental impact analysis

This study presents assessments for global warming potential corresponding with anaerobic coffee processing, inoculants, and mossto, respectively; based on one kg CP as well as one kg Cascara (by – product). Comparative greenhouse gas emissions for various methods adopted in coffee production were calculated from direct observation and experimentation data, in addition to secondary used to LCA assessment purposes. The ReciPe 2016 midpoint level (ML) method was applied using SimaPro v9.3.0.3 [44] [13]. In this study, energy consumed was from local electricity. The electricity demand required to operate the reactor for an hour is illustrated in Figure 6.5. Energy

demand attributed to the relevant stages and activities are shown in Table 6.2 for the impact of dry processes, and the mass balance shown in Table 6.3.

Table 6.2 Energy demand every stage

Materials Arabica	Unit	Energy Input		
		Anaerobic	Inoculant	Mossto
Processing Flow				
Motor Cycle (Petrol)	L	0.25	0.25	0.25
Washing CB (Water)	L	20.0	20.0	20.0
Depulping	kWh	-	-	0.06
Reactor Fermentation	kWh	2.13	2.13	2.13
Dehulling	kWh	0.04	0.04	0.03
Roasting Coffee	kWh	0.44	0.45	0.46
Roasting Coffee Skin	kWh	-	0.65	0.63
Grinding Coffee	kWh	0.19	0.20	0.20

*Data were measured.

Table 6.3 Mass balance by processing method for Andungsari coffee

Stages process	Processing flow (kg)		
	Anaerobic	Inoculant	Mossto
Cherry Beans (CB)	25.0	25.0	25.0
Depulping	-	-	12.5
Inject Inoculant	-	1.25	-
Inject Raw Mossto	-	-	2.3
Fermentation	25.0	26.3	14.8
Drying CB/Coffee Pulp	11.0	11.3	7.5
Drying Cherry Skin	-	6.5	6.25
Dehulling	4.8	4.8	4.9
Hand Sorting	4.4	4.5	4.6
Roasting GB	3.8	3.9	3.95
Roasting HS	5.2	5.5	-
Roasting CS	-	-	5
Grinding	3.8	3.9	3.95

*Data were measured.

6.7 Results and discussion

6.7.1 Physical coffee quality

In the coffee processing, approximately 25kg of cherry beans (CB) were involved per batch reactor. The motor stirrer equipment automatically rotated clockwise for five minutes every hour, maintaining a set rotation speed of 25 Rpm for mixing the CB. The anchor motor function was employed to release the CB when fermentation was complete. The water heater in this reactor was activated when the temperature of the CB during fermentation decreased; a gate valve would automatically open to allow the flow of hot water as needed. The temperature set point was maintained at 30°C to 35°C for the fermentation in this study [183][184][163]. The radiator was

used for a water cooling system with the water jacket temperature set point. This reactor also measured COD, BOD, and TSS as considerations during fermentation [132]. The default energy demand per hour in the reactor is displayed in Figure 6.5, while Figure 6.4 illustrates a study aimed at enhancing the quality of GB and the flavors of the coffee.

Smallholder coffee farms can manage the coffee processing depending on the targeted product. In on-farm production, smallholders need to manage the coffee plantation, including fertilization, pest control, proper periodic harvesting, and technological support for processing from cherry beans to green beans. Due to poor management, defects in green beans can occur in the plant due to insects, technology, or unpredictable seasons [185]: partial black seeds cause by heavy rain during harvest, whole black seeds from overripe CB or insects, and spotted black caused by moisture content in storage of GB. All types of CB can be attacked by insects, including *Hypothenemus hampei*, which causes holes in the ostioles. Remaining CB will rot, the CB will become low density, or will fall due to *saprophytic* microorganisms. Furthermore, GB defects due to processing are cracked seeds, seeds mixed with parchment skin, freckles, and husk skin (Figure 6.6) by processing. Storage also affects seed defects, such as more than one hole in the seeds due to insects and brown seeds because they were stored with a moisture content of >12%. Defects of GB caused by insects can be avoided by selecting appropriately ripe CB, but this does not mean that unripe or overripe CB cannot be harvested. Still, arranging a picking schedule for each tree branch is necessary.

SNI-based scoring points range from 0.2 which marks minimum rank to a maximum rank of 1 [15]. In order to determine this grade, beans which had defects were counted and multiplied by the respective score for the type of defect. Score ranges for grades between 1 and 6 are shown in Table 6.1. These are the result of multiplying the scores in Table 6.4 by the count of defective beans in a 300g sample. Defect scores for anaerobic, inoculant and mossto were evaluated at ICCRI laboratory located in Jember, East Java Province, Indonesia [172].



Figure 6.6 On–off farm handling on coffee processing

The final score was first grade, if GB defects are left and not sorted, this will affect the taste of the coffee. The final defect score in this study was between 5.5 and 6 (Table 6.4). GB defects affect the flavor because the aroma and flavor resulting from on-farm problems will cause greater bitterness. Furthermore, it was crucial to handle coffee carefully both on and off the farm to maintain the first grade with scores less than 11.

Table 6.4 Defect score analysis

No	Type of Defect (Seed)	Defect score	QS An	SV An	QS In	SV In	QS Mos	SV Mos
1	1 Black seed	1	0	0	0	0	0	0
2	1 Half seed	0.5	0	0	0	0	0	0
3	1 Cracked black	0.5	0	0	0	0	0	0
4	1 Dried cherry	1	0	0	1	1	0	0
5	1 Dark brown	0.25	0	0	0	0	0	0
6	1 HS big-sized	1	0	0	0	0	0	0
7	1 HS medium-sized	0.5	0	0	0	0	0	0
8	1 HS small-sized	0.2	0	0	0	0	0	0
9	1 Parch skin seed	0.5	0	0	0	0	0	0
10	1 Parch big-sized	0.5	2	1	1	0.5	3	1.5
11	1 Parch medium-sized	0.2	0	0	0	0	0	0
12	1 Parch small-sized	0.1	0	0	0	0	0	0
13	1 Cracked seed	0.2	15	3	15	3	14	2.8
14	1 Pale seed	0.2	0	0	0	0	0	0
15	1 Hole seed	0.1	5	0.5	5	0.5	5	0.5
16	1 Hole (more than 1)	0.2	0	0	0	0	0	0
17	1 Freckles seed	0.1	10	1	10	1	10	1
18	1 Branch big-sized	5	0	0	0	0	0	0
19	1 Branch medium-sized	2	0	0	0	0	0	0
20	1 Branch small sized	1	0	0	0	0	0	0
Final defect score			5.5		6		5.8	

Quantity seeds = QS; Score value = SV; Anaerobic = An; Inoculant = In;
Mossto = Mos.

6.8 Sensory coffee quality

Sensory analysis gave a score to coffee beans depending on their sensory attributes. All Q graders had distinct organoleptic reference ranges, but professionals followed a precise, uniform technique during rating, and have calibration regularly. The material being tested was anonymous. The medium roasted coffee beans were evaluated under an SCA protocol [182], for aroma profiles in laboratory-based studies done at CSI and ICCRI. Table 6.5 presents the test results, which are used to validate the observations from the fermentation reactor. We combined the overall scores and presented the combined flavor notes from the panelists in Table 6.6. We detailed the taste observations during the cup-test when evaluating the inoculant. The mango flavor is present due to the effective extraction of cherry skin during fermentation, resulting in a tropical fruit aftertaste in the cup. The lemon flavor is typically attributed to mucilage during fermentation, contributing to good acidity.

Table 6.5 Sensory quality attributes for Andungsari coffee by processing method

Cup test Attributes *	Panelist CSI			Panelist ICCRI		
	Anaerobic	Inoculant	Mossto	Anaerobic	Inoculant	Mossto
Fragrance	7.75	8.25	8.25	8.25	8.38	8.38
Flavor	8	8.25	8	7.75	8.38	8
Aftertaste	8	8	8	7.75	7.75	7.75
Acidity	8	8	8.25	7.75	7.5	7.75
Body	8	8.25	8.25	7.75	7.88	7.75
Uniformity	10	10	10	10	10	10
Balance	8	8.25	8	7.75	8	7.88
Clean Cup	10	10	10	10	10	10
Sweetness	10	10	10	10	10	10
Overall	8	8.25	8	7.75	8	7.88
Total Score	85.75	87.25	86.75	84.75	85.89	85.39

*Data were measured from panelist CSI and ICCRI

Table 6.6 Total score, classification, and description by processing method

Processing Method*	Compile Score	Quality Classification	Notes Description
Anaerobic	85.25	Excellent-Specialty	Fruit, berry, clean, dry fruit, molasses, grape, juicy, floral, chocolate, complex, brown-sugar, spicy-chili-like
Inoculant	86.57	Excellent-Specialty	Brown sugar, fruit, berry, clean, citrus, caramel, tropical fruit, chocolate, coffee blossom, sweet, balanced, mango aroma, rose tea, star fruit.
Mossto	86.07	Excellent-Specialty	Brown sugar, fruit, berry, clean, citrus, caramel, chocolate, balanced, molasses, black tea, lemony, greenish, honeyed

*Data were measured from panelist CSI and ICCRI

Another study on flavor scores in anaerobic processes gave flavor notes for dried fruits, red fruits, and acetic acidity with scores above 80 [21]. Fermentation using inoculants has an impact on the quality of sensory characteristics. This is interesting, especially in the last few years; specialty coffee has become a demand segment, moving from regular to particular products, especially using technology [116]. In this study, farmers can improve the quality of GB up to Excellent-Specialty through the use of a reactor by controlling the temperature with a stirrer system. The inoculant for each attribute averages above point 8 (Figure 6.7). The impact of fermenting CB was identified in the note description, product of GB has the advantage of tropical fruit and sweet and balanced aromas (inoculant and mossto). On the other hand, others got points below 8 in several attributes. A score below 85 means GB is considered a Very Good-Specialty coffee, highly-valued but not of the highest quality [182][6].

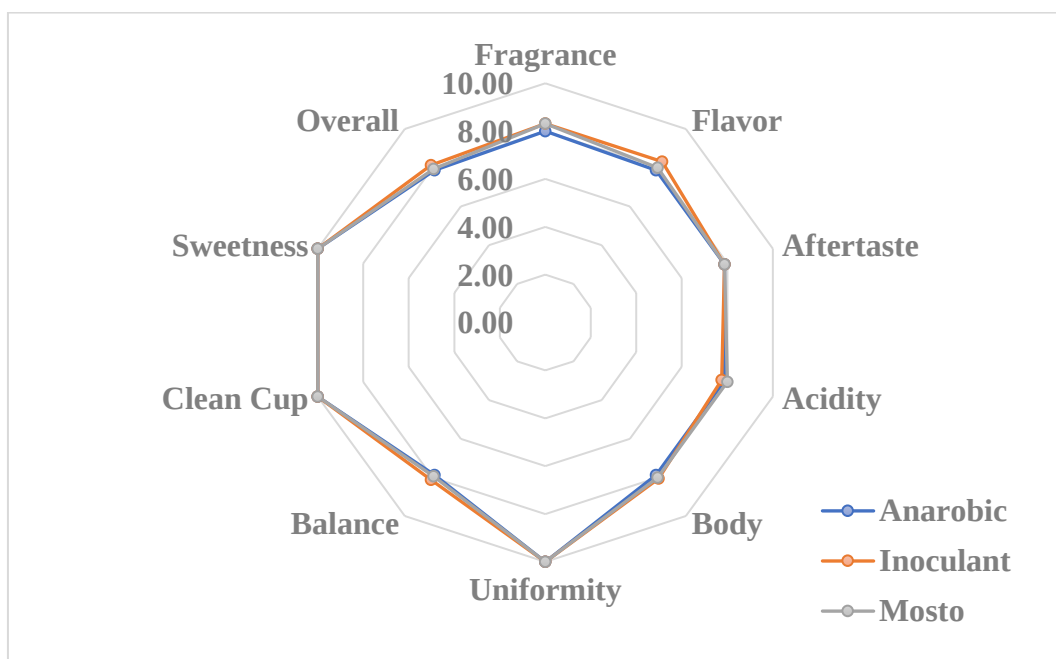


Figure 6.7 Sensory diagram of Andungsari variety of coffee based on processing method

The notes were described by the panelists for each processing method. Brown sugar flavours were caused by the perfect roasting time, with the color of a medium roast (Agtron 55) [20], fruity, tropical fruit, citrus, and coffee blossom (flower and fruit groups) were caused by the cherry skin and mucilage being properly fermented. Chocolate, caramel, and molasses flavors were balanced and juicy due to proper extraction and medium roasting. Meanwhile, the black tea note tastes like dry leaves tea but is also greenish (like tea extract).

6.9 Impact assessment

The LCA included data from the mass balance, wastewater, and gas production during fermentation (Table 6.2 and Table 6.3). We decided on four days of fermentation based on the results of physical tests; one day of fermentation did not leave any traces on the physical and sensory CB. If fermentation is carried out for two days or three days, this is commonly done in full wash processing, and the score value during this fermentation time is still below 82. Five-day fermentation causes an unfavorable acid (sour) taste for the panelists. Fermentation of five to more than ten days can cause the taste of wine in GB. The description of the wine taste does not match COE requirements. However, gas production and wastewater characteristics such as COD, BOD, and TSS are essential in this LCA. Figure 6.8 to Figure 6.10 provide illustration of the gases produced during fermentation. Meanwhile, Figure 6.11 shows the observed values of COD, BOD, and TSS.

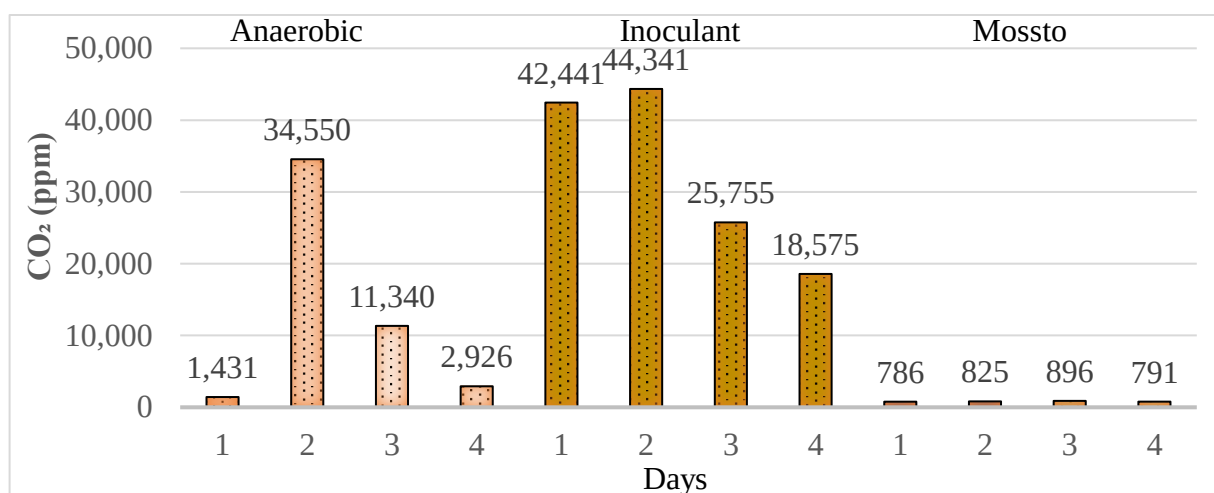


Figure 6.8 CO₂ production during fermentation

Production gas from the reactor was measured automatically in the reactor, but also this work still captured and measured it using Gas Chromatography (GC) for comparison; we tested the gas at the Politeknik Negeri Jember. Figure 6.8 illustrates the highest average of gas from inoculant processing, approximately 44,341 ppm CO₂ on the second day; a decrease in inoculant fermentation CO₂ gas occurred on the fourth day, was about 18,575 ppm. We analyzed this as caused by a mixture of pineapple, sugar, and yeast, causing increased CO₂ production. Including anaerobic, on the second day, it reached 34,550 ppm CO₂. The CO₂ production with the Mossto method is lower compared to other methods, despite using wastewater from inoculants as fermentation material. The CO₂ production during the Mossto fermentation ranged from 791 ppm to 896 ppm, starting from the beginning of the fermentation to the end.

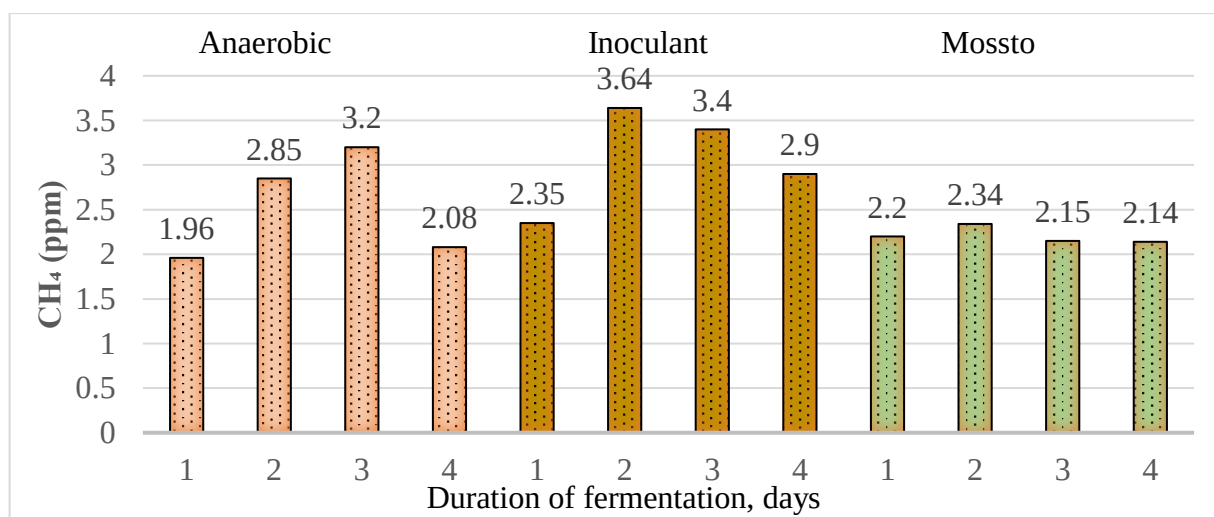


Figure 6.9 CH₄ production during fermentation

On the other hand, during fermentation gas CH₄ was produced. Figure 6.9 illustrates the CH₄ gas levels during anaerobic fermentation. At the beginning of fermentation, CH₄ concentration was 1.96 ppm, which increased to 3.2 ppm on the third day of fermentation and then decreased to approximately 2.08 ppm at the end of the process. In contrast to the inoculant method, approximately 3.64 ppm of gas was produced on the second day, gradually decreasing towards the end of

fermentation. While in mossto fermentation the production of CH₄ was between 2.14 ppm and 2.34 ppm.

Furthermore, Figure 6.10 illustrates the release of N₂O gas during fermentation. The inoculant methods still result in higher levels than anaerobic and mossto, with about 2.94 ppm of N₂O gas at the beginning, although the levels decrease sharply. This work was considered of the gas production to accumulated for calculations to the secondary database in ReciPe 2016 for evaluate of LCA.

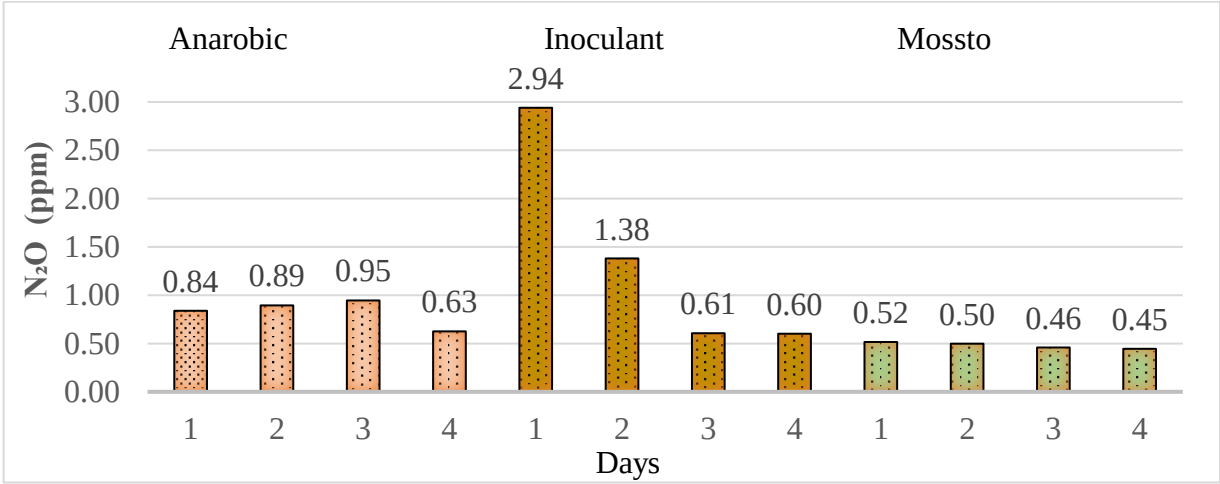


Figure 6.10 N₂O gas release during fermentation

This study also considered fermentation wastewater by measuring COD, BOD, and TSS concentration [5]. Mossto processing provides a higher wastewater contribution than anaerobic and inoculant, the utilizing anaerobic wastewater increases wastewater concentration in mossto process [170], but when wastewater was final flow, it is potential for ingredient cascara syrup [55].

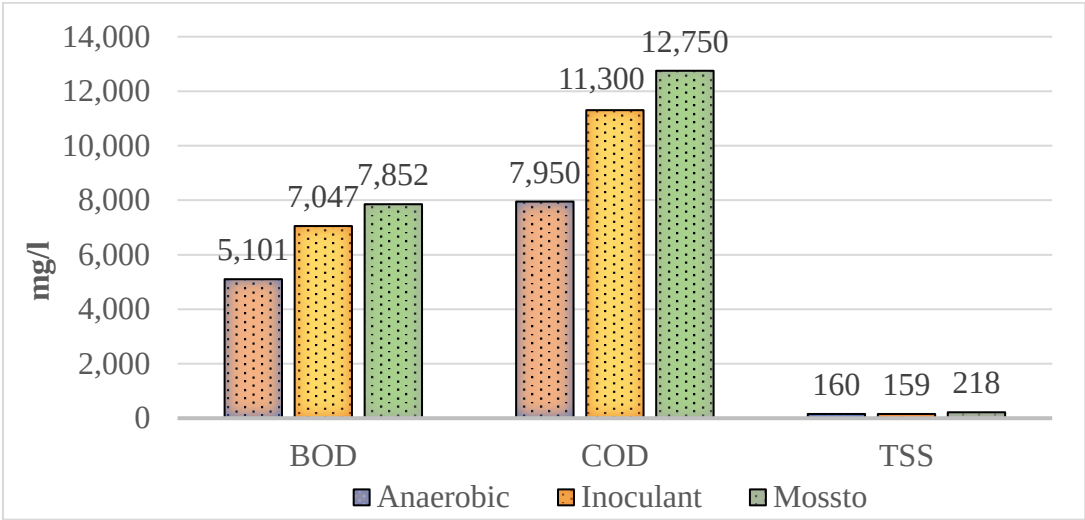


Figure 6.11 Chemical properties wastewater

The mass balance for calculation of the LCA was described in Table 6.3. The anaerobic method does not remove the cherry skin (Cs), so after fermentation, it is dried, and the husk skin is peeled, producing GB and Husk skin (HS). From these three methods, the potential for by-product novel food to become coffee tea was between 5 and 5.5kg, producing approximately 4.8 - 4.9kg GB. Across all fermentation stages, 25kg raw CB and 12.5kg Pulp Beans (PB) produce wastewater of

1kg (anaerobic), 2.25kg (inoculant), and 1.95kg (mossto). This study was also conducted on Hs and Cs roasted as a by-product of Cascara.

The GWP contribution caused by using electricity during four days in the reactor contributes to higher potential GWP than other contributors (Figure 6.12). Energy consumption was 2.13kWh, which is the cause of the main contribution compared to de-pulping, dehulling, roasting, and grinding stages. The GWP contribution during processing, anaerobic processing from CB to CP was 1.39kg CO₂-eq per one kg CP; contribution for operating the reactor from local electricity was 0.67 kg CO₂-eq and 0.72 kg CO₂-eq for the remaining processes. Meanwhile, in the inoculant processing (fruit injection) contributes a GWP of 0.03 kg CO₂-eq. Furthermore, in mossto processing, wastewater from inoculant fermentation (raw – mossto) contributes a GWP of 0.02 kg CO₂-eq.

Table 6.7 Results of this study compared with other processes and by-products

Coffee processing*	Stages		By-Product
	CB to GB	CB to CP	Coffee Tea
Anaerobic	0.9 kg CO ₂ -eq	1.39 kg CO ₂ -eq	0.17 kg CO ₂ -eq
Inoculant	0.98 kg CO ₂ -eq	1.47kg CO ₂ -eq	0.19 kg CO ₂ -eq
Mossto	0.99 kg CO ₂ -eq	1.5kg CO ₂ -eq	0.2 kg CO ₂ -eq

*Data were calculated

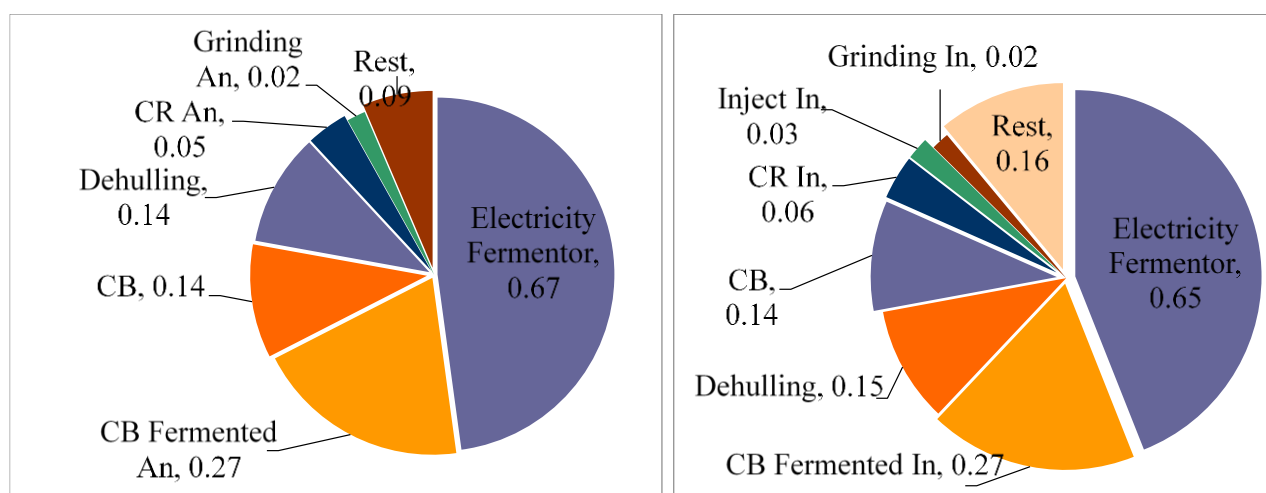


Figure 6.12 Comparison of the contribution of anaerobic and inoculant

The impact of GWP on anaerobic processing per kg GB from CB to GB was 0.9kg CO₂-eq, and from CB to CP was 1.39kg CO₂-eq (Table 6.7). This anaerobic process also produces Husk Skin (HS), which was 7.5kg dried, and from roasted HS was 5.2kg cascara (by-product coffee tea). The GWP contribution of roasted HS was 0.17kg CO₂-eq per kg HS roasted. Inoculant processing contributes 1.47kg CO₂-eq for one kg CP, stages from CB to CP. Furthermore, producing GB has emissions of 0.98kg CO₂-eq per kg GB. Another impact of GWP from roasted inoculant HS was 0.19kg per kg roasted inoculant HS from 6.5kg dried HS to 5.5kg roasted HS. Finally, from wet CS 12.5kg to 6.5kg CS dried, this product is generally called cascara and can be consumed as tea [186]. From dried CS to CS roasted, approximately 5kg contributed GWP was 0.2kg CO₂-eq for one kg roasted CS. Meanwhile, CB to CP mossto processing is the highest; it was 1.5kg CO₂-eq per kg CP and 0.99 kg CO₂-eq per kg GB (Figure 6.13).

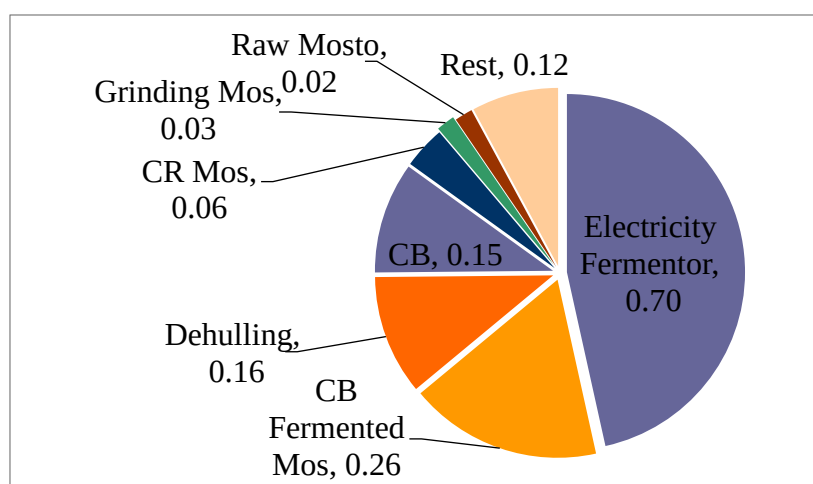


Figure 6.13 GWP contribution of mossto processing

This study compares the GWP of the dry methods of coffee processing (anaerobic, inoculant, and mossto). The mass balance of raw materials influences the GWP contribution from each process, meaning that a good coffee bean yield (without defects) can provide quality GB and low GWP. It would be best for farmers to implement a regular red-picking schedule, primarily if they focus on specialty processing. Furthermore, the capacity of this reactor is relatively tiny, with a CB of 25kg and yield of dried GB between 4.4 and 4.9kg. The total power of 335 watts in the reactor has the potential for a reactor capacity of between 70 and 100kg/batch. Arabica by-products, such as cascara from wet processed cherry skins, are generally only dried in the sun and not roasted, but cascara roasted reduced fatty acids [52]. Other case, during the fermentation process with inoculant from lactic acid bacteria, an increase in the flavor compounds aldehyde, furan, and acid would increase sour and nutty odor. However, if over-fermented it will produce over-acidity and become sour; it is a flavor defect and has the potential to score below 7.5 [187].

6.10 Conclusion

The novel stainless steel fermentation reactors were designed and approved for producing high-quality and specialty coffee. Monitoring temperature control, gas production, water jacket systems, and wastewater concentration measurements support the reactor by providing primary data for evaluating environmental impact. High quality coffee was achieved through controlled hand pickling, fermentation control, and processing. The coffee high-grade classification was obtained based on sensory perception. The sensory perception indicated that the inoculant modified the flavour attributes, enhanced the quality, and increased their SCA scores. The utilisation of wastewater for mossto methods was the solution to obtain optimalization of beans quality and increase SCA scores, even lower than inoculants. The anaerobic SCA score was lower than that of the inoculants and mossto, caused by anaerobic fermentation without the addition of materials. The GWP of Anaerobic coffee and the subsequent use of the by-product (cascara) was also lower than that of Inoculant and Mossto. Different studies on fermentation with other tools may produce different results. However, the fermentation reactor, with the ability to provide key indicators, is a valuable tool for smallholder coffee producers in conducting environmental impact evaluations and enhancing coffee quality.

7 Roasting impacts and by-products

7.1 Chapter introduction

This chapter presents two significant aspects of coffee production that can be important for industrial ecology approaches – the roasting stage and the production of salable by-products from otherwise disposed waste streams. The roasting of coffee is one of the main processes to finalise the flavor of the coffee product, but it uses energy for heating, which can potentially be a sink for waste energy produced in other stages of the coffee production cycle. In order to understand the amount of energy required and what chemical processes it drives, this chapter investigated the roasting profile and, energy consumption and emissions. The chapter also looks at the production of “coffee tea” – referred to as cascara – as an upgrade product from the husk skin, cherry or coffee flowers.

7.2 Downstream coffee production (coffee roasting)

While coffee production can be impacted by climate change, it is also important for the sector to consider how it can improve its own performance environmentally. Mitigation of emissions from all processes in the coffee processing chain using alternative energy should be a priority as a contribution to mitigating the impacts that threaten the industry. Utilizing wastewater from coffee processing into biogas is a further step towards Sustainable Coffee Production (SCP) [27].

Arabica coffee is often processed for different markets relative to Robusta. Robusta products are commercial products (lower price and lower quality requirement), so they are handled on the plantation [28], with the specific processing methods being important for the impact on sustainability. Almost all Robusta processing is carried out using the dry process, which currently benefits farmers most [29]. Coffee processing produces around 0.42kg CO_{2eq} per kg cherry emissions from transportation and 0.08kg CO_{2eq} per kg Coffee roasted from LPG Sources and Local Grid electricity [30]. Generally, coffee processing is divided into two types - wet processing and dry processing [31][32][5]. Figure 2.1 describes the wet and dry coffee processing processes, divided into on-farm and off-farm categories. It should be noted that the on-farm processes in each processing type are not segregated at the same point, so it is not a simple matter to separate the flows and processes. Primary products (On-Farm) can be sold directly to coffee processors, while secondary products (Off-Farm) are segmented by smallholders, and Small-Medium Enterprise (SMEs).

Coffee roasting is part of the off-farm processes; small producers can roast coffee by buying Green Beans (GB) from suppliers, determining the roast profile and aiming to develop the best aroma, color, and taste [33]. The roasting method can be *fast*, *medium*, or *slow roast* [34]. Moreover, all stages in the coffee process contribute to Global Warming Potential (GWP), with most coffee processing using fossil fuel sources. Replacing LPG with biogas is one potential method for mitigation of the emissions produced in the coffee roasting stages. For example, coffee process by smallholders in Jember contributed emissions of around 1.2kg CO_{2eq} per kg Coffee Powder (CP) with scenario fossil fuels, and biogas this was reduced to 0.42kg CO_{2eq} per kg CP [27].

LCA is used to calculate the potential emissions from coffee roasting, with the use of energy sources such as solar panels and the local electric grid compared. A previous study has demonstrated solar

panels and local grid electricity leading to 0.318 CO_{2eq} , 0.744 CO_{2eq} per kg CR [35]. The scenario of biomass as energy in the coffee processing process in Mexico was previously shown to produce lower emissions than fossil energy [36]. Economically, CR has been shown to provide a beneficial impact compared to GB products in the Robusta Bromo Mountain coffee farmer group [37], but the importance of selective processing during the production process and considering the use of alternative energy as a supporting energy source needs further investigation – from direct economic, environmental and potential marketing perspectives. Smallholders in coffee processing are essential to sustainable coffee production [23]; through collaboration with smallholders, the industry will be strong and sustainable with quality GB [38].

In the case of coffee, it is important to define the functional unit for evaluation. Roasters use the color profile to indicate various levels of roast. In this case, the roast color profile tested is based on codes #95 very light, and #25 very dark [39]. As roasting progresses, changes can be seen physically occurring with time and changes in temperature during the roasting process, with coffee from a water weight content of 12% to around 5% [40]. The changing color during coffee roasting also has a relation with the coffee taste [39]. There has not been any previous detailed explanation of the emissions arising at each stage of the roasting process. The novelty of this research is to explain the potential emissions from the coffee roasting process explicitly by dividing it into three roasting stages: first, the Dehydration stage; second, the Maillard reaction stage; and third, the Development stage. A coffee roasting curve was formed at each stage, which became a reference for smallholders to determine the roast profile.

In this study, we discuss the potential emissions generated by the roasting stage of coffee with Arabica and Robusta from two different types of processing. Potential emissions reduction analysis has been undertaken with LCA, using SimaPro software and the ReCipe 2016 method. Two different energy sources: solar panels-biogas and local grid electric-LPG, are used for comparison.

7.3 Case study and methodology

This study used raw dry coffee materials, Arabica and Robusta, from the Processing Group at the Indonesian Coffee and Cocoa Research Institute (ICCRI). The coffee roasting was done at a company in Jember Regency, East Java. LCA is used for the analysis of Global Warming Potential (GWP) [41][42] in SimaPro V9.3, with the ReCipe 2016 midpoint level method as an impact assessment [43][44]. The Eco-Invent database was used to calculate the GWP of production using Local electricity – LPG (LL), and Solar Panels-Biogas (SB). Consumption of LPG and electricity was measured experimentally. Figure 7.1 shows the flowsheet of coffee roasting assessment boundaries. Data were collected during August and September 2022, using direct observation and experimentation at the Gusto Coffee Company, Jember, East Java-Indonesia.

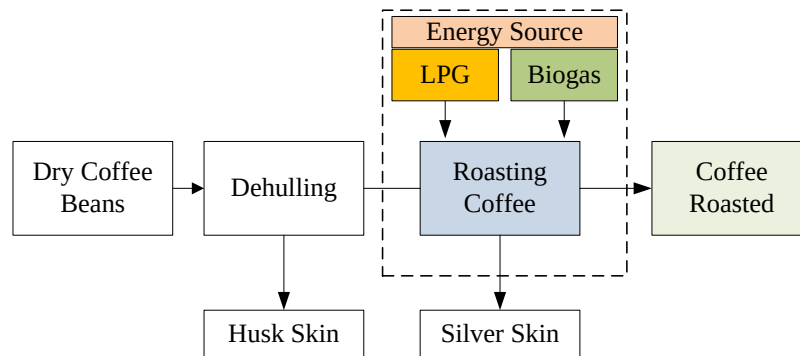


Figure 7.1 The scope of the study is presented in the dash-line

The functional unit defined for this study is one kilogram of coffee roasted at a medium level (*Agtron* 55). This study uses a roasting application and monitoring to display graphs during the process, including temperature, time, and gas consumption (Figure 7.2). The monitoring system is connected via a USB cable to a microcontroller coffee roaster machine. Drum speed control ranges from 60 to 75 rpm as a variable for control motor rotation, airflow control for heat power, and heat losses; it also detects bean temperature and drum temperature in real-time, and the gas pressure indicator is read during the roasting process—gas pressure is converted to gas consumption in this monitoring system. The monitoring system readings are presented as a roasting curve and can be saved in the form of images and exported to Excel files. At the same time, observations record the amount of electricity demand using a digital power meter (Figure 7.2) during the roasting process. We completed the analysis by comparing the GWP of the two energy sources and separating it into the three contributing stages of the coffee roasting process; Dehydration, Maillard, and Pyrolysis [45]. The real-time monitoring system records temperature increases or decreases and time during the roasting process. These temperature changes help to identify the changing processes in roasting the coffee. These three stages can be read through the monitoring system, divided in time ranges from 0 to 4 minutes, 4 to 8 minutes, and 8 to 10 minutes. Data is stored as a reference for the roastery for the roasting stage with the same type of coffee beans. This study used coffee roaster samples, in a roaster machine with a capacity of 200g.

Table 7.1 shows the specific tools utilised. These tools were connected to software for the monitoring system on temperature, time, and gas pressure. Solar panels are used during the dehulling and roasting processes, with four monocrystalline type panels and 100A batteries (Table 7.2). However, this study does not detail the GWP impact due to the dehulling process, because it is focused on the three stages of the roasting process, which should eventually be able to determine the relative impact of alternative roast levels, taste profiles and beans. Figure 7.3 shows a roaster machine, solar panels, and AC-DC power meters.



Figure 7.2 The company's coffee roaster machine application



Figure 7.3 (a) Solar panel, (b) Coffee roaster machine, (c) AC power meter (black), DC power meter (white)

Table 7.1 Roaster machine specifications

No	Materials*	Parameters
1	Drum Stainless 304	125mm; tick 2mm, L 120mm
2	Tray Stainless 304	L x W x H: 220 x 65 x 40 mm
3	Body Stainless 304	2mm thick, L x W x H: 380 x 270 x 270 mm
4	Gas Indicator	0 - 100 millibar
5	Temperature	Digital Beans, Monitoring Connections
6	Capacity	100-200g per batch
Specification*	Power (Watt)	
7	Motor Drum	15
8	Air Flow Fan	10
9	Cooling Fan	10
Total power (Watt)		35

*Data taken observation roaster machine

Table 7.2 Installation specifications

No	Type Panel*	Monocrystalline	Energy DC	DC to AC
1	Maximum Power (P_{max})	100 W	-	-
2	Maximum Power Current (I_{max})	5.62 A	-	-
3	Maximum Power Voltage (V_{max})	17.8 VDC	-	-
4	Open Circuit Voltage (V)	21.8 VDC	-	-
5	Battery (Gel)	-	100 Ah, 12 V	-
6	Inverter Cosine Wave	-	-	1000 W
7	Power Meter Indicator	-	-	100 A

*Data taken installation

The coffee roasting mass balance inventory is presented in Table 7.3. Roasting milestone parameters were measured respectively; raw material, bulk density in GB, bulk density in CR, apparent swelling, turning point, first crack, and second crack. Next, the emissions factor was applied to calculate LCA [46]. The amount of energy and electricity consumption is explained in Table 7.4. Observation of gas consumption with a flow meter and pressure, for each phase of the roasting process, from minutes 0-4 (dehydrate), 4-8 (Maillard), and 8-10 (develop). The gas consumption was recorded on the monitoring system and using a gas pressure indicator and gas flow meter indicator for gas flow measurement. Gas consumption is based on the three stages of the roasting process. The gas cylinder is placed on the scale and connected to the monitor system. The initial to final gas weight at each stage is recorded and described in Table 7.4. The LCA input data for the LL Scenario selected low voltage electricity Indonesia (ID), with electricity voltage transformation from medium to low voltage, Cut-off-S was selected as the database for electrical energy input. Low voltage electricity ID, photovoltaic, 3kWp slanted-roof installation, Cut-off-S was used for the SB Scenario.

Table 7.3 Roasting parameters

No	Roast type*	Coffee	Moisture, %	Beans mass, g	Roast mass, g	Bulk density in beans, g/ml	Bulk density in roasting, g/ml	Apparent swelling, %	Charge Temp, °C	Turning point temp, °C	First Crack temp, °C	Second Crack temp, °C	End Temp, °C
1	R55	A FW	12% ± 0.5	100	86.6	0.714	0.421	46.87	180	92 ± 1	194 ± 1	205 ± 1	210 ± 1
2	R55	A Nat	12% ± 0.5	100	86.2	0.64	0.383	44.04	180	92 ± 1	196 ± 1	205 ± 1	210 ± 1
3	R55	R FW	12% ± 0.5	100	87.7	0.73	0.391	63.74	180	92 ± 1	194 ± 1	205 ± 1	210 ± 1
4	R55	R Nat	12% ± 0.5	100	86.7	0.684	0.398	49.00	180	94 ± 1	193 ± 1	204 ± 1	209 ± 1

*Data were measured

Table 7.4 Fuel consumption parameters

No	Roast type*	Coffee	Gas Consumption LPG, g				Electric	
			Pre heat, 0-5min	Dehydration, 0-4min	Maillard, 4-8min	Develop, 8-10min	Consumption, kWh	
1	R55	A FW	4	6	2.3	1.2	0.02	
2	R55	A Nat	4	6.3	1.5	1.4	0.02	
3	R55	R FW	4	4.5	2.3	2	0.02	
4	R55	R Nat	4	3.5	3.4	2.5	0.02	

*Data were measured

7.4 Environmental impact analysis

This study used a 100g GB coffee sample. The input temperature is fixed the same; 180° C. This temperature is used as a reference when inputting GB at the start of roasting [47]. Furthermore, the water content was set at 12% uniformly based on National Standard Indonesia for coffee dried. However, each GB has a different density depending on the variety of beans and the meter above sea level of the plantation. This results in a difference in temperature for each sample at the turning point, where for a moment, the temperature of the coffee beans is lowest and then starts to rise. In the coffee roasting process, the beans change color and size, which is affected by high temperatures; these changes occur between 160° C – 300° C [48]. The initial turning point temperature of coffee beans can vary due to processing and physical characteristics of GB such as; size and variety of raw material. Table 7.4 describes the electricity consumption as a total of 0.2 kWh, with an estimate of 0.08 kWh between dehydration and maillard, and 0.04 kWh for development phase.

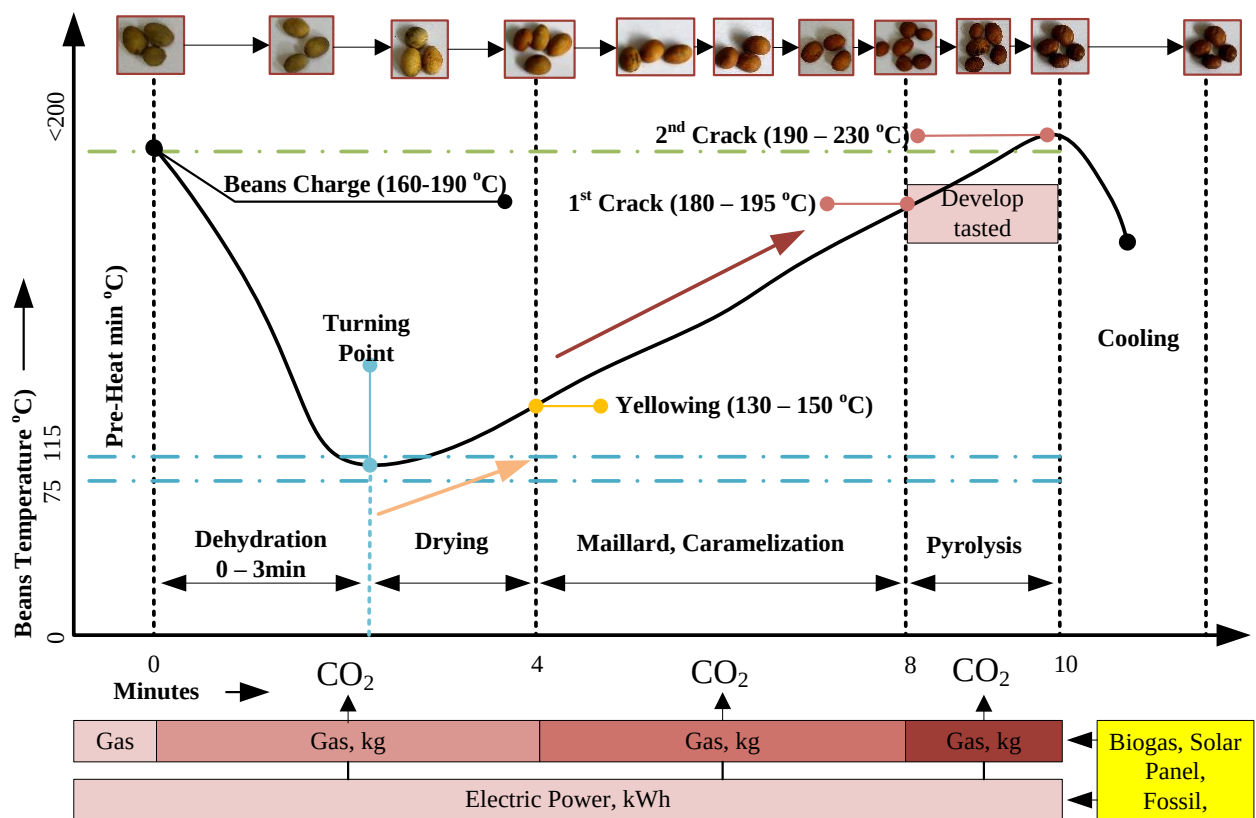


Figure 7.4 Roasting milestones

Figure 7.4 describes the turning point range between 2-3 minutes; if the turning point is at 3-5 minutes, the heat power is low. In 3-4 minutes, the temperature of the beans reaches 130° C – 150° C, and the color changes due to the low GB moisture content (dehydration-drying phase). Furthermore, in the period between 4-8 minutes, the temperature will rise to the point where the coffee beans begin to show apparent swelling between 180 – 195 temperatures (Maillard reaction phase); the “first crack” is heard in this phase. Finally, in the 8th-10th minutes which make-up the development phase, the temperature rises between 195-230 and the formation of the final profile is achieved. In this phase, there is a second “crack” sound. It is important to monitor the target coffee color, because at this stage the determination of coffee caramelization and flavor is achieved. The

results of the analysis show that the contribution of emissions from the development phase is lower than the maillard and dehydration phases. This is due to a decrease in gas consumption during this phase.

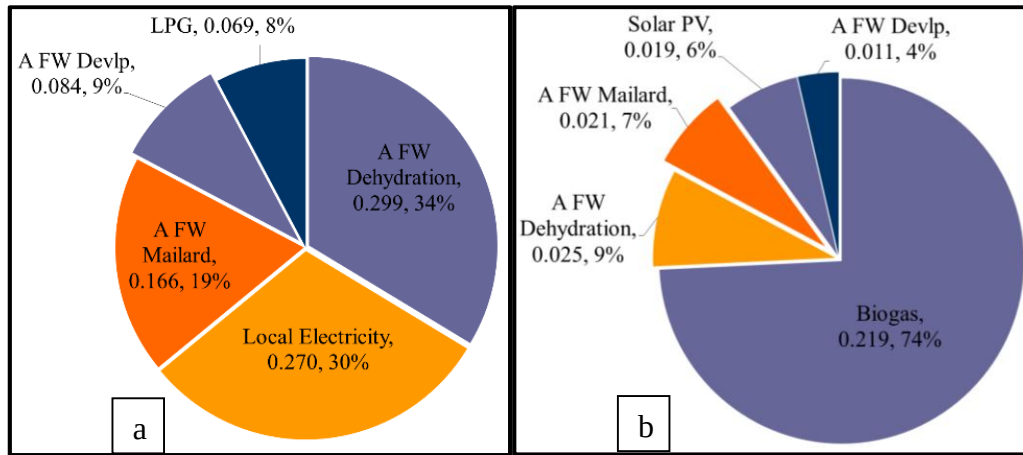


Figure 7.5 (a) Carbon Contribution of coffee roasting Arabica FW by LL energy source, (b) SB energy source

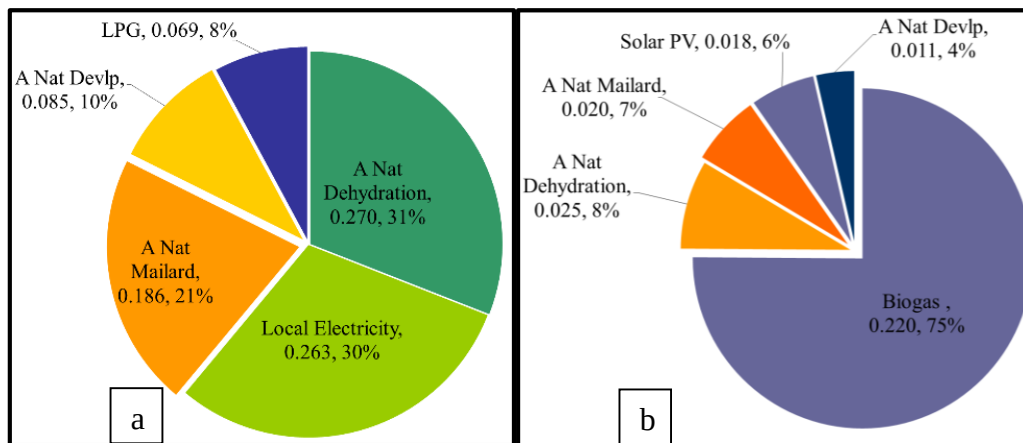


Figure 7.6 (a) Carbon Contribution coffee roasting Arabica Natural by LL energy source, (b) SB energy source

Figure 7.5 compares the two LL and SB scenarios for the FW Arabica roasting, the contribution of GWP per one kg CR of LL energy sources at the dehydration stage were 0.299kg CO_{2eq} , Maillard 0.166kg CO_{2eq} , and development 0.084kg CO_{2eq} . For the LL scenario, the use of Local Electricity and LPG contribute GWP 30% and 8%. When compared with the SB scenarios for the FW Arabica, dehydration was only 0.025kg CO_{2eq} , Maillard 0.021 CO_{2eq} , and development 0.019kg CO_{2eq} , these scenarios are obviously lower than the LL scenarios. The use of biogas is a clearly preferable option that can utilize liquid and solid waste converted into energy towards SCP [13].

The main contributor to energy and emissions for coffee roasting in the SB scenario is the biogas, between 73 – 74% of the total, with a GWP contribution of 0.2kg CO_{2eq} – 0.22kg CO_{2eq} per kilogram CR. In the LL scenario, the GWP of the LPG system contributes 0.063kg CO_{2eq} – 0.068kg CO_{2eq} per kg CR. As seen in Figure 7.6b, the scenario of SB contributing to GWP is dominated by dehydration, Maillard, and development at 0.025kg CO_{2eq} , 0.020kg CO_{2eq} , and 0.018kg CO_{2eq} ,

respectively. Meanwhile, in Figure 7.6a, GWP for 1kg CR from the LL scenario is 0.27kg CO_{2eq} , 0.1856kg CO_{2eq} , and 0.0855kg CO_{2eq} from the main phases respectively.

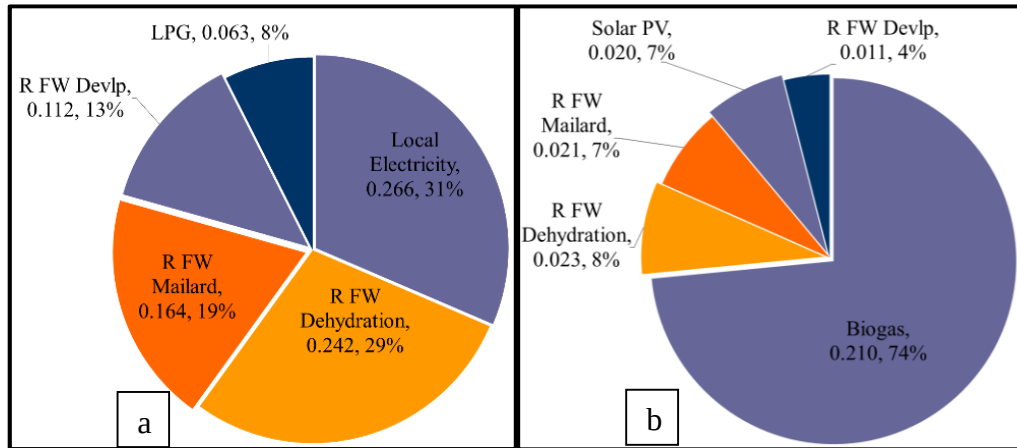


Figure 7.7 (a) Carbon contribution coffee roasting R FW by LL energy source, (b) SB energy source.

On the other hand, for robusta CR, Figure 7.7 illustrates the GWP for the Robusta type FW processing. The GWP contributor is higher in the dehydration phase than in the other two steps. Included in Figure 7.8 was the same type of coffee but using Natural processing. In this study, robusta has a higher density than arabica. Coffee with different densities may require additional power and heat, and produces a different taste depending on the roast profile [49]. Figure 7.9 describes each stage of coffee roasting with a total GWP for one kg of roasted coffee from both types of coffee with a two energy sources; LL energy source from 0.85kg CO_{2eq} to 0.89kg CO_{2eq} ; and SB 0.28kg CO_{2eq} – 0.3kg CO_{2eq} .

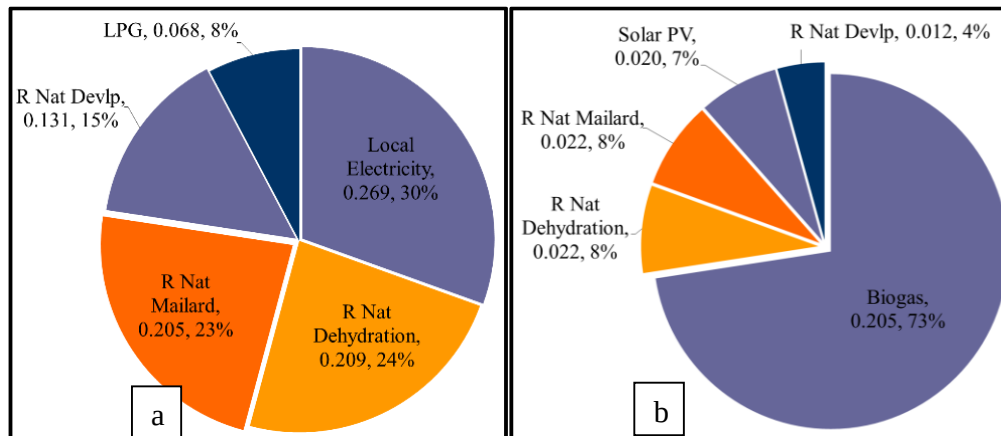


Figure 7.8 (a) Carbon contribution coffee roasting R Nat by LL energy source, (b) SB energy source

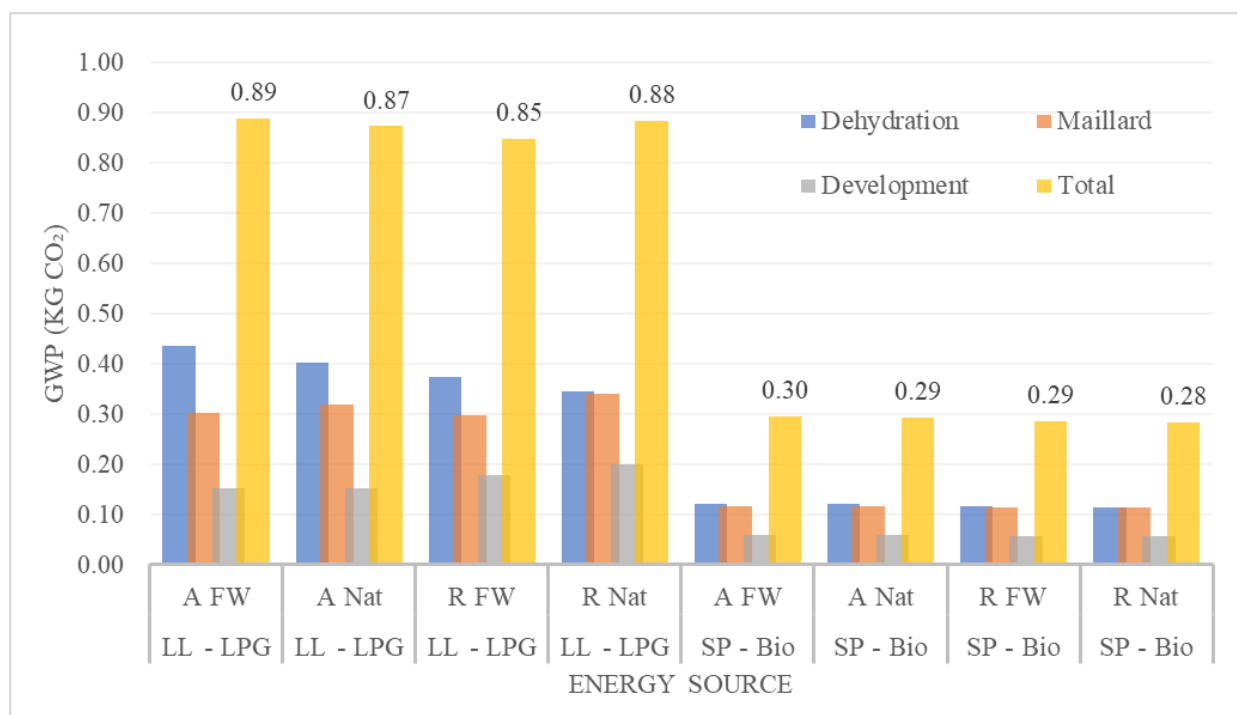


Figure 7.9 GWP coffee roasting based on stages

7.5 Summary of environmental assessment of coffee roasting

In the current study, the GWP contribution of one kg of roasted coffee under the LL scenario for Arabica and Robusta coffee with fullwash and natural processing is undoubtedly higher than the SB scenarios. The potential for reduction in emissions is not just beneficial environmentally, but could also provide a marketing advantage for coffee roasters. But to obtain the advantage of utilising biogas (specifically from coffee waste streams) it is important for the roasting to be done close to the coffee plantation. This is acceptable for domestic consumption, but much international coffee trade is currently at the green bean stage – rather than roasted beans. There are some limitations to this study. For example, there can be differences in each roasting process at the coffee roasting stage, especially on a home production scale. In this research, the roasting time is limited to 10 minutes, and the monitoring system on the roasting machine means that in household production with different capacities, gas and electricity consumption will be different. Non-uniform raw materials characteristics such as density, moisture content, and quality of raw materials, are challenges for coffee roasteries. A coffee roastery has a very important role in maintaining the consistency of roasted coffee product for sustainability in coffee production [50]. The use of renewable energy can be implemented using solar PV (SB-Scenario) which leads to lower GWP than Local electricity-LPG at the roasting stage from the dehydration phase. Research studies like this are possible as initiatives towards reducing environmental impacts in the off-farm sector as a mitigation strategy to overcome the effects of climate change. Future studies will aim to further classify the emissions associated with different levels of coffee roast, and different coffee bean types.

7.6 Valorization of coffee by-products

The coffee plant offers more than just a drink made from roasted coffee beans; various by-products are produced during cultivation and production [51]. Cherry skin and silver skin coffee by-products have the potential to produce cascara [52], but the coffee husk is also a type of waste that arises from

dry method coffee production. Cascara has become an important opportunity to reduce environmental impact [53]. Cascara produced from Arabica or Robusta coffee has different taste and aroma profiles. Samples with a sour taste and fruity aroma were most dominant in the Arabica cascara samples. In contrast, bitter flavors and aromas (such as floral, black tea, and hay-like) dominated the Robusta cascara samples [4] (cascara was not roasted in this case). Cascara contains polyphenols [54] and antioxidants, and has a low caffeine content [55].

The typical cascara process only consists of drying the raw material in the sun until the water content is between 10-12%, then it can be brewed [56]. Cascara as a by-product is currently a relatively novel food; with various methods of brewing [57]. Cascara can be drunk by adding lemon and honey [58], and especially by adding coffee blossom. Coffee husk skin is rarely used for cascara production because of dust particles in the feed. So, size sorting and dust cleaning need to be done for this waste. Meanwhile, the tannin content of Arabica cascara tea is superior in yield, pH, ash content, antioxidant activity, and caffeine content. Regarding organoleptic scores, Arabica cascara tea produced from fresh cherry skin was most preferred by panelists [59]. Total dissolved solids (TDS) and pH are used for solubility levels, especially in tea investigations [60], which also use TDS and pH as references for flavor and volatile compound [61]. Even though this study does not yet examine volatiles, it provides an basis for the author's further research, to outline the impacts and opportunities for processing by-products from coffee skins.

CS and HS coffee by-products were used to produce novel food (cascara) and fuel (briquettes). In previous research, Cascara processing did not go to the roasting stage to process this waste; therefore the novelty of this study is that the authors identified by-products, carried out roasting with the observation of parameters of time, temperature, and level of cascara roasted towards Sustainable Novel Food (mainly) and the rest Fuel. This study aims to analyse the potential to develop a product from coffee waste skin by considering roasted by-products (CS and HS), which are scored on the parameters cup-test, taste-mouthfeel attributes, and aroma attributes. The remainder of the material is potential fuel (briquettes).

7.7 Observation and experimental method

Experimental and observational methods were applied in this study. This study used two types of coffee skin waste: Cherry Skin, produced from the wet method of coffee processing and Husk Skin produced from the dry method. The raw material is from the Andungsari Arabica variety. CS is obtained after pulping (separating the skin and pulp of the beans), while HS is obtained after hulling. HS has mixed particles (fine (dust), medium, and coarse). Sorting is selected for the advanced stage of HS. Next, the roasting stage is chosen to determine the profile; we refer to SCA profiling [62][11][63] and apply it to cascara as a color profiling consideration. The roasting stage uses medium roasting. The roasting temperature applied here is the typical tea roasting temperature of 80 – 120° C [64][65][66]. We conducted the cup test for aroma attribute parameters: floral, sweet, and roasted; and taste and mouthfeel attributes: bitterness, astringency, and sweet aftertaste [66]. The water content of the material is around 7% ± 0.5, then it is roasted like tea until the maximum water content is between 2 and 5% [65][67]. The panel for sensory evaluation was composed of 10 panelists (six men and four women, 30 – 38 years old), all of whom were from the Coffee Science Institute (CSI) and Vilos Laboratory, Jember, Indonesia. Figure 7.10 shows the flow of processing by-products into coffee tea (cascara). The sample is 1,000g CS, and sorted HS. We evaluate cascara brewing with TDS and pH of Cherry Skin Roasted Ground (CS R G), Cherry Skin Roasted (CS R),

Husk Skin Roasted Ground (HS R G), Husk Skin Roasted (HS R), Husk Skin Raw (HS Raw), Husk Skin Raw Ground (HS Raw G), CS Raw Ground (CS Raw G), and CS Raw. A ten-point scale was used for grading the six flavors in which 0 – 2 was “very weak,” 3-4 was “weak,” 5-6 was “neutral,” 7-8 was “strong,” and 9-10 was “very strong” [68].

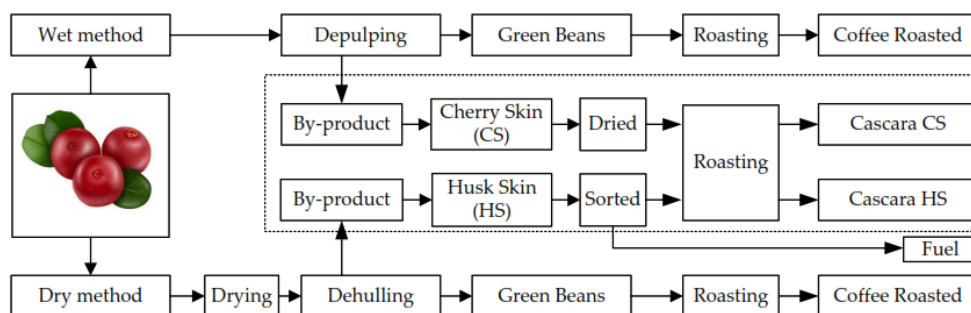


Figure 7.10 Scope of by-product cascara study

Wet and dry coffee methods are adjusted to market or commodity demand and conditions of excess raw materials and specialty coffee requests. There are two ways of wet processing: full-wash and semi-wash. Both require large quantities of water. Full-wash and semi-wash, through the de-pulping stage, produce CS by-products and water, while full-wash from fermentation produces wastewater (potential biofuel feedstock). There are various dry processing methods, with the most common being the “natural” process. This method is environmentally friendly, but the taste of this process is difficult to control. Alternatives include the Anaerobic methods, with options including: anaerobic without the addition of other ingredients; anaerobic with an injection of fruit material (Inoculant); anaerobic with an injection of lactic acid bacteria (LACTIC); anaerobic with CO₂ injection (Carbonic Maceration) and, anaerobic with pulp injection of wastewater inoculant (Mosto). The choice of method is adjusted to demand, but generally, the dry methods, such as anaerobic and natural, are chosen.

This study used anaerobic HS and full-wash CS samples. We set the roasting temperature between 90 and 100° C for 10 minutes. Samples were taken from each stage and weighed to calculate the roast yield distributions cascara. Figure 7.11 shows the weight loss during roasting. Various products are roasted in addition to coffee, including tea, and tartary buckwheat. Weight loss during roasting can be used as a reference for roasted coffee color, taste, aroma and quality [69], and when brewing as an antioxidant reference [70]. Similarly, roasting is used to change the content of volatile compounds, chemical content, profiling, etc [71][72], even tarty buckwheat can be roasted to improve its antioxidant profile [73]. The authors` have not found any references about roasted cascara, although several varieties of cascara in Aceh have the same characteristics as tea [74], cascara in the European market is sold as a novel alternative beverage [75].

Through this study, the author applies husk-skin sorting to separate alternative streams for co-products. HS selection is determined by sorting into sizes of 7.5mm, 6.5mm, and 5.5mm. Figure 7.12 shows HS raw materials sorted by size. We use sizes 7.5 and 6.5 for the HS roasts so, the potential fraction of raw HS for use in cascara is 40.6%. Pixel is a small type of coffee used for commercial ground coffee. Meanwhile, the remaining fraction (33.2%) has the potential to be used as fuel in the form of briquettes which can be used as alternatives for wood used in traditional roasting of coffee. The energy potential in HS is calculated based on the resulting combustion

treatment, with a calorific value of 30.54Kcal/kg [76]/ The overall heat potential is calculated using equation(1).

Heat potential HS:

$$Hp\ HS = Cap\ Hs \times HHV\ HS \tag{1}$$

Where :

Hp HS = Heat Potential HS (kWh/kg).

Cap HS = Husk Skin quantity (kg)

HHV = Higher Heating Value, 30.54 (Kcal/kg)

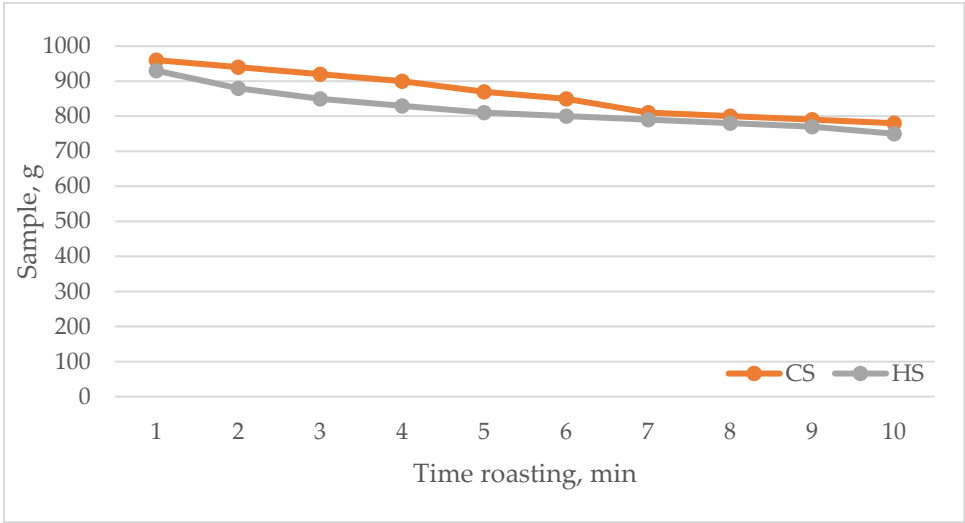


Figure 7.11 Weight loss of sample during roasting

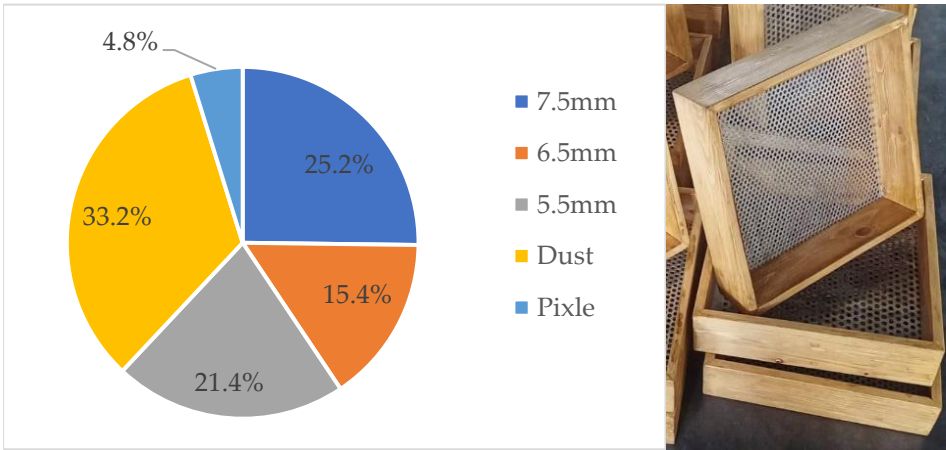


Figure 7.12 Size distribution of sorted HS and manual sortation screens 7.5mm, 6.5mm, and 5.5mm

Figure 7.13 illustrates the physical differences of raw HS, 1,000g of raw HS is sorted to produce 252g of 7.5mm HS; 6.5mm size 154g, 5.5mm size 214g, dust 332g, and pixel 48g. Cascara production via HS requires more ingredients than CS, as in the latter 1,000 g can be roasted directly without sorting to produce 780g CS R medium. In contrast, around 2 or 3kg of HS material is

required to get around 1 kilogram of roasted HS, as only sizes 7.5mm and 6.5mm are utilized. HS 5.5mm can be used as cascara, but we must adjust the roasting temperature and time to avoid producing a dark roast.



Figure 7.13 Raw HS (a) ; Sorted HS of size 7.5mm (b), 6.5mm (c), 5.5mm (d), and pixel (e)



Figure 7.14 CS R (a), CS raw(b), HS R (c), HS raw(d)

Figure 7.14 shows the difference between roasted CS (a) and raw CS (b), roasted HS (c), and raw HS (d). Raw CS and HS are soft (without roasting), and have a water content between 8-10%. Meanwhile, CS and HS harden after roasting. Figure 7.15 shows the extraction results for each cascara from CS. CS R G samples were ground and brewed at a temperature of 98° C, and TDS and pH measurements were carried out from one minute to eight minutes on multiple samples. We use this parameter as a measurement of solution extraction. The mineral water we use is TDS 152. We can see the difference in Figure 7.15 and Figure 7.16; the TDS of cascara from CS differs from HS.

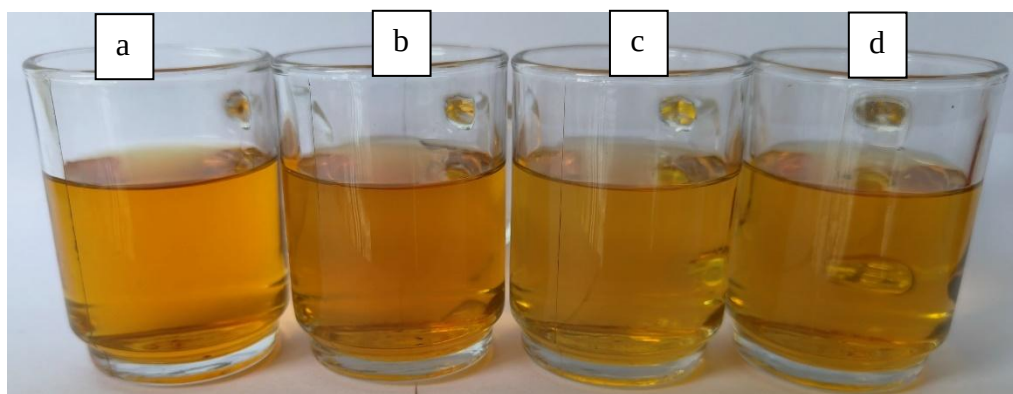


Figure 7.15 CS roasted ground (a), CS roasted (b), CS raw ground (c), CS raw (d)

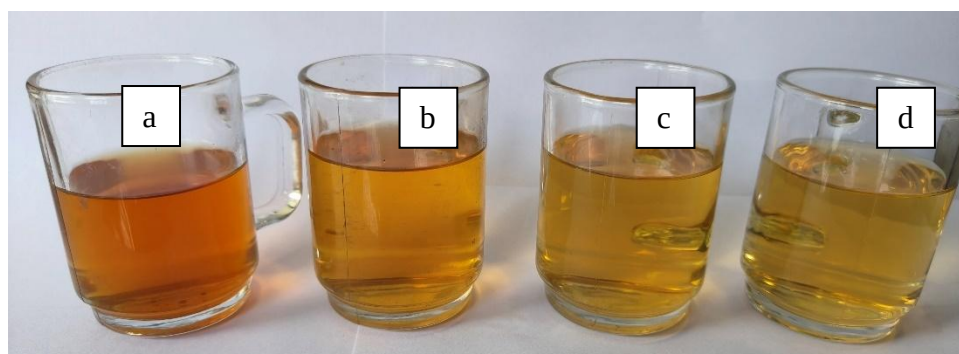


Figure 7.16 HS roasted ground (a), HS roasted (b), HS raw ground (c), HS raw (d)

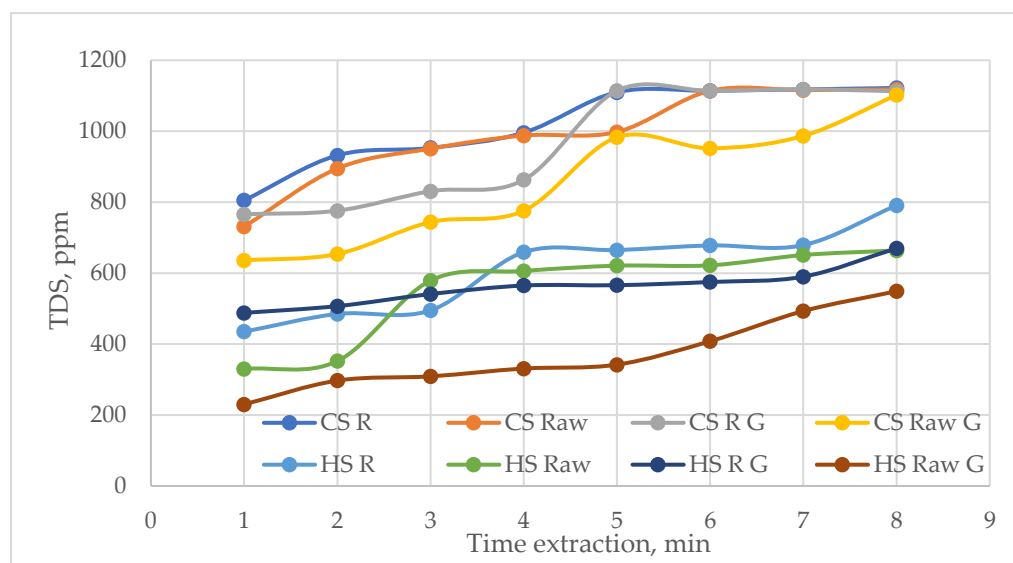


Figure 7.17 TDS of cascara samples

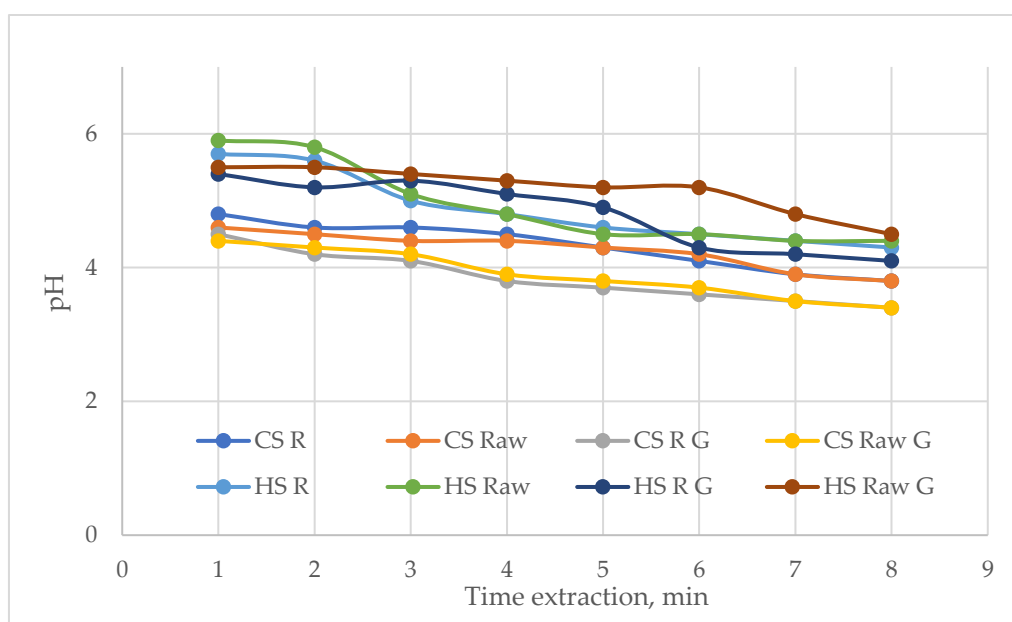


Figure 2. 1 pH Cascara sample

Figure 7.17 shows the TDS of cascara. The extraction groups are different for each CS and HS type; even though HS consists of parchment and cherry skin, the TDS is still lower than CS. TDS tends to increase from one to eight minutes, showing that extraction progresses across the period time.

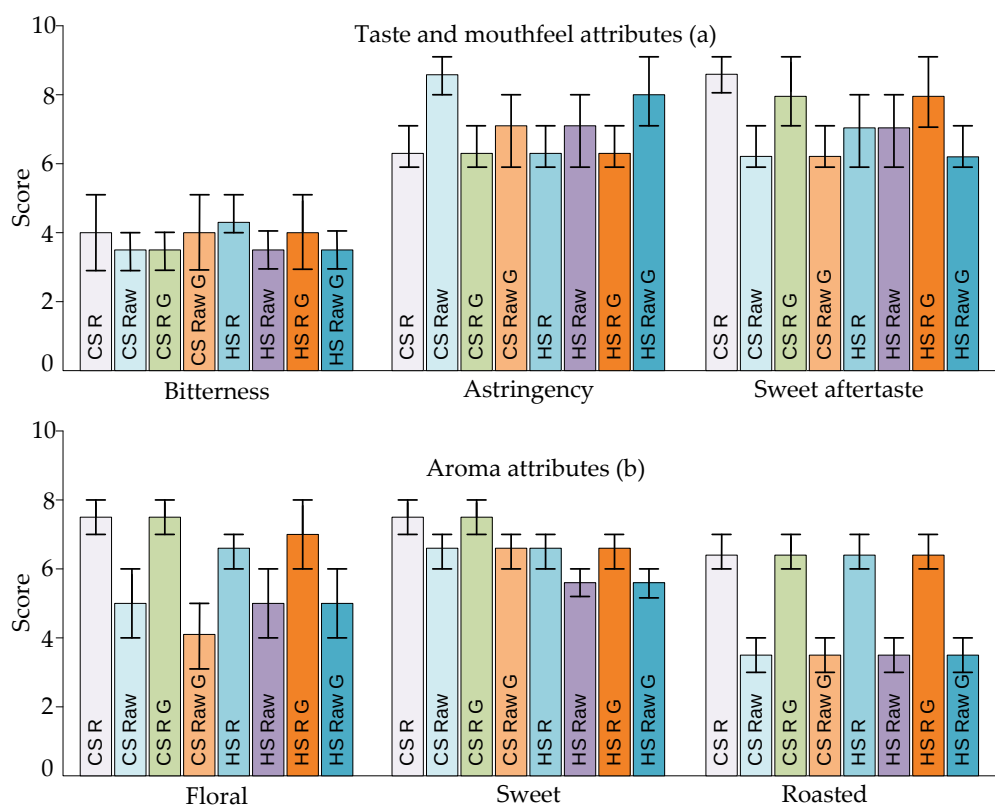


Figure 7.18 Taste and mouthfeel (a), and aroma attributes (b)

Based on a cup test, panelists evaluated the taste, mouthfeel, and aroma. We brewed cascara with a ratio of 1:15 (cascara: water), with the time of extraction to serving being up to 8 minutes. TDS for CS R was found to be higher than the others. The floral and sweet attributes also represent the

panelists' preferences; the scores ranged between 7 and 8. CS R aroma is strong (7-8) showing that the medium roast is suitable for cascara (Figure 7.18). In contrast, light roast tastes astringent, while dark roast tastes like smoke (roasted). 1kg CS produces 785g of roasted CS, while 2.5kg raw HS produces around 1,015g of 7.5mm and 6.5mm (HS Sized). 1kg HS (7.5mm and 6.5mm) becomes 750g HS roasted. So, 2.5kg of raw HS can produce 830g of dust, 535g of HS 5.5mm, and 120g of GB pixels. The remaining HS sorting dust reaches 33.2% and can be used for combustion in a mechanical dryer. However, if dust and HS 5.5mm are used as fuel, dust + HS 5.5mm reaches 54.6%, or as much as 1.365g from 2.5kg raw HS. By making HS pellets from these materials, the HS calorific value reaches 16,898 kJ/kg [18] and has been reported up to 18.98 MJ/kg in Ethiopia [77]. Making charcoal requires 2.5kg HS to produce 1kg char, with a density of 970kg/m³ and a higher heating value (HHV) of around 30.54 Kcal/kg [76]. If dust and HS 5.5mm are used as raw pellets, raw HS of around 4.5kg is required to produce 1kg of charcoal. About 1.8kg is the feedstock for cascara (HS 7.5mm and 6.5mm), and 216g GB pixel for commercial coffee. The Indonesian National Standard (SNI) briquette was 5,000 kcal/g, mixing 75% HS + 25% coconut shell. The calorific value was 2.57×10^7 kJ/kg [78]. Utilization of this waste from HS is a solution for implementing renewable energy (biomass waste), and reducing CO₂ emissions.

Figure 7.19 illustrates the mass flows of by-products from two processing methods: full-wash and anaerobic. The estimated CB requirement is between 4.8 and 5kg to produce 2.4 – 2.5kg CB wet or around 1.2kg CB dried. Through the medium roasting method, around 1kg of roasted CS is produced. Meanwhile, in the anaerobic method, 1kg roasted HS, requires around 2.5kg raw HS and 9 – 10 kg CB. The potential fuel from this process is 0.5kg char [76].

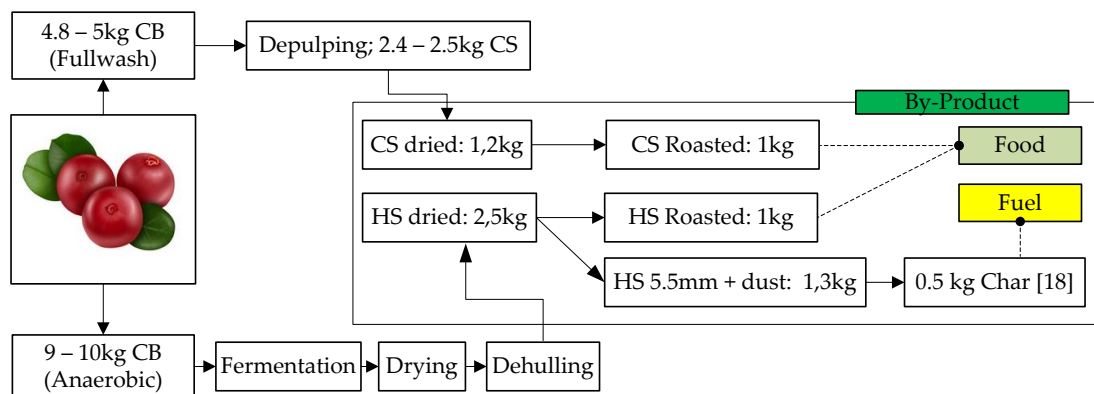


Figure 7.19 Sustainable novel food and potential fuel from by-products

7.8 Summary of novel food and potential fuel from coffee by-products

This study describes the potential use of CS waste as a food product for sustainable coffee production (SCP). From cherry beans (CB) we can produce roasted CS 18% -20 % and roasted coffee (CR) between 15% -16 %. So, in total this reaches 36% as food products, when CS or HS Cascara are used for novel sustainable foods. One kg CS produces 785g of roasted CS, one kg HS produces 406g of 7.5mm and 6.5mm sizes, 214g of 5.5mm sized material, 332g of dust, and 48g of Green beans Pixle (for commercial coffee powder). One kg of HS is mixed (7.5mm and 6.5mm) to produce 750g of roasted HS. To get 1kg HS (7.5mm and 6.5mm) requires at least 2.5kg raw HS, raw HS 5.5mm + dust of 1,365g potentially for fuel. The wet and dry coffee processing methods produce solid and liquid waste which can be turned into by-products to provide novel sustainable

food from CS and HS, while an additional fuel (briquette potential) stream is produced from HS dust or HS sized 5.5mm.

8 Pilot plant industrial ecology coffee framework and by-products

8.1 Chapter introduction

Indonesia is one of the largest coffee producers in the world, 54.6% of Indonesia's coffee production is exported to more than 10 countries [188]. The long-term challenge facing Indonesian Standard Coffee (IS Coffee) [189] is to elevate the standard of commercial coffee to specialty coffee that can compete on a global scale [190]. Coffee has become a lifestyle beverage for various age groups, both old and young [192]. Certainly, the sustainability of coffee production needs to be maintained. Climate change has impacted coffee production [81], with impacts on rainfall fluctuations in Java and Sumatra, the dominant coffee production regions. Flowering failure in 2023 decreased Robusta production by 18% and Arabica by 7% [193].

Smallholders, in their crucial role, are ensuring the long-term sustainability of coffee production, even in the face of climate change [194][100]. Culturing Arabica varieties, nurtured under the shade of trees, is a testament to their commitment to the environment. These smallholders, who rely on coffee plantations as their primary source of income, show us that sustainability is not just a concept but a way of life [195]. The sustainability of coffee production is further fortified by effective farm management practices [196], such as the use of organic fertilisers [197], pruning, and regenerative farming techniques [88]. Moreover, their efforts to mitigate the production of 3F products (Food, Fuel, and Feed) in crop-livestock systems [198], and integrating wastewater management practices are significant steps towards reducing the environmental impact of coffee production [199] instilling confidence in a sustainable future.

During our observations in the Besuki Residency, which encompasses four Regencies: Banyuwangi, Situbondo, Bondowoso, and Jember, we discovered that farming integration has not been implemented in the coffee production centers of the region. However, we found that the coffee-livestock farming integration system has not only effectively enhanced the economy for smallholder farmers, but also significantly improved their livelihoods [200]. Furthermore, integrating coffee and pepper cultivation has been shown to reduce GWP contributions [87] and improve production quality by addressing waste issues. Although all members of the group have similar tasks and contributions, the relationships between them are mutually beneficial and form a sense of group solidarity.

Coffee farmers face various challenges due to the difference in farm conditions. For instance, implementing crop-industry-livestock integration and analyzing environmental impacts and economic sustainability can be difficult in community forests (CF) and community forests managed by organisations (CF-O). However, the fact that coffee production is entirely processed by smallholder farmers provides an opportunity for the implementation of Information, Education, Communication, and the utilisation of by-products such as biogas and organic fertilizers for export-quality coffee production [201][119]. Unfortunately, there are very few comprehensive studies on the 4Fs (Food, Feed, Fuel, Fertilizer) and GWP in coffee production towards Sustainable Coffee Production (SCP) in Brazil and Vietnam [111].

Moreover, the potential of Food (Cascara) presents an opportunity for waste utilization [186][8]. Multiple studies on the utilization of wastewater as a raw material for biogas production have been

conducted [13][202][203]. This certainly presents an opportunity in the integration towards Industrial Ecology Coffee (IEC), where smallholders play a crucial role as gatekeepers of coffee production sustainability [204] through coffee plantation integration. Importantly, this waste utilization also contributes significantly to reducing waste discharged into the environment, thereby positively impacting GWP.

We have conducted studies on smallholder groups regarding GWP in the wet processing of coffee using fossil energy sources [130], evaluating the use of waste for biogas production [13], utilizing coffee husks to produce cascara [8], as well as testing organic fertilizers, implementing organic pesticides, and conducting pesticide content tests in Green Beans (GB). Furthermore, under these conditions, we have integrated digester technology to produce biogas, implemented solar panels in coffee production through technology dissemination funding from BRIN [14], and utilized Matching Fund (MF) for flavor quality enhancement technology [205] in smallholder coffee groups.

Finally, in-situ studies were conducted in the Andungsari Coffee Smallholder Group in Bondowoso, East Java, Indonesia, as a pilot site for IEC. This serves as an IEC application solution to produce 4F (Food, Feed, Fuel, Fertilizer), improve production quality, reduce emissions, and utilize by-products as efforts for economic sustainability and environmental impact reduction.

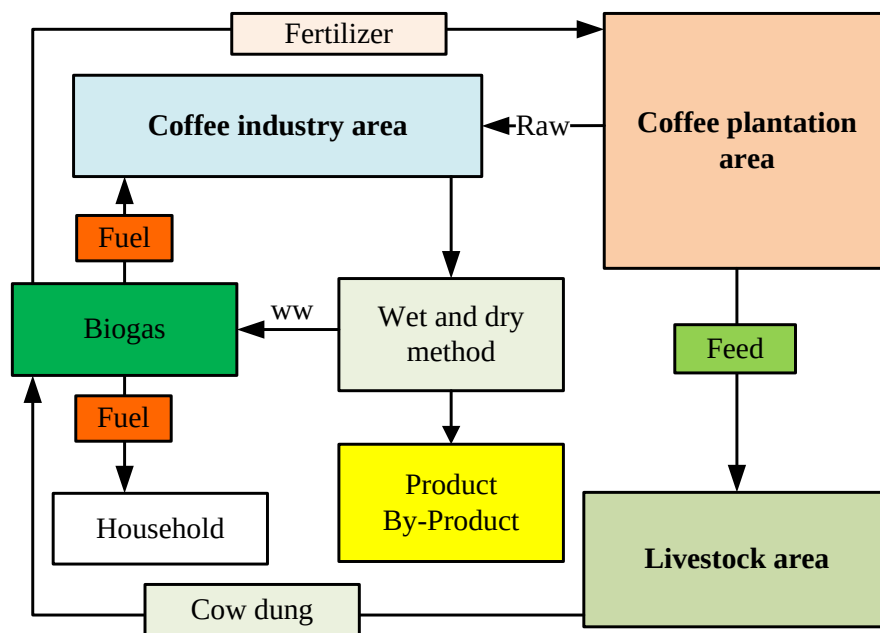


Figure 8.1 Industrial ecology coffee model.

Life Cycle Assessment (LCA) [17], and Life Cycle Costing (LCC) were applied to coffee production [36]. The aim of this study is to examine the environmental impact and economic sustainability of 4F through reducing fossil energy use and utilizing solid and liquid waste in coffee production. The authors conducted environmental impact analyses on coffee processing from cherry beans (CB) to green beans (GB), and from GB to Coffee Powder (CP) using the LCA method [87][89]. Additionally, scenarios for energy supply from biogas and solar panels [13], and LCC analysis were also outlined in the implementation of IEC. Some of the by-products are utilized as animal feed, while the remainder is used as fertilizer. Figure 8.1 illustrates the integration of IEC at the pilot site, involving Arabica coffee farms with various varieties, as well as shade trees such as Lamtoro

(*Leucaena leucocephala*), macadamia, avocado, and cinnamon. The industry groups at the location process coffee using both wet and dry methods, while utilizing by-products. Livestock is used as a source of biogas, with additional liquid waste from coffee production, feed from shade trees, and organic fertilizer from digester residue (slurry). This study represents the implementation of IEC in the field towards Sustainable Coffee Production (SCP), as an effort to maintain coffee production sustainability by smallholders and produce sustainable 4F coffee.

8.2 Materials and methodologies

8.2.1 Profile of case study area

"Smallholder" is often used to describe rural producers, primarily in developing country regions, who rely on family labor and sometimes share finances [117]. Furthermore, smallholders are often characterised as farmers with low-technology production systems and limited capacity for independent marketing, performing administrative tasks, and storing and processing their products with limited land. However, Arabica coffee farmers choose intercropping patterns with shade trees [206], which are more productive than robusta, considered an annual crop with limited intercropping models. We conducted observations on more than ten processing groups in each district located in three districts: Bondowoso, Banyuwangi, and Jember (referred to as the "Besuki Residency"), specifically focusing on the processing of Arabica varieties. Certainly, there are processors in Banyuwangi who have successfully won the Cup of Excellence [207], but unfortunately, the raw materials come from Bondowoso. With this condition, on-site studies have become an opportunity to implement IEC.

On-site studies were located in Andungsari, Bondowoso, serving as a pilot for IEC implementation, situated in three locations in Pakis Village, at an altitude ranging from 1,048 to 1,400 meters above sea level (Latitude: -7.9231361, Longitude: 113.708889), with a total of 10 hectares of smallholder gardens. Since 2020, the authors have been providing assistance and monitoring. Based on observations around the "Besuki Residency," we conclude the status of smallholders as presented in Table 8.1.

Table 8.1 Possible status of Indonesian smallholder coffee farmers

Status	Independent	Organized	Organic Certified	Coffee Certified	Uncertified	Legal	Illegal	CF-O	CF	Arabica
Independent			✓	✓	✓	✓	✓		✓	✓
Organized				✓	✓	✓	✓	✓	✓	✓
Organic Certified	✓					✓			✓	✓
Coffee Certified	✓	✓				✓		✓	✓	✓
Uncertified	✓	✓					✓	✓	✓	✓
Legal	✓	✓	✓	✓				✓	✓	✓
Illegal	✓	✓		✓	✓			✓	✓	✓
CF-O		✓		✓	✓	✓				✓
CF	✓	✓	✓	✓		✓	✓			✓
Arabica	✓	✓	✓	✓	✓	✓	✓	✓	✓	

Source: Compiled by the author from interviews and observation.

CF-O = community forests by organization, CF = community forests

8.2.2 Scope of coffee processing and valorization of by-products

Coffee processing typically involves two methods: the wet method and the dry method [4][5]. The taste of coffee can vary depending on the process of production and the brewing method used, even if the quality of the coffee remains the same [6]. The scope of this research is two selected coffee processing methods: wet and dry. Wet methods include Fullwash (FW) and Semiwash (SW), while dry methods include Natural (Nat) and Anaerobic (An). In addition, coffee production waste was recycled for food products. To do this, wet coffee husks are dried and roasted, then ground into powder. However, it is important to sort the husk skin (HS) by size, with pieces ranging from 5.5 mm to 7.5 mm. The remaining dust from the HS is composted as fertilizer. Tests have been conducted on the C/N ratio, organic C content, and N content. The liquid waste from the process is mixed in with biogas production. Although the waste husks have not yet been used as livestock feed, the Andungsari group uses feed from the plantation to manage and feed their livestock. Economically, the reuse of waste has many benefits such as reducing fuel costs for cooking, increasing the supply of organic fertilizer, and closing the operational cost cycle with a closed loop. For instance, energy costs for digester maintenance can be reduced by producing biogas as a substitute for LPG.

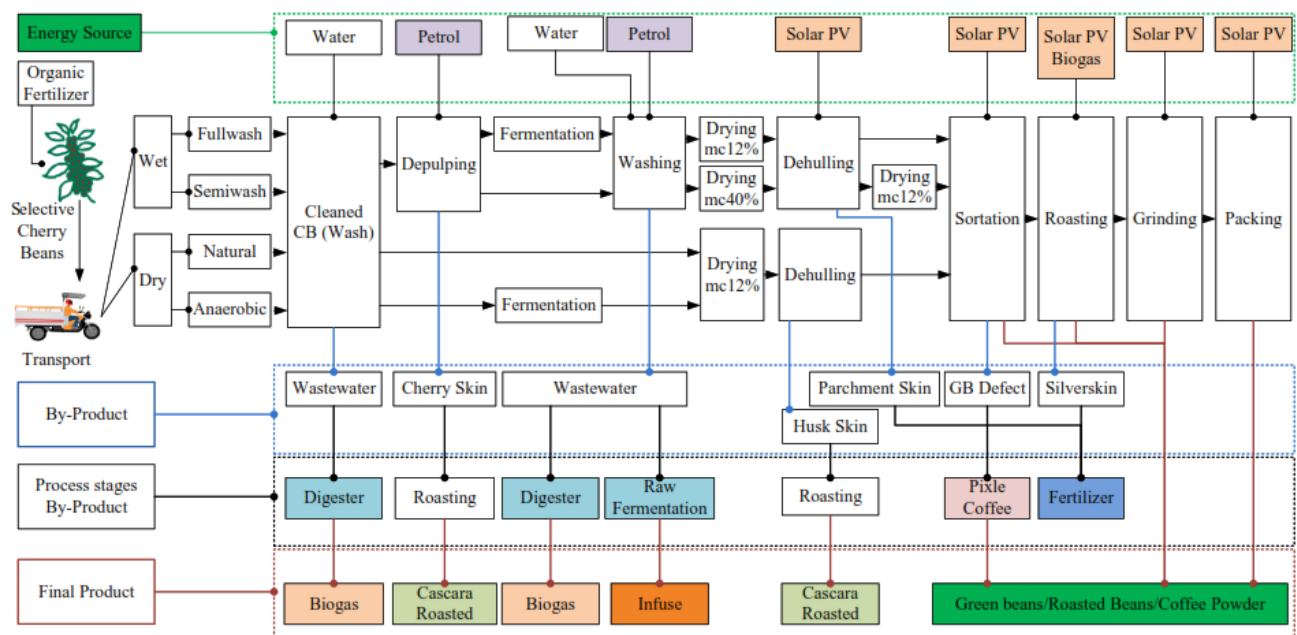


Figure 8.2 Scope of coffee processing and valorization of By-Products

8.3 Environmental impact assessment

LCA is a methodology that evaluates the potential environmental impact of a product's production process. This assessment relies on analyzing resource consumption and the emissions released into the environment [208]. LCA also helps in identifying opportunities to improve environmental performance, which can assist industries that produce and process coffee in implementing more environmentally efficient practices. The assessment covers the processing of coffee from Cherry Beans (CB) to Green Beans (GB), Cherry Beans (CB) to Coffee Powder (CP), as well as By-Products Cs and Hs into Cascara. The stages of LCA include defining goals and scope, inventory analysis, impact assessment, and interpretation of results, according to ISO standard procedures

[209][210]. The author used SimaPro 9.3.03 software and chose ReCipe (2016) midpoint level to consider GWP.

8.4 Goal and scope

This study explores the use of wet processing methods, such as FW and SW, followed by dry processing methods, such as natural and anaerobic, as well as wastewater substitute for biogas energy [13], the use of shade plants to produce animal feed, and the use of digester residues as fertiliser. The identification of per hectare of smallholder coffee farms in Andungsari Coffee, Bondowoso, Indonesia was conducted. The study focused on Arabica coffee mix varieties (Andungsari, Komasti, and Lini S) and shade plants such as Macadamia, Cinnamon, Lamotoro, and others (Table 8.2). The Functional Unit (FU) represents qualitative and quantitative function aspects proposed to be met by a product or process. In this LCA, the authors outline the production per hectare in 2023 to produce each kg of Green Beans (GB), Coffee Powder (CP), Cascara Cherry skin (Cs), and Cascara Husk skin (Hs). The authors then elaborate on energy substitution, potential animal feed availability, and fertiliser production. For this purpose, an evaluation using LCA [209][210], and LCC is applied, which provides a reference basis to the inventoried input and output data.

8.5 Inventory analysis

Inventory data was collected during the 2023 harvest season in Andungsari smallholder farms through observation and experiments. The collected data included coffee harvest details ranging from April to September, such as the number of coffee plants, livestock, energy requirements, input and output production, waste production, biogas production, and by-product fertiliser production. This information was essential for the study. Smallholder farmers used wet and dry methods such as Full Wash, Semi Wash, Natural, and Anaerobic to produce coffee. Figure 8.2 depicts the upstream and downstream coffee production process in smallholder farms. The cherry skins were harvested from the plantation and transported to the production site using a motorcycle, which was about 3-4 km away. In comparison to previous years, the coffee production in smallholder farms experienced a decline due to unpredictable rainy conditions. Some coffee plants failed to flower, which resulted in lower production compared to 2021 and 2022. Figure 8.3 shows the average harvest per hectare in Andungsari farms. In the year 2023, harvest experienced a shift in schedule with the peak harvest occurring from June to July. Unlike 2021, there was no harvesting in February and November in 2023. This shift provided a more stable production time for the entire year.

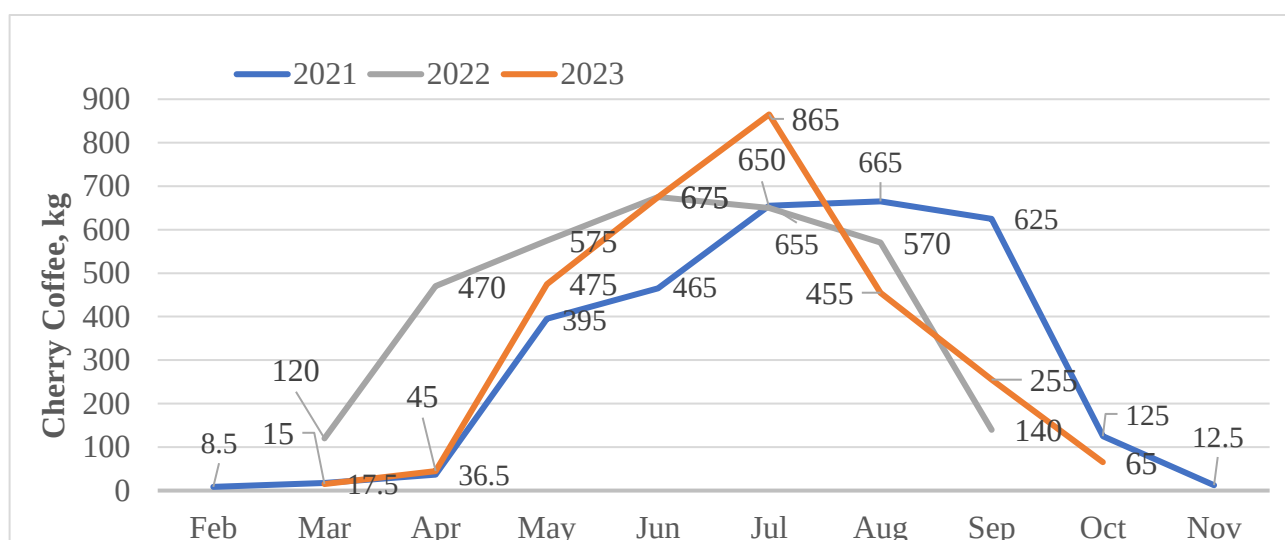


Figure 8.3 Andungsari Arabica coffee smallholder harvest by month (2021-2023)

The study involved conducting surveys, group discussions, and collecting data from small-scale farmers regarding the inputs and outputs of production materials in the supply chain. The observation also focused on managing waste disposal and identifying social aspects, production culture, technology, and processing control. The collected data was used to support cost analysis. However, the study's limitation was that it only used data from the 2023 harvest. Table 8.5 presents the inventory of material flow per hectare for both wet and dry processing methods in different harvest years.

Table 8.2 Average coffee plantation and coffee shade/ha/year

Coffee Plantation/ha	Total	Average Production, kg	Benefit
-Mixed variety [130]	2,500	2,850 Cherry Beans	Food (Coffee)
Coffee shade/ha*			
-Macadamia	300	150	Food (Like peanuts)
-Cinnamon	30	5	Food (Powder)
-Avocado	80	450	Food (Fruit)
-Lamtoro	200	109,500	Feed (Livestock)

*Observed data from the Andungsari group.

Andungsari Smallholder Group applied organic fertiliser obtained from the remaining slurry from the digester, mixed with cow dung. Based on observations in farming, cows produce about 25kg of manure per head per day, a total of 200kg of cow manure from eight cows. Coffee plantations require fertiliser of around 37.5 tons/ha with a population of 2,500 coffee trees, so the average per coffee tree is 15 kg/year. In addition, in the Andungsari Group, pruning is done up to 4 times per year; pruning is done on coffee trees that already have more than 12 main branches. Pruning each tree can remove five to six large branches. Twigs are buried in the soil as compost, and this pruning helps as an additional fertiliser and reduces unproductive branches. Biogas supporting data, smallholders fill digesters once per week, and biogas production is around 7m³/day, with a digester volume of 16.5m³. The slurry of the digester is about 1,095kg/year. Thus, this study identifies fuel parameters as gasoline used in transportation, de-pulping, and dehulling. Electrical energy is obtained from a 400wp Solar panel with a 200Ah, 12VDC battery, and 2.4 kWh electricity potential. APOS U

database parameters in software were selected for energy sources: petrol, biogas, and solar panel slanted roofs. Table 8.3 shows the inventory of technology used in the processing process and the energy sources used through IEC.

Table 8.3 Technological parameters used

Stages*	Tech Used	Energy Source	
		Non-IEC	IEC
Material transportation	Motorcycle, 100kg/batch	Petrol	-
Depulping CB	Engine 5hp, 300kg/h	Petrol	-
Fermentation area	Electric Light, 0.02kWh	-	Solar Panel
Washing	Engine 5hp, 300kg/h	Petrol	-
Dehulling	Electric Motor 1.5kWh 150kg/h	-	Solar Panel
Sortation Sized	Electric Motor 0.37kWh 150kg/h	-	Solar Panel
Roasting	Electric Motor 0.08kWh 6kg/h	-	Solar Panel
	Gas Stove 0.22m ³ /h	-	Biogas
Grinding	Electric Motor 0.75kWh 20kg/h	-	Solar Panel
Packing	Electric Motor 0.25kWh 20kg/h	-	Solar Panel

IEC=Industrial Ecology Coffee

*Observed data from the Andungsari group.

8.6 Impact assessment

Inventory data are collected and used in impact assessments on SimaPro software, based on primary data obtained from coffee production inputs and outputs, along with additional information on emission factors. The ReCipe (2016) Midpoint Level (ML) is applied in these assessments [44][79], fuel consumption is calculated using characteristic factors [46]. Also, the calculation of biogenic impact factors on the environment needs to be considered [211]. The investigated impact categories were as follows: Global warming potential (GWP); Stratospheric ozone depletion (ODP); Ionizing radiation (IRP), Ozone formation, Human health (HOFP), Fine particulate matter formation (FPMF), Ozone formation, Terrestrial ecosystems (EOFP), Terrestrial acidification (TAP), Freshwater eutrophication (FEP), Marine eutrophication (MEP), Terrestrial ecotoxicity (TETP), Freshwater ecotoxicity (FETP), Marine ecotoxicity (METP), Human carcinogenic toxicity (HTPc), Human non-carcinogenic toxicity (HTPnc), Land use (LOP), Fossil resource scarcity (FFP), Water consumption (WCP).

8.7 Lifecycle costing (LCC)

The social aspect of smallholders is a crucial factor to consider for sustainable coffee production. To evaluate the total economic costs associated with the life cycle of the analyzed system, a methodology called Life Cycle Costing (LCC) is used. While smallholders typically determine production costs, other expenses must be taken into account when considering the size of coffee production. For instance, biogas and solar panels can serve as energy substitutes [212][213]. Furthermore, to reduce environmental impact, the application of IEC scenarios is considered through the valorization of by-products. The cost of managing wastewater into biogas, by-products, and new food products is factored into the LCC. The author divides several cost criteria: (i) CB raw materials,

(ii) energy, (iii) labor, and (iv) other materials using spreadsheet tools, with consideration of the Discount Rate [214], and Single Present Value (SPV) [215][216]. The LCC formula is described below [217]:

$$LCC_c = C_T + Op\ OnF + Op\ Off + E_c + C_U \quad (1)$$

Where:

LCC_c = Life Cycle Costing of Coffee (IDR/kg)

$Lc\ OnF$ = Labor Cost On-Farm (IDR/kg)

$Lc\ Off$ = Labor Cost Off-Farm (IDR/kg)

E_c = Energy Cost (IDR/kg)

C_U = Cost of Utility (IDR/kg)

$$LCC_{BP} = Op\ Off + E_c + C_U \quad (2)$$

LCC_{BP} = Life Cycle Costing of By-Product (IDR/kg)

LLC helps smallholder coffee farms by providing economic indicators for the cost of coffee products and derivatives. These indicators help farmers improve their production efficiency, cost-effectiveness, projections, and production plans. This can lead to fair trade, organic certification, and geographical indication (GI) solutions [218][38]. The author presents several LCC scenarios, including the Biogas scenario, where cow dung is used to produce biogas, animal feed is made from shade plants, and coffee processing waste is transformed into coffee husk and pulp. Other scenarios include the potential use of by-products like cherry skins and husk skins to make fertilizer and animal feed.

8.8 Coffee production assessment

8.8.1 Mass balance for coffee processing

Andungsari Coffee Group, a smallholder, has been employing unique agricultural practices for a significant period. They have been using organic fertilizers, applying about 15kg per tree annually, split into two applications. The first application is at the onset of the rainy season, around November, and the second is at the end of the rainy season, approximately January. This results in each tree receiving approximately 7.5kg of fertilizer per period. The group also utilizes organic pesticides derived from local plants like Caliandra and Aloe Vera. They prune unproductive twigs, which are then stockpiled in the soil and mixed with Dust Hs to create compost, serving as a natural fertilizer. The results of the organic fertilizer testing are presented in Table 8.4. Additionally, the smallholders prune their coffee trees in March-April and June-July, coinciding with the peak of the red-picking season. The trimmed twigs aid the branches and young cherries in absorbing nutrients more efficiently.

The processing of FW and SW coffee beans takes longer than natural or anaerobic coffee processing. In a batch of 2,850 kg of coffee beans (CB), approximately 45% is cherry skin (Cs), and the remaining 55% is wet parchment coffee (Wet-GB). Table 8.5 shows that 1,583 kg of Wet-GB is

obtained from raw CB, with 735 kg of Cs FW-SW used as coffee tea (Cascara). FW processing requires 36 hours of fermentation, while SW does not require fermentation. After fermentation, Wet-GB is washed, and SW is washed immediately. Wastewater from washing is used as an input for the digester, mixed with cow dung to produce biogas. In wet processing, the wastewater produced from washing is 1,951 kg, and the pulp is 128 kg. The Cs waste, which is dried and has a moisture content of 10-12%, weighs 604.4 kg after peeling the parchment skin.

In the study, a red pick produced into GB for specialty coffee has a maximum of 3% defect (crack), brown, black, hole [15][219]. Furthermore, if GB is cracked during processing, it is called Pixel Beans (Pb). The impact of using organic pesticides on GB is also discussed. The GB was tested at the Center for Seed and Plantation Plant Protection in Surabaya-Indonesia, and no parameters for Isoprocab, Profenofos, and others were detected (Table 8.6). This is important for maintaining the quality of GB, which is a determinant of export quality. In the past, there have been cases (between 2008-2012) where Isoprocab content exceeded 0.03ppm and Carbaryl was between 0.02-0.03 when exporting GB to Japan, resulting in the beans being shipped-back [119].

Finally, both types of GB are roasted, resulting in different products. Roasted Beans (RB) are specialty coffee, while RB commercial is made from Pixel beans (Pb). The CS in FW and SW are also roasted to create a roasted aroma and reduce the astringent taste [8]. The coffee powder produced from FW and SW processing weighs 508.3 kg and 508.5 kg, respectively.

Table 8.4 Organic fertilizer test

Parameters*	Test Method	Result	Unit	Source	SNI requirement[220]
N-Total	SNI 19-7030-2004	2.42	%	own	Max 6
N-Total	NA	1.15 - 2.23	%	[201]	-
K ₂ O	SNI 2803-2010	2.37	%	own	-
C-Organic	Furnace 550°C	48.53	%	own	Min 15
C/N Ratio	Conversion	20.02	%	own	15 - 25
C/N Ratio	NA	10.22 - 22.68	%	[201]	-
pH	SNI 2803-2010	10.13		own	4 - 9
pH	NA	5.54 - 7.17		[201]	-

*Observed data and compiled from ref.

Table 8.5 Mass balance of coffee processing

Steps*	Input-Output (kg)	Activity cost	Processing method, and costing							
			FW,kg	Lc,IDR	SW	Lc,IDR	N	Lc,IDR	An	Lc,IDR
	Input									
Fertilizing	Organic fertilizer	Pruning, Fertilizing	37,500	1.2	37,500	1.2	37,500	1.2	37,500	1.2
Harvesting	Cherry coffee	Selective Harvest	2,850	2.85	2,850	2.85	2,850	2.85	2,850	2.85
	Water		2,000	-	2,000	-	-	-	-	-
	Output									
Pulping	Depulp beans	Separate Skin	1,583	0.2	1,583	0.2	-	-	-	-
	Cherry skin (Cs)		1,267	-	1,267	-	-	-	-	-
Fermentation	Wet coffee beans	Beans Fermentation	1,583	0.4	-	-	-	-	2,594	0.4
	Wastewater		-	-	-	-	-	-	257	-
Washing	Coffee beans washed	Cleaning pulp	1,504	0.2	1,504	0.2	-	-	-	-
	Pulp		128	-	128	-	-	-	-	-
	Wastewater		1,951	-	1,951	-	-	-	-	-
Drying	Dried beans Mc 40%	Beans Drying	-	-	916	0.5	-	-	-	-
	Dried beans Mc 12%		737	1.0	-		1,368	1.0	1,369.4	1.0
	Cs dried	Skin Drying	735	0.5	735	0.5	-	0.5	-	0.5
Dehulling	Dehulled beans Mc 12%	Separate Dried Skin	604.4	0.2	-	-	609	0.2	609.4	0.2
	Dehulled beans Mc 40%	Separate Dried Skin	-	-	783	0.2	-	-	-	-
	Husk skin (Hs)	Separate Dried Skin	-	-	-	-	759	0.3	760	0.3
	Parchment skin (Ps)	Separate Dried Skin	133	-	133	-	-	-	-	-
Drying	Dried beans Sw	Beans Drying	-	-	604.6	0.5	-	-	-	-
Sortation	Grade beans	Grading Defect	594.5	0.3	594.7	0.3	599	0.3	599.6	0.3
	Pixel beans (Pb)		9.9	-	9.9	-	9.7		10	
	Hs Sorted Sized 5.5-7.5mm	Sizing Hs	-	-	-	-	494	0.3	498	0.3
	Dust Hs		-	-	-	-	265.7		262.2	

FW=Fullwash, SW=Semiwash, Nat=Natural, An=Anerobic, Mc = Moisture content; Lc=Labor Cost, IDR x10⁶

Table 8.5 (continued)

Steps	Input-Output (kg)	Activity cost	Processing method and costing							
			FW,kg	Lc,IDR	SW	Lc,IDR	N	Lc,IDR	An	Lc,IDR
	Output									
Roasting	Roasted beans	Roasting Coffee	535	0.5	535	0.5	539	0.5	539.7	0.5
	Pb roasted	Roasting Coffee	8.9	-	8.9	-	8.8	-	8.8	-
	Cs roasted	Roasting Cs	573.0	0.5	573.0	0.5	-	-	-	-
	Hs roasted	Roasting Hs	-	-	-	-	384.9	0.5	388.3	0.5
	Silver skin (Ss)		13.4	-	13.4	-	13.5		13.5	
Grinding	Coffee powder (Cp)	Grinding Cp	508.3	0.4	508.5	0.4	512.2	0.4	512.7	0.4
	Pb powder	Grinding Cp	8.5	-	8.5	-	8.3	-	8.3	-
	Cs powder	Grinding Cs	544.4	0.4	544.4	0.4	-	-	-	-
	Hs powder	Grinding Hs	-	-	-	-	365.7	0.4	368.9	0.4
Packing	Cp packing	Packing Cp	508.3	0.4	508.5	0.4	512.2	0.4	512.7	0.4
	Pb packing	Packing Cp	8.5	-	8.5	-	8.3	-	8.3	-
	Cs packing	Packing Cs	544.4	0.4	544.4	0.4	-	-	-	-
	Hs packing	Packing Hs	-	-	-	-	365.7	0.4	368.9	0.4

FW=Fullwash, SW=Semiwash, Nat=Natural, An=Anerobic, Mc = Moisture content

Lc=Labor Cost, IDR x10⁶

*Observed data

Table 8.6 Pesticide analysis

Parameters	Test Method	Result	LmQ	Unit	Source
Ametryin	UPLC-MS	Not Detected	0.05	ppm	own
Diphenylamine	UPLC-MS	Not Detected	0.03	ppm	own
Profenofos	UPLC-MS	Not Detected	0.03	ppm	own
Tebuconazole	UPLC-MS	Not Detected	0.06	ppm	own
Isoprocab	UPLC-MS	Not Detected	0.03	ppm	own, [119]
Carbaryl	NA	NA	0.01	ppm	[119]

NA=Not Available, UPLC-MS= Ultra-performance liquid chromatography-mass spectrometry, LQ=Level Maximum Quantity

Dry processing using the natural method is simpler for coffee processing. After peeling and separating them from their husk skin, the coffee beans are selectively dried to a moisture content of about 12%. Approximately 2,850 kg of coffee beans are sun-dried, resulting in 1,368 kg of dried beans. These dried beans are then peeled to obtain 609 kg of green beans and 759-760 kg of husk skin. The husk skin is sorted into mixed sizes of 5.5, 6.5, and 7.5mm, producing 494-498 kg of husk skin that can be roasted and 262.2-265.7 kg of dust skin. The roasted husk skin is then used to produce 384.9-388.3 kg of roasted Cascara product after being coarsely ground. This Cascara product can be further ground to make 335.7-368.9 kg of Cascara powder. The dust skin is composted and used for organic fertiliser mixtures. Composting takes over 30 days, but the resulting C/N ratio can be used as organic fertiliser [221].

Anaerobic processing requires fermentation for 96 hours, after which the coffee beans are dried. The wastewater produced during this stage is used for biogas manufacturing mixtures, resulting in 257 kg of wastewater from raw 2,850kg of CB. Sun-drying in anaerobic processing is faster than natural processing, and decay in coffee pulp accelerates drying. The next steps are the same as in the natural method, which includes dehulling, sorting, roasting, grinding, and packing. Anaerobic processing produces a composition similar to the natural method (Table 8.5).

8.8.2 Energy supply in industrial ecology coffee

Wet and dry processing cannot be separated from technology, energy and emissions of course. Table 8.3 outlines technologies in fuel use. 5hp engine usage, 300kg/h capacity for Cs stripping and washing process. Gasoline fuel is needed in the use of a 5hp engine with a capacity of 300kg/h. Transportation also uses motorcycles, and other technological needs have also been outlined. Furthermore, after the CB dried approximately 12% of moisture content, it can be stored for the next 6 months in a coffee plastic bag. The process of dehulling of parchment and husk skin can be done gradually; this depends on the market demands.

Table 8.7 Coffee processing energy consumption

Material Arabica*	Processing	Energy	FW	SW	N	An
Harvesting	Motor Vehicle	Petrol,l	2.9	2.9	2.9	2.9
Cherry Beans (CB)	Depulping	Petrol,l	5.7	5.7	-	-
Get Flavor	Fermentation	Solar Panel,kWh	0.5	-	-	1.4
Washing	Cleaning Pulp	Petrol,l	3.2	3.2	-	-
Cleaning skin	Dehulling	Solar Panel,kWh	7.4	17.2	13.7	13.7
Green Beans (GB)	Sorted GB	Solar Panel,kWh	1.5	1.5	1.5	1.5
Husk skin (Hs)	Sorted Hs	Solar Panel,kWh	-	-	3.8	3.8
GB Grade	Roasting Coffee	Solar Panel,kWh	7.4	7.4	7.5	7.5
		Biogas,m ³	87.2	87.2	87.9	87.9
GB Pixel (Pb)	Roasting Coffee	Solar Panel,kWh	0.1	0.1	0.1	0.1
		Biogas,m ³	1.5	1.5	1.4	1.4
Cherry skin (Cs)	Roasting Skin	Solar Panel,kWh	9.2	9.2	-	-
		Biogas,m ³	107.8	107.8	-	-
Hs	Roasting Skin	Solar Panel,kWh	-	-	6.2	6.2
		Biogas,m ³	-	-	72.4	73.0
Coffee Roasted (CR)	Grinding	Solar Panel,kWh	20.1	20.1	20.2	20.2
Pb Roasted defect	Grinding	Solar Panel,kWh	0.3	0.3	0.3	0.3
Cs Roasted	Grinding	Solar Panel,kWh	10.7	10.7	-	-
Hs Roasted	Grinding	Solar Panel,kWh	-	-	14.4	14.6
Coffee Powder (CP)	Packing	Solar Panel,kWh	3.2	3.2	3.2	3.2
Pb R defect	Packing	Solar Panel,kWh	0.1	0.1	0.1	0.1
Cascara Cs	Packing	Solar Panel,kWh	3.4	3.4	-	-
Cascara Hs	Packing	Solar Panel,kWh	-	-	2.3	2.3

FW=Fullwash, SW=Semiwash, N=Natural, An=Anerobic

*observed data

Table 8.7 describes the use of energy at each stage of the process, harvesting using motorcycles. 2,850kg CB is transported with a carrying capacity of 100kg/batch. The distance from the garden to the processing site is recorded at an average of 3.5km for one trip, requiring an average of 2.9 litres of petrol for a round trip. FW and SW require 5.7 litres of petrol for CB peeling and washing 3.2 litres. Electricity in this process uses solar panels and biogas is used for energy. The author converts LPG needs to biogas, although the use of biogas is partial because the capacity of biogas per day is around 7m³. Accumulation per ha in Table 8.5 as a reference for data input in SimaPro software for LCA calculations. Biogas, solar panels, and petrol emission factors are used for input data LCA [211][46]. In this study, the author also involved the roasting stage on Cascara from CS and HS. Based on scenarios on IEC applied of biogas-solar panel energy sources. 400WP solar panel installation, 200Ah, 12V battery storage, 3kW pure sinus wave inverter. In Table 8.7, biogas consumption at the GB roast stage reaches 87.2m³ with a total of GB 594.5 kg (Table 8.5). In addition to the coffee production period, biogas can be used for stoves in smallholders.

8.9 Environmental impact analysis

The production of coffee has a significant impact on the environment, particularly with regard to GWP. The process involves both upstream and downstream production, and it's important to consider the impacts of GWP at every stage of the process. The use of industrial ecology principles can help smallholder coffee farmers to produce coffee in a more sustainable and environmentally-friendly way. This approach involves utilizing waste to create product-added value, implementing energy-efficient practices, and reducing the impact of GWP.

Figure 8.1 demonstrates the interconnectedness of three different aspects of coffee production - the coffee plantation, the industry, and livestock - in the context of SCP A to Z solutions. It shows how coffee beans from plantations can be seamlessly integrated into the coffee industry as input materials, which then process the coffee. The resulting wastewater can be recycled and mixed with cow dung to create biogas, illustrating the holistic approach of SCP A to Z solutions.

The authors monitored a three-year harvest cycle for smallholder coffee farmers between 2021 and 2023. It is important to utilize the liquid and solid waste cycle to prevent environmental risks. Figure 8.4 outlines the production of waste and potential by-products including wastewater (Ww) between 946-1798 kg/ha and 223 kg CS at peak harvest between May and August from the wet processes, while dry methods produce 231 kg Hs/ha.

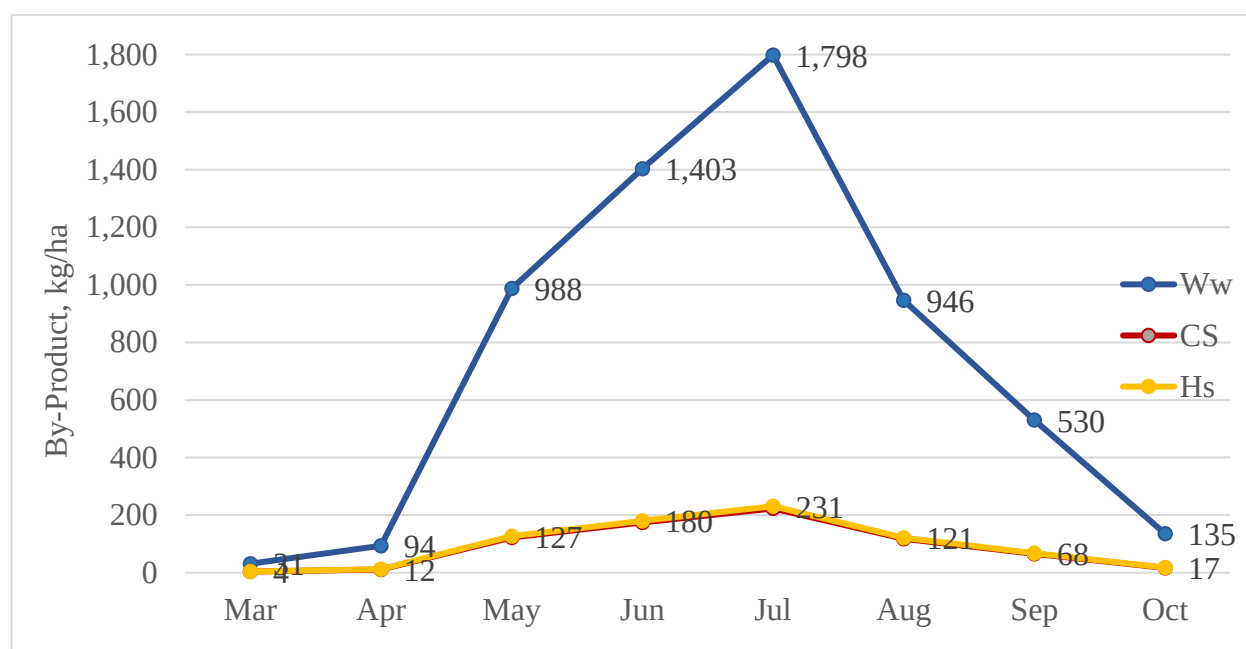


Figure 8.4 Potential By-Product/ha

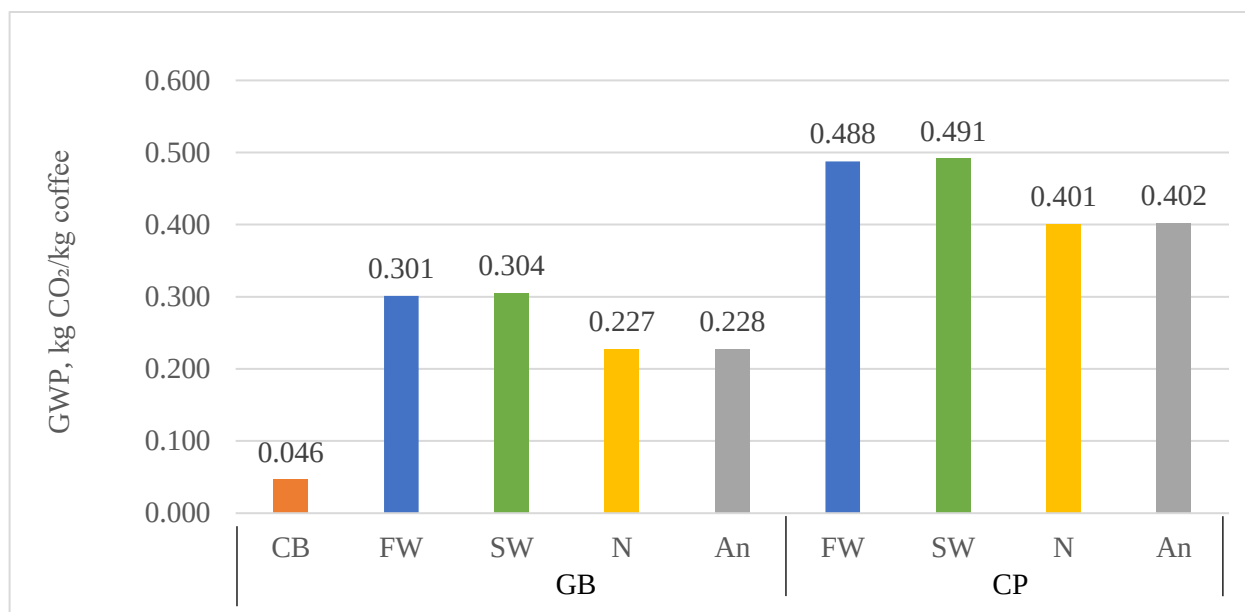


Figure 8.5 Comparison of GWP coffee processing

CP = Coffee Powder, SW= Semiwash, FW= Fullwash, N=Natural, An = Anaerobic, GB=Green Beans, CB = Cherry Beans.

In Figure 8.5, Cherry Beans (CB) produce a GWP impact of 0.046kg CO₂-eq/kg CB; This is due to transportation from the plantation to the processing site. In addition, organic fertilizers also contribute to producing CO₂ even though it is low. The process of processing CB to produce Coffee Powder (CP), FW and SW wet processing methods contribute 0.488kg CO₂-eq, and 0.491kg CO₂-eq consecutively per 1kg CP. While in dry method from CB to CP on natural achieves 0.401kg CO₂-eq/kg CP. Next, wet and dry processing from CB to GB on FW, SW, and N was 0.301kg CO₂-eq, 0.304kg CO₂-eq, 0.227kg CO₂-eq, respectively, and 0.228kg CO₂-eq for An process. The contribution of each of these treatments has been outlined in Figure 8.6.

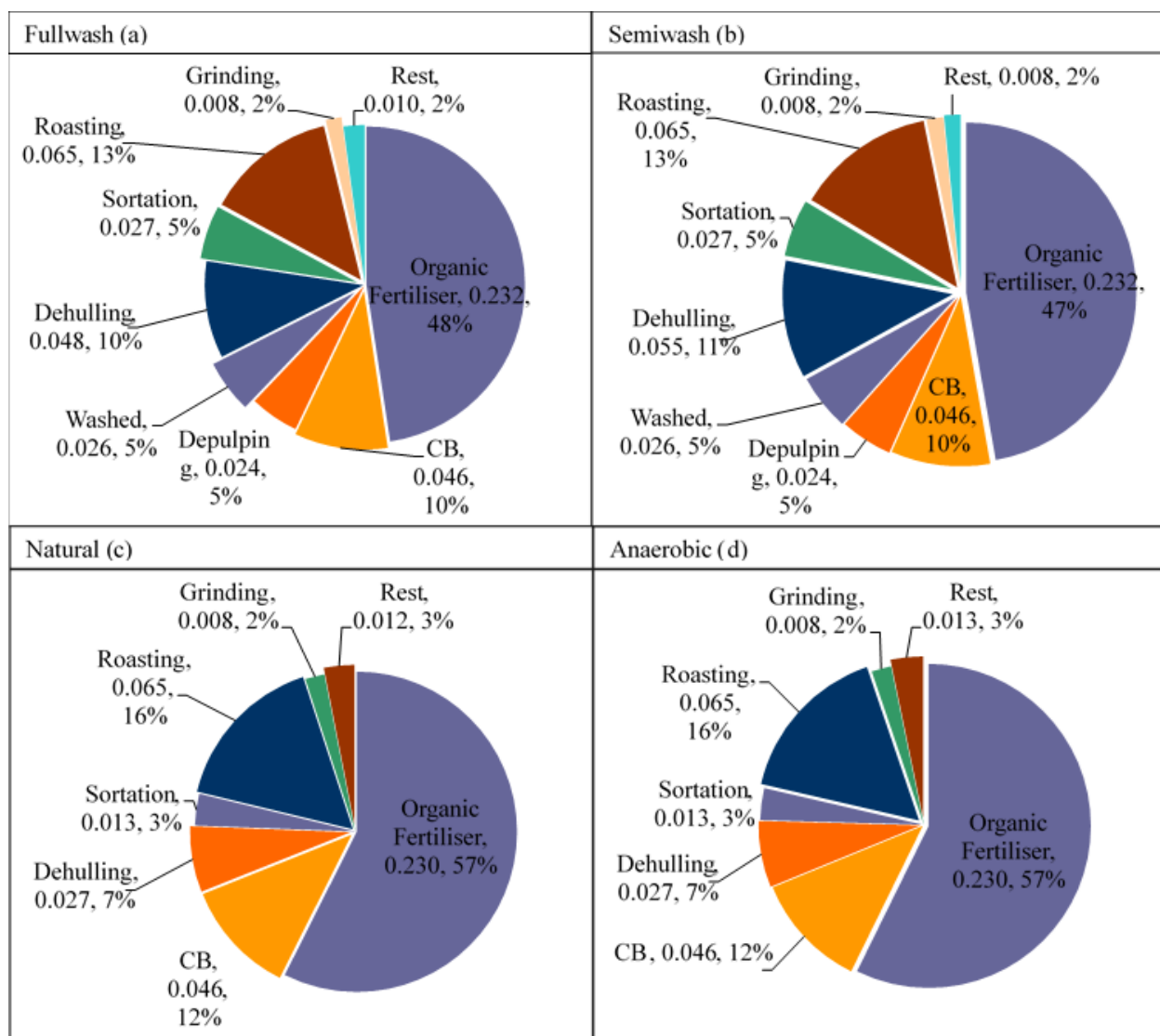


Figure 8.6 GWP contribution (a) Full wash, (b) Semi wash, (c) Natural, (d) Anaerobic

This study chose the Cut Off-U database as an input for fertiliser and biogas, and APPOS-U on gasoline. In Figure 8.6a and Figure 8.6b, illustrations of GWP contributors to the wet processing process (FW-SW), organic fertiliser contributes 0.232 kg of CO₂-eq; this impact is caused by the use of cow manure as an energy source (biogas and organic fertiliser). This contribution reaches 48% in FW and 47% in SW. In addition, the impact of GWP on dehulling is seen Figure 8.6 (b) as 1% higher than FW or 0.055 kg CO₂-eq in SW and 0.048 kg CO₂-eq FW. In contrast to the dry method of raw manure as a GWP contributor of 0.230 kg CO₂-eq, this percentage is higher than the wet method, which is 57%. It can be seen that, dry processing is shorter processing stage than wet process.

The author also elaborates on the impact of GWP on wet and dry coffee skin processing through roasting stages for coffee skin [8]. Although, without roasting the skin, coffee can be made as a tea ingredient, it has the disadvantage of having an astringent taste and a dry skin aroma. Furthermore, Figure 8.7 shows the impact of GWP because roasting Cs and Hs produce the same impact of 0.106 kg CO₂-eq. However, Cascara Hs has a sorting stage of 5.5 – 7.5mm size to produce Cascara, or GWP contribution of 0.014 kg CO₂-eq.

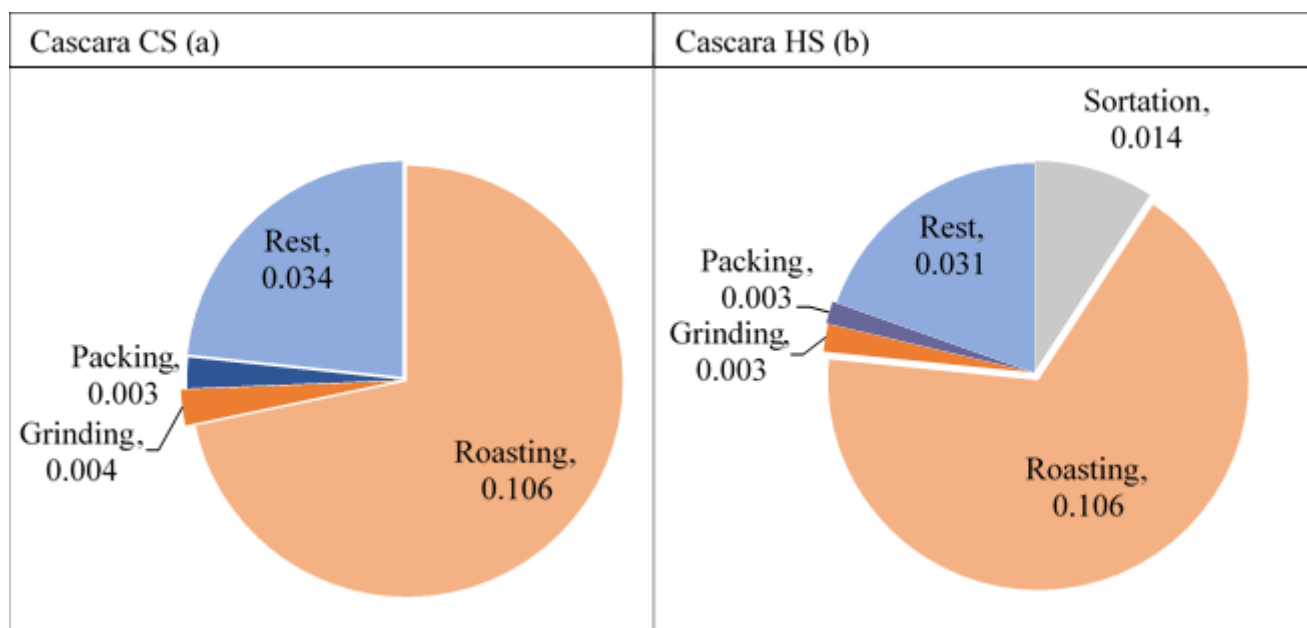


Figure 8.7 GWP contributions (a) CS, (b) HS

Figure 8.8 describes the impact category of coffee processing from CB to CP and By-Product CS and HS. HTPnc has the highest impact from this processing; FW was 309.36×10^{-3} kg 1,4-DCB, and SW was 313.64×10^{-3} kg 1,4-DCB. Some impacts due to the processing of By-Product CS and HS are lower than those of CB, such as HOFp, EOFp, and TETp. HOFp is a respiratory and long-term health risk [44][43]. The long-term impact of EOFp and TETp is a risk to biodiversity when discharged directly into water and soil [222]. Although CS and HS treatment contributes to the environment, reprocessing can add value to smallholders and reduce the impact of direct discharge. The water use impact category is higher for FW and SW, between 7.25 and 8.81×10^{-3} m³/kg coffee. Meanwhile, N and An are between 0.53 and 0.91×10^{-3} m³/kg coffee.

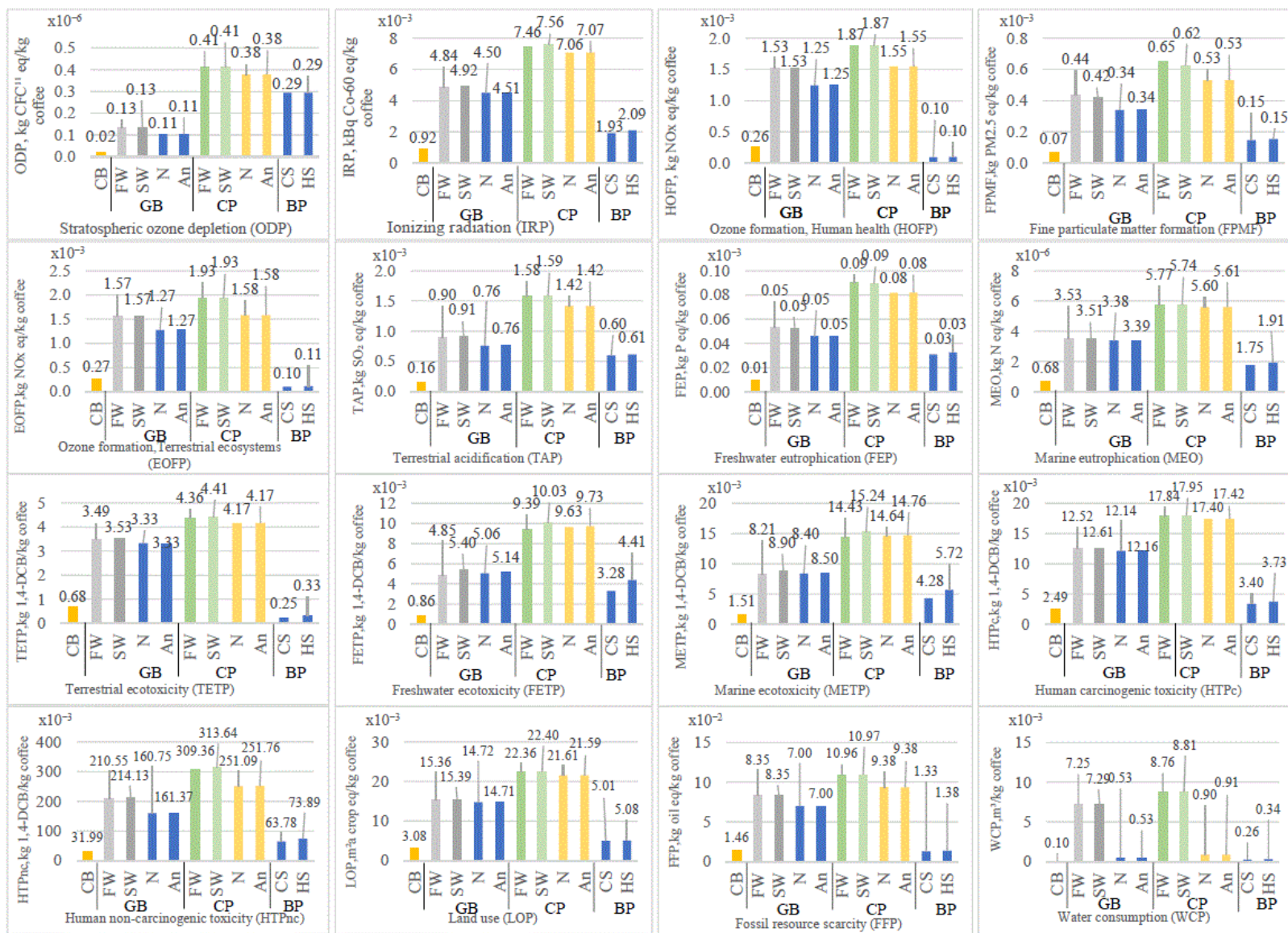


Figure 8.8 Impact on all categories and coffee processing methods for CB to CP and by-products (BP).

8.10 Life cycle cost analysis

This study examines the impact of alternatives of CS and HS and concludes that Cascara has a higher selling value than CS and dry HS. Even though dry HS cannot be consumed directly due to dust, HS dust reaches up to 35%. The utility cost is meant to cover biogas and solar panel maintenance. Through the smallholder empowerment stage, alternative CS drying and HS sorting are applied to reduce direct disposal in the garden, which poses a risk to soil and water. The author outlines alternative value-added products, mainly using coffee processing by-products. Figure 8.9 illustrates that the CS and HS alternative produces cascara compared to direct disposal, or HS sold at IDR 300/kg, even if wet CS is not sold directly.

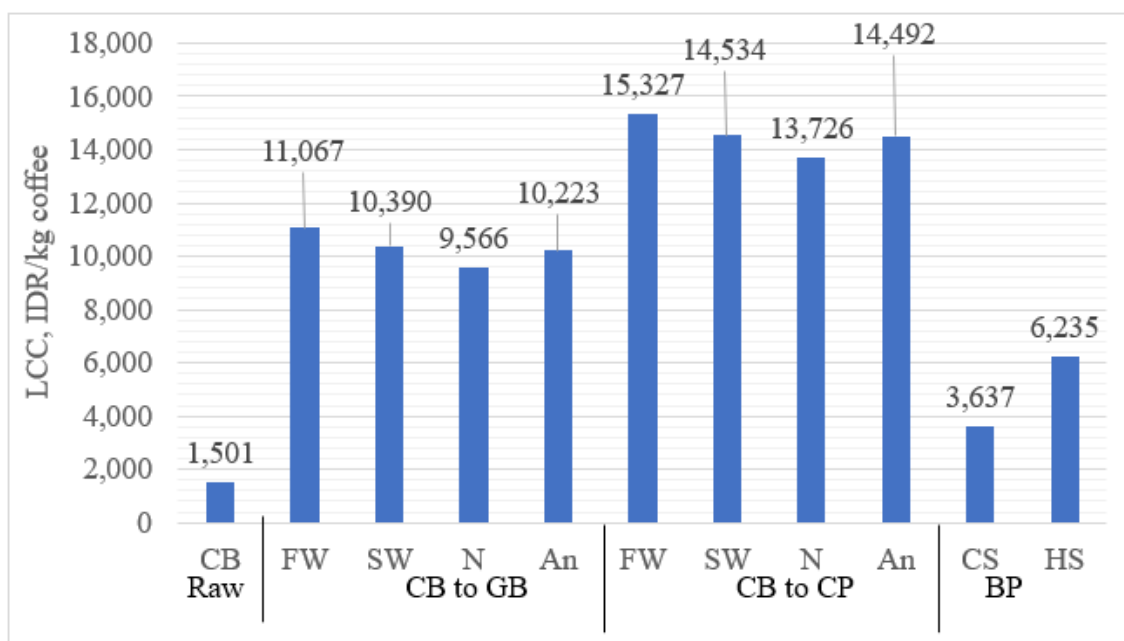


Figure 8.9 Life cycle costs (LCC) of coffee production for different processes

The cost of producing 1kg of Cherry Beans (CB) is approximately IDR 2,764.4, which includes expenses such as fertilizer application, pruning, and coffee plant maintenance per year. The highest estimated cost per 1kg of Green Beans (GB) is contributed by FW at IDR 17,122.4, as FW processing has a longer process chain compared to other processing methods. The cost of processing Coffee Powder (CP) ranges from IDR 20,755.2 - 22,409.4 per kg of CP. By-product utilization is assumed to be 100%, and it is used to produce Novel Food (Cascara) at the cost of IDR 3,637.1 and IDR 6,235 per kg Cascara, CS and HS, respectively.

8.11 Sustainable coffee production incorporating IEC

Sustainable coffee production is a multifaceted concept that encompasses a wide range of environmental, social, and economic considerations. The principles of industrial ecology can play an important role in improving the sustainability of coffee production by minimizing waste, optimizing resource use, and encouraging a circular economy approach in the coffee supply chain. In this study, we have applied IEC to the Andungsari smallholder group to incorporate the principles of industrial ecology through various initiatives:

1. **Energy Resource Efficiency:** In coffee production, this involves reducing direct water discharge by at least 1,951 kg/ha/year (as shown in Table 8.5) to produce biogas. Additionally, energy

consumption during processing is optimized through the periodic use of solar panels for production and the implementation of organic fertilisers. Technologies such as coffee skin recycling systems are utilized to produce Cascara, yielding approximately 544.4kg of CS material and 365.7 to 368.9 Cascara from HS. These IEC practices applied to the Andungsari Group help achieve Sustainable Coffee Production (SCP) through the Smallholder Gatekeeper role in Coffee Production. Final waste from Dust skin is managed through strategies such as composting to fertilize the soil.

2. **Closed-Loop System Implementation:** This study's IEC implements a closed-loop system where waste from one process becomes a resource for another. In coffee production, this could involve recycling coffee processing by-products to produce biogas or dry fuel for traditional stove burning.
3. **Life Cycle Assessment:** LCA evaluates the environmental impact of a product or process throughout its life cycle. Applying LCA to coffee production can help identify environmental impact points, such as energy-intensive processing or transportation emissions, and guide decision-making to reduce these impacts through measures such as switching to renewable energy sources or optimizing transportation logistics.
4. **Life Cycle Costing:** LCC evaluates the total cost per kg of product throughout the production cycle, including operational costs (plants maintenance, fertiliser, and harvest), production operations, energy costs, and technology maintenance costs for each batch process.

By integrating IEC principles through LCA and LCC into coffee production, stakeholders can improve the sustainability of the coffee supply chain, reduce environmental impacts, improve resource efficiency, and contribute to the long-term survival of coffee farming communities as Smallholder Gatekeepers of Coffee Production.

8.12 IEC and environmental aspects

Agroecological farming practices, a key component of industrial ecology, offer significant benefits to the coffee industry. By modelling industrial systems on natural ecosystems, these practices aim to minimize waste and maximize resource efficiency. For coffee production, this means reducing the use of synthetic inputs like pesticides and fertilizers, thereby lowering the ecological footprint. Techniques such as agroforestry, composting, and natural pest control [223], are instrumental in this approach.

The Andungsari smallholder group has implemented various practices to promote sustainability. They use organic fertilizers (as listed in Table 8.4) and pesticides (as listed in Table 8.6) to ensure the safety of their produce. To conserve water, they opt for dry coffee production methods like Natural and Anaerobic. To further reduce water consumption and pollution, they have implemented water-saving technologies like optimizing wet milling and wastewater treatment systems. Lastly, they also use the fermentation of Cherry Beans to utilize overripe raw materials.

The industrial ecology principles highlight the significance of waste reduction and recycling. In line with this, coffee production produces different waste products such as coffee husks and wastewater. However, these waste by-products can be transformed into valuable resources through composting, animal feed, or bioenergy generation. This group has effectively implemented the use of by-products to create Cascara [8]. Improving energy efficiency is an important step in reducing greenhouse gas emissions and decreasing reliance on fossil fuels. Coffee processing facilities can achieve this by adopting renewable

energy sources, such as solar panels and digesters [13], biomass boilers, or energy-efficient equipment. Investing in these technologies can make a significant difference in reducing the carbon footprint of coffee production.

Supply chain transparency and fair trade practices are crucial for ensuring that smallholders are fairly compensated for their labor and for promoting sustainable practices. Certification schemes, such as those for organic fertilizers, help to meet environmental and social standards. Biodiversity conservation through maintaining healthy ecosystems and robust coffee production systems is also important. Shade-grown coffee practices, which mimic natural forest habitats, create habitat for wildlife and improve soil health, as shown in Table 8.2.

Carbon offsetting initiatives, such as reforestation projects that plant avocado and other fruit trees for shade crops, or carbon sequestration efforts, can help reduce the environmental impact of coffee production. Investing in climate-resistant coffee varieties and farming practices can also aid coffee farmers in adapting to changing environmental conditions, as evidenced by the mix-varietal Arabica plants (as shown in Table 8.2) [130].

Finally, certification labels provide information that supports ethical brands and reduces waste through the use of reusable coffee cups. By integrating the principles of industrial ecology into the coffee production process, stakeholders can work towards a more sustainable and resilient coffee industry that minimizes environmental impacts while supporting smallholder livelihoods and preserving natural ecosystems

8.13 Socio-economics of smallholder coffee production

As explained in the previous discussions, the smallholder farmer's group in Andungsari have been able to conduct coffee cultivation and production using Industrial Ecology approach, where their agricultural practices can be observed to be very sustainable, not only from the environmental perspectives but also for their livelihood. While the economic gains from coffee cultivation and production acts as their main source of income, the byproducts from the coffee production process have provide further economic gains in the form of cost reduction from energy consumption as well as fertilizer cost. Furthermore, with the coffee cascara further processed as an agricultural product, farmers can capitalize this product as their secondary income, complementing their strong economic foundation.

Currently, not all members of the farmer's group can conduct this approach as some of the limiting factors include base capital and resources of an individual farmer. Concerning this challenge, the farmer's group will need to develop a resource and benefit sharing scheme in order to ensure that all of the members can received the full benefit of Industrial Ecology application in coffee cultivation and production.

8.14 IEC scenario

Small-scale coffee farmers use sustainable methods to grow coffee. They either grow it under existing tree canopies or plant new shade trees around the plantation. This enhances soil quality and coffee plant health and provides a habitat for biodiversity. Farmers living near Community Forests (CF) collaborate with other farmers to manage coffee waste, such as coffee husks and wastewater. They turn them into organic compost, which they reuse as fertilizer in coffee plantations, creating a closed loop in the supply chain.

Smallholders also install solar panels on rooftops and use biogas as an energy source. They work closely with local coffee farmer cooperatives and food companies to develop coffee by-products, such as cascara or coffee snacks. This helps in utilizing every part of the coffee plant and creating added value for the local community. Additionally, they provide customers with information about coffee sources, varieties, and processing methods. This promotes awareness of the importance of choosing environmentally friendly products.

Meanwhile, the Community Forests Organization (CF-O) collaborates with smallholders to provide training on sustainable farming practices, waste management, and income source diversification. This helps improve farmer welfare and strengthens economic resilience.

Through scenario-based and scenario models, collaboration among stakeholders in the coffee industry can create a more ecologically, economically, and socially sustainable system in coffee production.

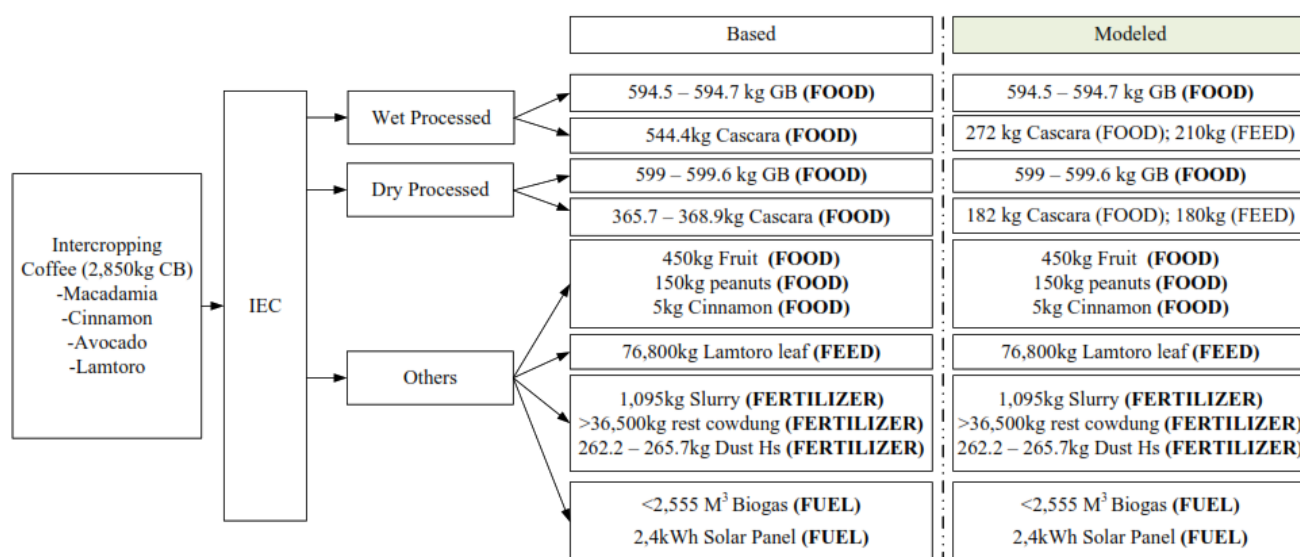


Figure 8.10 Base scenario and modeled scenario of IEC

In the presented scenario (Figure 8.10), the primary product, which is food, yields around 594.5 – 599.6 kg of GB using the wet-dry method. Cascara from CS produces 544.4 kg, while HS produces 368.9 kg. The main products obtained from shade trees per hectare per year are 459 kg of avocados, 150 kg of macadamia nuts, and 5 kg of cinnamon. Shade trees also contribute to livestock feed production, producing around 76.8 tons/ha/year, with fertiliser amounting to 37.86 tons/ha/year. Additionally, smallholders can obtain biogas with an annual accumulation of 2.555 m³ and 2.4 kWh from solar panels.

However, in the modelled scenario, some Cascara products are allocated for livestock feed, with a total potential of 7.719 tons/ha/year, with Cascara from CS and HS producing 454 kg/ha/year. Unfortunately, producing livestock feed from coffee husks poses challenges as it requires chemical additives such as Urea, NpK, HCL, and others [224]. The Andungsari coffee group manages a 10-hectare coffee plantation, which has a fertiliser potential of 36.7 tons/ha/year, covering 98% of the fertiliser requirement, with the remaining 2% sourced from composted pruning leaves. Livestock feed potential is substantial, reaching 76.8 tons/ha/year, while the feed requirement for eight animals totals 73 tons/year. Meanwhile, the potential availability of livestock feed for 10 hectares amounts to 768 tons/year. Additionally, biogas production amounts to 2,555 m³/year, sufficient for household cooking needs within the group, averaging 1,095 m³/year.

However, for off-farm processing of the 10 hectares, the requirement is 1,950 m³/year, covering approximately 74.8%. Through the implementation of IEC at Andungsari Kopi, significant social and economic impacts are realised through the supply of Feed, Fuel, and Fertilizer from within, albeit not entirely.

8.15 Conclusions of the case study

The Andungsari Coffee smallholder group has implemented the IEC scenario using a scenario-based approach. The production per ha coffee plantation in the harvesting period of 2023 produced CB about 2,850kg, which resulted in Green Beans (GB) (Food) between 594.5kg and 599.6kg, for wet and dry processing methods. Additionally, Cascara products (Food) from wet and dry methods produced between 365.7 and 544.4 kg, then Dust Skin from Hs about 265.7kg. The generated wastewater, approximately 2,079 kg/ha/year, was used as raw for biogas. The current biogas energy potential (Fuel) contributes to 74.8% of a 10-ha coffee plantation, and it can supply fertiliser up to 98% of the entire plantation in situ.

In contrast to animal feed, which is widely available, only about 5% is used from the total potential of animal feed in Andungsari Group. However, only 5% of the total availability of Feed in the plantation is required. By applying the IEC condition in situ, the GWP contribution for FW and SW was 0.488kg CO_{2-eq}/kg CP and 0.491kg CO_{2-eq}/kg CP. Meanwhile, the GWP contribution for Natural and Anaerobic was 0.401kg CO_{2-eq}/kg CP and 0.402kg CO_{2-eq}/kg CP. For by-products, it contributes to a GWP of 0.147kg CO_{2-eq}/kg Cascara from Cs and 0.156kg CO_{2-eq} /kg Cascara from Hs. LCC for CP between Wet and Dry Methods was from IDR 20,755.2 to 22,409.4, and LCC for Cascara from Cs was approximately IDR 3,637.1, For Hs was IDR 6,235. It can be concluded that educating and raising awareness among smallholders and consumers about the environmental impact of coffee consumption can motivate them to make more sustainable choices. Thus, implementing IEC impacts Sustainable Coffee Production (SCP) for smallholders, especially for gatekeepers in smallholder coffee production in the long term.

9 Conclusions and further work

9.1 Summary and novelty of this work

On the basis of the various sub-studies in this thesis, full wash and semi wash processing are the best methods to make it easier to sell coffee. In addition, if the utilization of by-products is sustainable, cascara can create a beneficial income stream. Natural processing is the most common choice when smallholders don't have other technology, even if it takes longer in the drying process. Natural processing has a lower cost than the full wash and semi wash processes. Anaerobic processing without additional fermentation is an option during peak harvests, as a substitute for natural processing. However, there are limitations in the use of fermentation as a step determine quality and flavor. Other processes such as CM, Lactic, and Hd are not a priority, as they are niche processes that do not fit the dominant market, so there is limited demand. Figure 9. 1 combines the LCA results of this study and compares with previous studies. From an environmental perspective, the natural processing method has the lowest carbon footprint – particularly with the integration of industrial ecology solutions utilizing biogas. From a quality perspective, the anaerobic process can be used to produce high quality coffee, but is more expensive than natural, and has a slightly higher footprint. The reuse of wastewater for biogas can dramatically lower the emissions though.

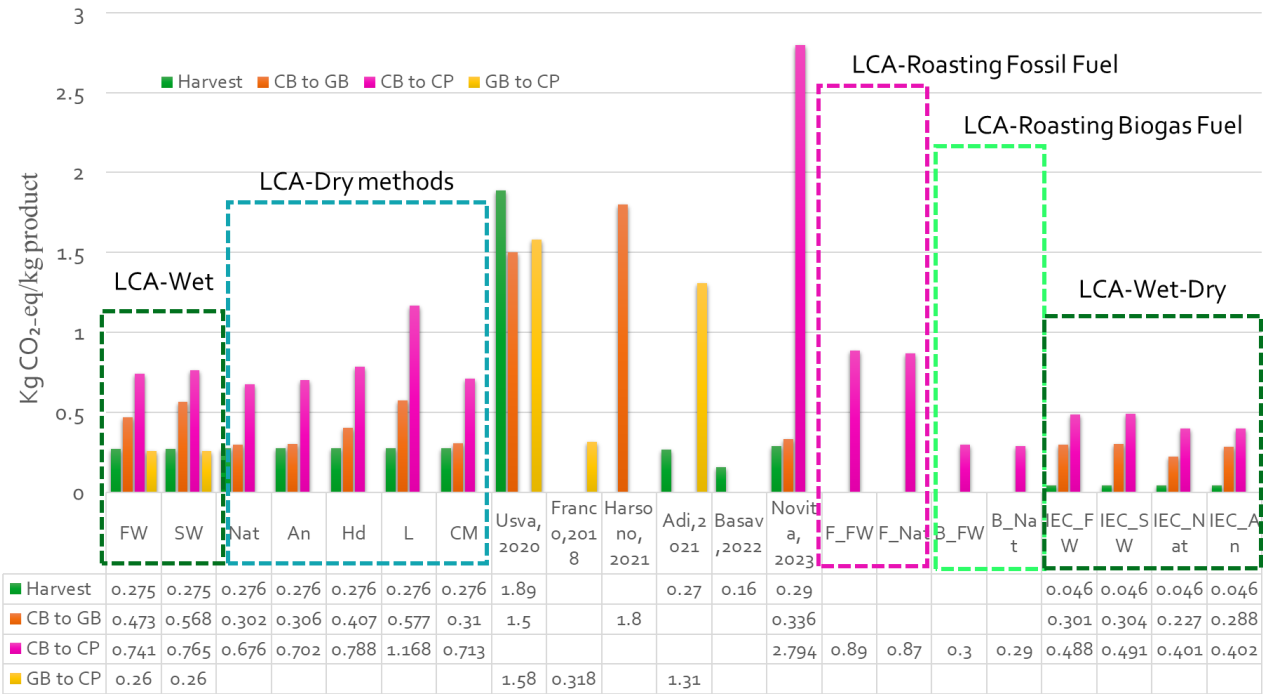


Figure 9. 1 Combined comparison of GWP in this study with previous research

9.2 Conclusions

This research explored different aspects of sustainable coffee production, including industrial ecology coffee, life cycle assessment, life cycle cost analysis, and the use of pilot plants on coffee plantations. The main objective was to develop sustainable coffee production and provide valuable insights into how the coffee industry can achieve sustainability. The model pilot plant as a means to implement IEC, LCA, and the sustainability of coffee plantations and production, shows great potential to enhance the overall

sustainability of the coffee industry. By applying IEC principles, coffee plantations can reduce their environmental impact, improve resource efficiency, and create a more sustainable environment for farmers and surrounding communities.

Some of the key points of novelty in this work include:

1. This study used a combination of methods to evaluate environmental impacts and economic potential of 10 different coffee processing methods. Typical studies only evaluate one or two processes at most. Here the study considered standard wet processes (Full Wash and Semi-Wash); and dry processes used where water is more scarce (Natural process), as well as more-novel dry processes that could be used to upgrade coffee quality (Anaerobic, Lactic Acid, Hydro-Honey, Carbonic Maceration, Inoculant, Mossto, Wine).
2. Industrial Ecology principles were applied to reduce environmental impacts by waste valorization in the form of biogas production from wastewater and processing of coffee husk or coffee cherry skin to produce coffee tea “cascara” as a by-product. In particular, the consideration of cascara is quite unique in literature.
3. In this study the quality of the coffee product was assessed, in addition to the environmental and economic considerations – which is very rare in the literature.

By combining scientific knowledge, technological innovation, and commitment to sustainability, we can create an efficient, eco-friendly, and inclusive coffee industry for all stakeholders. Sustainable Coffee Production goals can be achieved by considering environmental, economic, and social factors that benefit all parties involved. Therefore, all stakeholders must encourage and support continuous efforts towards sustainability in coffee production.

9.3 Further work

This study highlights the significant advantages of implementing the IEC concept in coffee production. This approach not only reduces the environmental impact of coffee production but also enhances resource efficiency, minimizes waste, and improves the welfare of coffee farmers. The use of LCA and LCC methods has proven to be a valuable tool in evaluating the environmental and economic impacts of various coffee production processes, helping stakeholders make more sustainable decisions.

Future research is planned to further-develop on the findings:

1. **Production process optimization:** Conduct further research to optimise the coffee production process using the principles of industrial ecology. These include increased energy use efficiency, more effective waste management, and applying environmentally friendly technologies.
2. **Pilot plant development:** To test and implement new technologies that support SCP and build pilot plants on coffee farms. These pilot plants can test various innovations in coffee processing, renewable energy use, and waste management.
3. **More in-depth LCA and LCC studies:** Conduct a more in-depth study of the life cycle of coffee products and analysis of total production costs, with further detail on alternative applications of waste and control of production processes. This will help identify areas where improvements can be made to improve the sustainability of coffee production.

4. **Education and training:** A crucial component of this research plan is the implementation of education and training programs for coffee farmers. These programs will focus on sustainable agricultural practices, the implementation of IE, and the use of new technologies. By increasing their awareness and understanding of the importance of sustainability in coffee production, we can significantly contribute to the long-term goals of this research.
5. **Collaboration and partnership:** Building partnerships with research institutions, government, and private companies to support the development of Sustainable Coffee Production (SCP). These collaborations can include the exchange of knowledge and resources, as well as financial support for innovative projects.

Implementing this research plan is expected to achieve long-term goals to produce more environmentally sustainable, economic, and social coffee, improve the welfare of coffee farmers and strengthen the resilience of the global coffee industry.

References

- [1] F. Tansil, "Welcome to The Heaven of Specialty Coffee Exotic & Unique Indonesian Coffee."
- [2] Directorate General for National Export Development, "Indonesian Coffee," *Export News Indones.*, vol. 7, no. 23, p. 93, 2014.
- [3] F. Fitriani, B. Arifin, and H. Ismono, "Indonesian coffee exports and its relation to global market integration," *J. Socioecon. Dev.*, vol. 4, no. 1, p. 120, 2021, doi: 10.31328/jsed.v4i1.2115.
- [4] Y. Wibowo, B. H. Purnomo, and A. Kristio, "The Agroindustry Development Strategy for Java Ijen-Raung Arabica Coffee , in Bondowoso Regency , East Java The Agroindustry Development Strategy for Java Ijen-Raung Arabica Coffee , in Bondowoso Regency , East Java Strategi Pengembangan Agroindustri Hili," no. August 2021, 2022, doi: 10.21776/ub.industria.2021.010.02.5.
- [5] M. Banti and E. Abraham, "Coffee Processing Methods, Coffee Quality and Related Environmental Issues," *J. Food Nutr. Sci.*, vol. 9, no. 6, pp. 144–152, 2021, doi: 10.11648/j.jfns.20210906.12.
- [6] R. N. Valenzuela Antezana and G. I. Luna-Mercado, "Effect of processing methods (washed, honey, natural, anaerobic) of catimor coffee on physical and sensory quality in Alto Inambari, Peru," *Coffee Sci.*, vol. 18, 2023, doi: 10.25186/v18i.2111.
- [7] A. A. Muliasari, R. K. Dewi, H. F. Rochmah, A. R. Malala, and P. G. Adinurani, "Improvement generative growth of coffea arabica L. using plant growth regulators and pruning," *E3S Web Conf.*, vol. 226, pp. 1–9, 2021, doi: 10.1051/e3sconf/202122600003.
- [8] A. Irawan, B. C. McLellan, and S. D. Hastutik, "Developing Coffee Cherry Skin and Coffee Husk by Products as Sustainable Novel Food and Fuel," vol. 1, no. 1, 2024.
- [9] M. Soares, A. Pandey, P. Christen, M. Raimbault, and C. R. Soccol, "A Novel Approach for the Production of Natural Aroma Compounds Using Coffee Husk," in *Coffee Biotechnology and Quality: Proceedings of the 3rd International Seminar on Biotechnology in the Coffee Agro-Industry, Londrina, Brazil*, T. Sera, C. R. Soccol, A. Pandey, and S. Roussos, Eds. Dordrecht: Springer Netherlands, 2000, pp. 419–425.
- [10] P. S. Nigam and A. Singh, *Cocoa and Coffee Fermentations*. 2014.
- [11] W. Jitjaroen, R. Kongngoen, and L. Panjai, "Aroma profiles and cupping characteristics of coffee beans processed by semi carbonic maceration process," *Coffee Sci.*, vol. 18, 2023, doi: 10.25186/v18i.2119.
- [12] L. W. Lee, M. W. Cheong, P. Curran, B. Yu, and S. Q. Liu, "Coffee fermentation and flavor - An intricate and delicate relationship," *Food Chem.*, vol. 185, pp. 182–191, 2015, doi: 10.1016/j.foodchem.2015.03.124.
- [13] A. Irawan and B. C. McLellan, "Study on biogas production from coffee wastes and cow-dung fermentation and its use towards reducing emissions from coffee roasting," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1201, no. 1, p. 012004, 2023, doi: 10.1088/1755-1315/1201/1/012004.
- [14] K. Riset *et al.*, "KemRiset, K., Teknologi, D. A. N., Riset, B., Nasional, D. A. N. I., Bidang, D., Riset, P., & Pengembangan, D. A. N. (2020). Kementerian riset dan teknologi/ badan riset dan inovasi nasional. 021, 6–8. enterian riset dan teknologi/ badan riset dan inovasi ," no. 021, pp. 6–8, 2020.

- [15] BSN (Badan Standardisasi Nasional), "SNI 01-2907-2008: Biji Kopi," *Badan Standardisasi Nas.*, pp. 1–16, 2008.
- [16] S. S. Harsono, R. K. K. Wibowo, and E. Supriyanto, "Energy Balance And Green House Gas Emission On Smallholder Java Coffee Production At Slopes Ijen Raung Plateau Of Indonesia," *J. Ecol. Eng.*, vol. 22, no. 7, pp. 271–283, 2021, doi: 10.12911/22998993/138997.
- [17] G. J. Miito and N. Banadda, "A short review on the potential of coffee husk gasification for sustainable energy in Uganda," *F1000Research*, vol. 6, pp. 1–11, 2017, doi: 10.12688/f1000research.10969.1.
- [18] E. Oropeza-Mariano, M. E. Ortega Cerrilla, J. G. Herrera-Haro, E. J. Ramírez-Bribiesca, and T. Salinas-Ríos, "Use of pulp and husk of coffee in animal feed," *Agro Product.*, pp. 149–158, 2022, doi: 10.32854/agrop.v15i9.2171.
- [19] N. F. Lani Kingston, *How to Make Coffee: The Science Behind the Bean*, vol. 53, no. 9. 2017.
- [20] B. Mulyara, S. Supriyadi, Y. Rahmadian, and O. A. N. Ichsan, "Sensory Properties and Volatile Compound Profile of Anaerobic Fermented Gayo Arabica Coffee In Non-Washed Processing," *Pelita Perkeb. (a Coffee Cocoa Res. Journal)*, vol. 37, no. 3, pp. 239–254, 2021, doi: 10.22302/iccri.jur.pelitaperkebunan.v37i3.464.
- [21] E. J. M. Jimenez *et al.*, "Influence of anaerobic fermentation and yeast inoculation on the viability, chemical composition, and quality of coffee," *Food Biosci.*, vol. 51, no. November 2022, 2023, doi: 10.1016/j.fbio.2022.102218.
- [22] C. Wang *et al.*, "Potential of lactic acid bacteria to modulate coffee volatiles and effect of glucose supplementation: fermentation of green coffee beans and impact of coffee roasting," *J. Sci. Food Agric.*, vol. 99, no. 1, pp. 409–420, 2019, doi: 10.1002/jsfa.9202.
- [23] G. V. de Melo Pereira, A. da Silva Vale, D. P. de Carvalho Neto, E. S. Muynarsk, V. T. Soccol, and C. R. Soccol, "Lactic acid bacteria: what coffee industry should know?," *Curr. Opin. Food Sci.*, vol. 31, pp. 1–8, 2020, doi: 10.1016/j.cofs.2019.07.004.
- [24] E. Rossi, F. Pasciucco, R. Iannelli, and I. Pecorini, "Environmental impacts of dry anaerobic biorefineries in a Life Cycle Assessment (LCA) approach," *J. Clean. Prod.*, vol. 371, no. August, p. 133692, 2022, doi: 10.1016/j.jclepro.2022.133692.
- [25] N. Ariefandie and F. Zhu, "Coffee bean processing : Emerging methods and their effects on chemical , biological and sensory properties," *Food Chem.*, vol. 412, no. September 2022, p. 135489, 2023, doi: 10.1016/j.foodchem.2023.135489.
- [26] J. Baggenstoss, L. Poisson, R. Kaegi, R. Perren, and F. Escher, "Coffee roasting and aroma formation: Application of different time-temperature conditions," *Journal of Agricultural and Food Chemistry*, vol. 56, no. 14. pp. 5836–5846, 2008, doi: 10.1021/jf800327j.
- [27] E. Novita and M. E. Irfani, "Life Cycle Assessment of Organic Arabica Coffee Products," vol. 12, no. 1, pp. 186–200, 2023.
- [28] V. Byrareddy, L. Kouadio, S. Mushtaq, and R. Stone, "Sustainable production of robusta coffee under a changing climate: A 10-year monitoring of fertilizer management in coffee farms in Vietnam and Indonesia," *Agronomy*, vol. 9, no. 9, 2019, doi: 10.3390/agronomy9090499.

- [29] T. Hasan, S. Paputsara, S. B. Noveliska, and G. D. Adi, “Estimating the Benefit of Robusta Coffee Production in Semarang and Banjarnegara,” *Agroindustrial J.*, vol. 6, no. 1, p. 366, 2020, doi: 10.22146/aij.v6i1.53951.
- [30] U. M. D. E. C. D. E. Los, “No 主観的健康感を中心とした在宅高齢者における 健康関連指標に関する共分散構造分析 Title.”
- [31] A. S. C. de Bomfim *et al.*, “Spent Coffee Grounds Characterization and Reuse in Composting and Soil Amendment,” *Waste*, vol. 1, no. 1, pp. 2–20, 2022, doi: 10.3390/waste1010002.
- [32] F. M. Borém and E. T. De Andrade, “Processing and drying of coffee,” *Dry. Roasting Cocoa Coffee*, vol. 3, no. 12, pp. 141–170, 2019, doi: 10.1201/9781315113104-6.
- [33] R. Manurung, E. Apriliyanto, and O. I. A. Nugroho, “The Effect of the Coffee Roasting Machine on Increasing Production of Arabic Coffee KSM Galuh Lestari Dusun Gunungmalang in Indonesia,” *Proc. 1st Int. Conf. Law Hum. Rights 2020 (ICLHR 2020)*, vol. 549, no. Iclhr 2020, pp. 259–266, 2021, doi: 10.2991/assehr.k.210506.036.
- [34] S. Smrke, M. Wellinger, T. Suzuki, F. Balsiger, S. E. W. Opitz, and C. Yeretizian, “Time-Resolved Gravimetric Method to Assess Degassing of Roasted Coffee,” *J. Agric. Food Chem.*, vol. 66, no. 21, pp. 5293–5300, 2018, doi: 10.1021/acs.jafc.7b03310.
- [35] M. de los Á. Franco and K. Bartl, “Carbon Footprint of the Coffee Roasting Process Based on Two Technologies with Different Sources of Energy in Peru,” *Eur. J. Sustain. Dev.*, vol. 7, no. 3, pp. 90–98, 2018, doi: 10.14207/ejsd.2018.v7n3p90.
- [36] M. R. Giraldi-Díaz, L. De Medina-Salas, E. Castillo-González, and R. León-Lira, “Environmental impact associated with the supply chain and production of grounding and roasting coffee through life cycle analysis,” *Sustain.*, vol. 10, no. 12, 2018, doi: 10.3390/su10124598.
- [37] N. S. Hidayanti, J. M. M. Aji, and T. D. Hapsari, “Added value of robusta coffee products of ‘dwi tunggal’ farmer group in bromo mountain slope,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 672, no. 1, 2021, doi: 10.1088/1755-1315/672/1/012024.
- [38] A. Wijaya, P. Glasbergen, and S. Mawardi, “The mediated partnership model for sustainable coffee production: Experiences from Indonesia,” *Int. Food Agribus. Manag. Rev.*, vol. 20, no. 5, pp. 689–708, 2017, doi: 10.22434/IFAMR2017.0021.
- [39] M. Gancarz *et al.*, “Impact of Coffee Bean Roasting on the Content of Pyridines Determined by Analysis of Volatile Organic Compounds,” *Molecules*, vol. 27, no. 5, pp. 1–12, 2022, doi: 10.3390/molecules27051559.
- [40] R. Perren, R. Geiger, S. Schenker, and F. Escher, “Recent Developments in Coffee Roasting Technology,” *20th Int. Sci. Colloq. Coffee*, no. 2004, pp. 451–459, 2004.
- [41] The International organization for standardization, “ISO 14044 Environmental management-Life cycle assessment-Requirements and guidelines Management environnemental-Analyse du cycle de vie-Exigences et lignes directrices,” *Int. Organ. Stand.*, vol. 2006, p. 7, 2006, [Online]. Available: https://www.saiglobal.com/PDFTemp/Previews/OSH/iso/updates2006/wk26/ISO_14044-2006.PDF.

- [42] K.-M. Lee and A. Inaba, "Life Cycle Assessment: Best Practices of International Organization for Standardization (ISO) 14040 Series," *Comm. Trade Invest.*, no. February, p. 99, 2004, [Online]. Available: http://publications.apec.org/publication-detail.php?pub_id=453.
- [43] B. Comparison, "Fermentation (SmF) for the Recovery of Cellulases from Coffee Husks : A Life Cycle Assessment (LCA)," 2020.
- [44] E. Catalán, D. Komilis, and A. Sánchez, "Environmental impact of cellulase production from coffee husks by solid-state fermentation: A life-cycle assessment," *J. Clean. Prod.*, vol. 233, pp. 954–962, 2019, doi: 10.1016/j.jclepro.2019.06.100.
- [45] M. Okamura, M. Soga, Y. Yamada, K. Kobata, and D. Kaneda, "Development and evaluation of roasting degree prediction model of coffee beans by machine learning," *Procedia Comput. Sci.*, vol. 192, pp. 4602–4608, 2021, doi: 10.1016/j.procs.2021.09.238.
- [46] M. Steen, "Greenhouse gas emissions from fossil fuel fired power generation systems. <https://core.ac.uk/download/pdf/38616493.pdf>"
- [47] D. Pramudita, T. Araki, Y. Sagara, and A. H. Tambunan, "Roasting and Colouring Curves for Coffee Beans with Broad Time-Temperature Variations," *Food Bioprocess Technol.*, vol. 10, no. 8, pp. 1509–1520, 2017, doi: 10.1007/s11947-017-1912-5.
- [48] J. A. Hernández, B. Heyd, C. Irles, B. Valdovinos, and G. Trystram, "Analysis of the heat and mass transfer during coffee batch roasting," *J. Food Eng.*, vol. 78, no. 4, pp. 1141–1148, 2007, doi: 10.1016/j.jfoodeng.2005.12.041.
- [49] M. Münchow, J. Alstrup, I. Steen, and D. Giacalone, "Roasting conditions and coffee flavor: A multi-study empirical investigation," *Beverages*, vol. 6, no. 2, pp. 1–14, 2020, doi: 10.3390/beverages6020029.
- [50] K. A. Maspul, "Applying the Sustainable Knowledge and Behaviour to Coffee Roasters Professional in the UAE," *J. Pengabd. dan Pemberdaya. Masy. Indones.*, vol. 2, no. 1, pp. 1–8, 2022.
- [51] D. W. Lachenmeier *et al.*, "Coffee by-products as sustainable novel foods: Report of the 2nd international electronic conference on foods—'future foods and food technologies for a sustainable world,'" *Foods*, vol. 11, no. 1, 2022, doi: 10.3390/foods11010003.
- [52] A. Bobková *et al.*, "Comparative Analysis of Selected Chemical Parameters of Coffea arabica, from Cascara to Silverskin," *Foods*, vol. 11, no. 8, 2022, doi: 10.3390/foods11081082.
- [53] Z. Jiarong, S. Xuequan, L. Pinhe, Z. Tongze, J. J. A, and C. Harold, "Preliminary Characterization of Phytochemicals and Novel Compounds," *Foods*, vol. 11, pp. 1–19, 2022.
- [54] N. Arpi, M. Muzaifa, M. I. Sulaiman, R. Andini, and S. I. Kesuma, "Chemical Characteristics of Cascara, Coffee Cherry Tea, Made of Various Coffee Pulp Treatments," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 709, no. 1, 2021, doi: 10.1088/1755-1315/709/1/012030.
- [55] A. Heeger, A. Kosińska-Cagnazzo, E. Cantergiani, and W. Andlauer, "Bioactives of coffee cherry pulp and its utilisation for production of Cascara beverage," *Food Chem.*, vol. 221, pp. 969–975, 2017, doi: 10.1016/j.foodchem.2016.11.067.

- [56] E. K. Novita Sari, D. Hermanuadi, and A. Brilliantina, "Analisis Pindah Panas pada Pengeringan Kulit Biji Kopi (Cascara) dengan Menggunakan Mesin Pengering Tipe Flash Dryer_Cum UV," *J. Teknol. Pangan dan Has. Pertan.*, vol. 17, no. 1, p. 9, 2022, doi: 10.26623/jtphp.v17i1.4622.
- [57] N. Made, K. Indrayani, J. Gagung, and E. W. Purwanti, "Sebagai Produk Olahan Teh Celup Cascara Di Desa Taji Kecamatan Jabung Kabupaten Malang Analysis Of Added Value Of Arabica Coffee Skin (Coffea Arabica) As A Processed Product Of Cascara Tea Bags In Taji Village Jabung District Malang Regency," Vol. 7, No. 2, Pp. 67–74, 2022.
- [58] M. Muzaiifa, S. Rohaya, and H. A. Sofyan, "Karakteristik mutu kimia dan sensoris teh kulit kopi (cascara) dengan penambahan lemon dan madu," vol. 16, no. 1, pp. 10–17, 2022, doi: 10.21107/agrointek.v16i1.11409.
- [59] S. Oktaviani, Y. Yuwana, and L. Hidayat, "Coffee cherry's pulp variety and pulping delay time leading to cascara tea products," *Int. J. Agric. Technol.*, vol. 17, no. 5, pp. 1869–1886, 2021.
- [60] Q. Q. Cao *et al.*, "Effects of brewing water on the sensory attributes and physicochemical properties of tea infusions," *Food Chem.*, vol. 364, no. May, p. 130235, 2021, doi: 10.1016/j.foodchem.2021.130235.
- [61] M. Li *et al.*, "Effects of brewing water on the volatile composition of tea infusions," *Food Chem.*, vol. 429, no. April, p. 136971, 2023, doi: 10.1016/j.foodchem.2023.136971.
- [62] R. Preparation, S. Roaster, C. Preparation, and S. Preparation, "Specialty Coffee Association of America April 2005 Cupping Committee Specialty Coffee Association of America Cupping Protocols," no. April, 2005.
- [63] A. A. Catão *et al.*, "Coffee-roasting variables associated with volatile organic profiles and sensory evaluation using multivariate analysis," *Appl. Food Res.*, vol. 2, no. 2, 2022, doi: 10.1016/j.afres.2022.100223.
- [64] H. Dewiansyah, R. M. D. Ujianti, R. Umiyati, And F. Nurdyansyah, "Studi Pembuatan Teh Celup Dari Daun Kopi Robusta (Coffea Canephora) (Kajian Variasi Suhu Penyangraian Daun Umur Daun)," *Pro Food*, Vol. 8, No. 2, Pp. 50–59, 2022, Doi: 10.29303/Profood.V8i2.197.
- [65] I. G. N. B. P. B. Kusuma, N. K. A. N. Ratna, A. G. Kalalinggi, and I. W. R. Widarta, "Aktivitas Antioksidan dan Evaluasi Sensoris Teh Herbal Bunga Gumitir (Tagetes erecta L.)," *J. Ilm. Teknol. Pertan. Agrotechno*, vol. 5, no. 2, p. 39, 2020, doi: 10.24843/jitpa.2020.v05.i02.p01.
- [66] Q. Q. Cao *et al.*, "Sensory and chemical characteristics of Tieguanyin oolong tea after roasting," *Food Chem. X*, vol. 12, no. October, p. 100178, 2021, doi: 10.1016/j.fochx.2021.100178.
- [67] M. I. Prawira-Atmaja *et al.*, "Evaluasi Kesesuaian Mutu Produk Teh Dengan Persyaratan Standar Nasional Indonesia," *J. Stand.*, vol. 23, no. 1, p. 43, 2021, doi: 10.31153/js.v23i1.845.
- [68] Y. Q. Xu *et al.*, "Effect of the type of brewing water on the chemical composition, sensory quality and antioxidant capacity of Chinese teas," *Food Chem.*, vol. 236, pp. 142–151, 2017, doi: 10.1016/j.foodchem.2016.11.110.
- [69] N. A. Abdul Majid, M. F. Edzuan Abdullah, and A. Diana, "A Review of Quality Coffee Roasting Degree Evaluation," *J. Appl. Sci. Agric.*, vol. 10, no. 7, pp. 18–23, 2015.

- [70] T. K. and Hendryk Czech, Jan Heide, Sven Ehlert and R. Zimmermann, "Smart Online Coffee Roasting Process Control : Modelling Coffee Roast Degree and Brew Antioxidant Capacity for Real-Time Prediction by," *Foods*, vol. 9, p. 627, 2020.
- [71] I. Goto, S. Saga, M. Ichitani, M. Kimijima, and N. Narisawa, "Investigation of Components in Roasted Green Tea That Inhibit Streptococcus mutans Biofilm Formation," *Foods*, vol. 12, no. 13, 2023, doi: 10.3390/foods12132502.
- [72] X. Liu *et al.*, "Chemical characterization of Wuyi rock tea with different roasting degrees and their discrimination based on volatile profiles," *RSC Adv.*, vol. 11, no. 20, pp. 12074–12085, 2021, doi: 10.1039/d0ra09703a.
- [73] J. Y. Ryu, Y. Choi, K. H. Hong, Y. S. Chung, and S. K. Cho, "Effect of roasting and brewing on the antioxidant and antiproliferative activities of tartary buckwheat," *Foods*, vol. 9, no. 9, pp. 1–10, 2020, doi: 10.3390/foods9091331.
- [74] E. Murlida, S. Noviasari, C. Nilda, S. Rohaya, F. Rahmi, and M. Muzaifa, "Chemical characteristics of cascara tea from several varieties of coffee in Aceh Province," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 667, no. 1, 2021, doi: 10.1088/1755-1315/667/1/012078.
- [75] S. Eckhardt, H. Franke, S. Schwarz, and D. W. Lachenmeier, "Risk Assessment of Coffee Cherry (Cascara) Fruit Products for Flour Replacement and Other Alternative Food Uses," *Molecules*, vol. 27, no. 23, 2022, doi: 10.3390/molecules27238435.
- [76] A. Tesfaye, F. Workie, and V. S. Kumar, "Production and Characterization of Coffee Husk Fuel Briquettes as an Alternative Energy Source," *Adv. Mater. Sci. Eng.*, vol. 2022, 2022, doi: 10.1155/2022/9139766.
- [77] S. Amertet, Y. Mitiku, and G. Belete, "Analysis of a Coffee Husk Fired Cogeneration Plant in South Western Ethiopia Coffee Processing Industries," *Low Carbon Econolmy*, vol. 12, pp. 42–62, 2019, doi: 10.4236/lce.2021.121003.
- [78] B. Setyawan and R. Ulfa, "Analisis mutu briket arang dari limbah biomassa campuran kulit kopi dan tempurung kelapa dengan perekat tepung tapioka," *Edubiotik J. Pendidikan, Biol. dan Terap.*, vol. 4, no. 02, pp. 110–120, 2019, doi: 10.33503/ebio.v4i02.508.
- [79] I. Acosta-Alba, J. Boissy, E. Chia, and N. Andrieu, "Integrating diversity of smallholder coffee cropping systems in environmental analysis," *Int. J. Life Cycle Assess.*, vol. 25, no. 2, pp. 252–266, 2020, doi: 10.1007/s11367-019-01689-5.
- [80] S. Krishnan, *Sustainable Coffee Production*, no. September. 2017.
- [81] G. B. Bianco, "Climate change adaptation, coffee, and corporate social responsibility: challenges and opportunities," *Int. J. Corp. Soc. Responsib.*, vol. 5, no. 1, 2020, doi: 10.1186/s40991-020-00048-0.
- [82] Kementerian Pertanian, "Outlook Kopi Komoditas Pertanian Subsektor Perkebunan," *Pus. Data Dan Sist. Inf. Pertan. Sekr. Jenderal*, p. 116, 2016, [Online]. Available: <http://perpustakaan.bappenas.go.id/lontar/opac/themes/bappenas4/templateDetail.jsp?id=167009&lokal=lokal>.
- [83] Unique, "Coffee production in the face of climate change: Uganda," p. 5, 2018.

- [84] V. Lingnau, F. Fuchs, and F. Beham, “The impact of sustainability in coffee production on consumers’ willingness to pay—new evidence from the field of ethical consumption,” *J. Manag. Control*, vol. 30, no. 1, pp. 65–93, 2019, doi: 10.1007/s00187-019-00276-x.
- [85] My Coop, “Strengthening Management Capacities of Agricultural,” 2017.
- [86] S. Wulandari, I. K. Ardana, R. Massinai, and R. S. Hartati, “Accelerating the adoption of sustainable coffee-cattle integrated farming system,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 418, no. 1, 2020, doi: 10.1088/1755-1315/418/1/012011.
- [87] K. Basavalingaiah *et al.*, “Energy flow and life cycle impact assessment of coffee-pepper production systems: An evaluation of conventional, integrated and organic farms in India,” *Environ. Impact Assess. Rev.*, vol. 92, no. May 2021, p. 106687, 2022, doi: 10.1016/j.eiar.2021.106687.
- [88] Q. V. Le, S. Cowal, G. Jovanovic, and D. T. Le, “A Study of Regenerative Farming Practices and Sustainable Coffee of Ethnic Minorities Farmers in the Central Highlands of Vietnam,” *Front. Sustain. Food Syst.*, vol. 5, no. October, pp. 1–14, 2021, doi: 10.3389/fsufs.2021.712733.
- [89] I. Diyarma, T. Bantacut, and Suprihatin, “Assessment of Environmental Impact of the Gayo Arabica Coffee Production by Wet Process using Life Cycle Assessment,” *Acta Univ. Cibiensis. Ser. E Food Technol.*, vol. 23, no. 1, pp. 27–34, 2019, doi: 10.2478/aucft-2019-0004.
- [90] M. R. A. Noponen, G. Edwards-Jones, J. P. Haggard, G. Soto, N. Attarzadeh, and J. R. Healey, “Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management,” *Agric. Ecosyst. Environ.*, vol. 151, no. April, pp. 6–15, 2012, doi: 10.1016/j.agee.2012.01.019.
- [91] M. Adams and A. E. Ghaly, “Maximizing sustainability of the Costa Rican coffee industry,” *J. Clean. Prod.*, vol. 15, no. 17, pp. 1716–1729, 2007, doi: 10.1016/j.jclepro.2006.08.013.
- [92] I. Arzoumanidis, R. Salomone, L. Petti, G. Mondello, and A. Raggi, “Is there a simplified LCA tool suitable for the agri-food industry? An assessment of selected tools,” *J. Clean. Prod.*, vol. 149, pp. 406–425, 2017, doi: 10.1016/j.jclepro.2017.02.059.
- [93] G. Zeeman and S. Gerbens, “CH₄ emissions from animal manure,” *Work. Pap. Support IPCC Good Pract. Guid. Uncertain. Manag. Natl. Greenh. gas Invent.*, pp. 339–348, 1996.
- [94] J. Hobson, “CH₄ and N₂O emissions from waste water handling,” *Good Pract. Guid. Uncertain. Manag.* ..., pp. 441–454, 2000, [Online]. Available: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:CH4+and+n2o+emissions+from+waste+water+handling#1>.
- [95] D. Moran and E. Wall, “Livestock production and greenhouse gas emissions: Defining the problem and specifying solutions,” *Anim. Front.*, vol. 1, no. 1, pp. 19–25, 2011, doi: 10.2527/af.2011-0012.
- [96] S. C. Vac, G. E. Popița, N. Frunzeti, and A. Popovici, “Evaluation of greenhouse gas emission from animal manure using the closed chamber method for gas fluxes,” *Not. Bot. Horti Agrobot. Cluj-Napoca*, vol. 41, no. 2, pp. 576–581, 2013, doi: 10.15835/nbha4129259.
- [97] M. Hernández-Sarabia, J. Sierra-Silva, L. Delgadillo-Mirquez, J. Ávila-Navarro, and L. Carranza, “The potential of the biodigester as a useful tool in coffee farms,” *Appl. Sci.*, vol. 11, no. 15, 2021, doi: 10.3390/app11156884.

- [98] A. Sagastume Gutiérrez, J. J. Cabello Eras, L. Hens, and C. Vandecasteele, "The energy potential of agriculture, agroindustrial, livestock, and slaughterhouse biomass wastes through direct combustion and anaerobic digestion. The case of Colombia," *J. Clean. Prod.*, vol. 269, p. 122317, 2020, doi: 10.1016/j.jclepro.2020.122317.
- [99] S. Ait Lhaj Lahcen, S. I. Ahmed, N. Lahboubi, and H. El Bari, "Energetic Potential of Coffee Waste from Anaerobic Digestion and Combustion," *Ecol. Eng. Environ. Technol.*, vol. 24, no. 2, pp. 138–145, 2023, doi: 10.12912/27197050/156970.
- [100] Ditjenbun, "Direktoral Jenderal Perkebunan. 2020," *Stat. Perkeb. Indones.*, vol. 2020, 2022.
- [101] E. Firdissa, A. Mohammed, G. Berecha, and W. Garedew, "Coffee Drying and Processing Method Influence Quality of Arabica Coffee Varieties (Coffee arabica L .) at Gomma I and Limmu Kossa , Southwest Ethiopia," vol. 2022, 2022.
- [102] H. Sinaga, M. Nurminah, and A. Hilman, "Gayo coffee processing with natural , semi- washed and full-washed methods," vol. 01012, 2021.
- [103] S. Gonzalez-Piedra, H. Hernández-García, J. M. Perez-Morales, L. Acosta-Domínguez, J. R. Bastidas-Oyanedel, and E. Hernandez-Martinez, "A study on the feasibility of anaerobic co-digestion of raw cheese whey with coffee pulp residues," *Energies*, vol. 14, no. 12, pp. 1–11, 2021, doi: 10.3390/en14123611.
- [104] D. M. de J. Cassimiro *et al.*, "Wet fermentation of Coffea canephora by lactic acid bacteria and yeasts using the self-induced anaerobic fermentation (SIAF) method enhances the coffee quality," *Food Microbiol.*, vol. 110, no. September 2022, 2023, doi: 10.1016/j.fm.2022.104161.
- [105] P. Esquivel and V. M. Jiménez, "Functional properties of coffee and coffee by-products," *Food Res. Int.*, vol. 46, no. 2, pp. 488–495, 2012, doi: 10.1016/j.foodres.2011.05.028.
- [106] M. Doorn, W. Treatment, I. Guidelines, W. Irving, N. Greenhouse, and G. Inventories, "Chapter 6 wastewater treatment and discharge 2006," *IPCC Guidel. Natl. Greenh. Gas Invent.*, 2006.
- [107] RTI, "Greenhouse Gas Emissions Estimation Methodologies for Biogenic Emissions from Selected Source Categories : Solid Waste Disposal Wastewater Treatment Ethanol Fermentation," *US Environ. Prot. Agency*, no. 0210426, pp. 1–43, 2010, [Online]. Available: https://www3.epa.gov/ttnchie1/efpac/ghg/GHG_Biogenic_Report_draft_Dec1410.pdf.
- [108] R. Coffee and E. Java, "Revenue and Farming Management Analysis of Arabica," vol. 5, no. 11, pp. 139–143, 2015.
- [109] L. D. Vera-Acevedo, J. A. Vélez-Henao, and N. Marulanda-Grisales, "Assessment of the environmental impact of three types of fertilizers on the cultivation of coffee at the Las Delicias indigenous reservation (Cauca) starting from the life cycle assessment," *Rev. Fac. Ing.*, vol. 2016, no. 81, pp. 93–101, 2016, doi: 10.17533/udea.redin.n81a09.
- [110] B. V. da R. Pin *et al.*, "Energetic use of biogas from the anaerobic digestion of coffee wastewater in southern Minas Gerais, Brazil," *Renew. Energy*, vol. 146, pp. 2084–2094, 2020, doi: 10.1016/j.renene.2019.08.004.
- [111] C. Nab and M. Maslin, "Life cycle assessment synthesis of the carbon footprint of Arabica coffee: Case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom," *Geo Geogr. Environ.*, vol. 7, no. 2, pp. 1–19, 2020, doi: 10.1002/geo2.96.

- [112] C. Rican *et al.*, “Carbon Footprint across the Coffee Supply Chain : The,” vol. 3, pp. 151–170, 2013.
- [113] K. Usva, T. Sinkko, F. Silvenius, I. Riipi, and H. Heusala, “Carbon and water footprint of coffee consumed in Finland—life cycle assessment,” *Int. J. Life Cycle Assess.*, vol. 25, no. 10, pp. 1976–1990, 2020, doi: 10.1007/s11367-020-01799-5.
- [114] T. Quintão And P. Z. Brito, “Redalyc.Connoisseurship Consumption And Market Evolution: An Institutional Theory Perspective On The Growth Of Specialty Coffee Consumption In The Usa,” 2016, Doi: 10.5585/Remark.V15i1.3042.
- [115] Sanremo, “What is the Specialty Coffee,” Artikel .2023. source link: https://www.sanremomachines.com/wp-content/uploads/2024/02/HL_36003_04_EXE_EN_VIDEO.pdf
- [116] N. Córdoba, F. L. Moreno, C. Osorio, S. Velásquez, M. Fernandez-Alduenda, and Y. Ruiz-Pardo, “Specialty and regular coffee bean quality for cold and hot brewing: Evaluation of sensory profile and physicochemical characteristics,” *Lwt*, vol. 145, no. January, 2021, doi: 10.1016/j.lwt.2021.111363.
- [117] A. Irawan, “The smallholder coffee farmer’s livelihood adaptation strategies in Bengkulu, Indonesia,” *J. Strateg. Manag.*, 2023, doi: 10.1108/JSMA-04-2023-0082.
- [118] A. D. S. N. Campos, E. G. Satolo, P. A. B. Mac-Lean, and S. S. B. Júnior, “Economic sustainability analysis of the specialty coffee farmers in Garça/SP,” *Coffee Sci.*, vol. 16, 2021, doi: 10.25186/V16I.1993.
- [119] A. Nugroho, “The Impact of Food Safety Standard on Indonesia ’ s Coffee Exports,” *Procedia Environ. Sci.*, vol. 20, pp. 425–433, 2014, doi: 10.1016/j.proenv.2014.03.054.
- [120] N. LUTTINGER and DICUM GREGORY, “the Coffee Book,” *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013.
- [121] S. A. Gutierrez-Calle *et al.*, “Capillary electrophoresis as a tool for genotyping SH3 mediated coffee leaf rust resistance,” *Sci. Agropecu.*, vol. 12, no. 1, pp. 91–99, 2021, doi: 10.17268/SCI.AGROPECU.2021.011.
- [122] E. S. Yusuf *et al.*, “Sustainability of Arabica coffee business in West Java, Indonesia: A multidimensional scaling approach,” *Open Agriculture*, vol. 7, no. 1. pp. 820–836, 2022, doi: 10.1515/opag-2022-0144.
- [123] K. A. Maspul, “The Emergence of Local Coffee Brands: A Paradigm Shift in Jakarta Coffee Culture,” *EKOMA J. Ekon. Manajemen, Akunt.*, vol. 3, no. 1, pp. 135–149, 2023, doi: 10.56799/ekoma.v3i1.2221.
- [124] S. Pritantiwi, F. Fatimah, and H. Hermawan, “Determination of Product Life Cycle (PLC) for Formulation of Marketing Strategy UD. Matt Coffee Bondowoso,” *Int. J. Business, Technol. Organ. Behav.*, vol. 3, no. 1, pp. 1–10, 2023, doi: 10.52218/ijbtob.v3i1.255.
- [125] J. N. Wintgens and C. A. Zamarripa, *Coffee Propagation*. 2008.
- [126] T. M. Traore, N. L. W. Wilson, and D. Fields, “What explains specialty coffee quality scores and prices: A case study from the cup of excellence program,” *J. Agric. Appl. Econ.*, vol. 50, no. 3, pp. 349–368, 2018, doi: 10.1017/aae.2018.5.

- [127] K. A. Maspul, "Improving the Creative Process Strategy of the Specialty Coffee in Eastern Province Saudi Arabia in Strengthening Sustainability in the Coffee Value Chain," *EKOMA J. Ekon. Manajemen, Akunt.*, vol. 2, no. 1, pp. 244–254, 2022, doi: 10.56799/ekoma.v2i1.1249.
- [128] L. T. K. Trinh, A. H. Hu, Y. C. Lan, and Z. H. Chen, "Comparative life cycle assessment for conventional and organic coffee cultivation in Vietnam," *Int. J. Environ. Sci. Technol.*, vol. 17, no. 3, pp. 1307–1324, 2020, doi: 10.1007/s13762-019-02539-5.
- [129] R. Pramulya, T. Bantacut, E. Noor, M. Yani, and M. Romli, "Life Cycle Assessment of Gayo Arabica Coffee Green Bean at Aceh Province," *Habitat*, vol. 33, no. 3, pp. 308–319, 2022, doi: 10.21776/ub.habitat.2022.033.3.29.
- [130] A. Irawan and B. C. McLellan, "A comparison of life cycle assessment (LCA) of Andungsari Arabica coffee processing technologies towards lower environmental impact.," *J. Clean. Prod.*, p. 141561, 2024, doi: <https://doi.org/10.1016/j.jclepro.2024.141561>.
- [131] P. M. M. Martins, N. N. Batista, M. G. da C. P. Miguel, J. B. P. Simão, J. R. Soares, and R. F. Schwan, "Coffee growing altitude influences the microbiota, chemical compounds and the quality of fermented coffees," *Food Res. Int.*, vol. 129, no. November 2019, p. 108872, 2020, doi: 10.1016/j.foodres.2019.108872.
- [132] S. J. Martinez, M. H. S. Rabelo, A. P. P. Bressani, M. C. B. Da Mota, F. M. Borém, and R. F. Schwan, "Novel stainless steel tanks enhances coffee fermentation quality," *Food Res. Int.*, vol. 139, no. April 2020, 2021, doi: 10.1016/j.foodres.2020.109921.
- [133] P. L. L. Bertarini, M. S. Gomes, and L. D. Santos, "Evaluation of Arabica Coffee Fermentation Using Machine Learning," pp. 1–18, 2024.
- [134] F. T. Mejía *et al.*, "Energy Evaluation of the Mechanical Drying of the Grain of Coffea arabica from Honduras," *Asian J. Biol.*, no. September, pp. 8–14, 2021, doi: 10.9734/ajob/2021/v11i130131.
- [135] H. Prono-Widayat, N. Arpi, R. Andini, M. Muzaifa, and F. Gunawan, "Chemical analysis of cascara tea from wine coffee processing with a different fermentation times," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 667, no. 1, pp. 2–7, 2021, doi: 10.1088/1755-1315/667/1/012104.
- [136] S. Gmunder, C. Toro, J. M. Rojas Acosta, and N. Rodriguez Valencia, "Environmental footprint of coffee in colombia," *Fed. Colomb. Café*, vol. 2, 2018.
- [137] I. Rizkya, K. Syahputri, R. M. Sari, and S. Christin, "Analysis of Defective Causes in Coffee Product Using Decision Tree Approach," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 851, no. 1, 2020, doi: 10.1088/1757-899X/851/1/012029.
- [138] M. Garc and J. E. Candelo-becerra, "applied sciences Quality and Defect Inspection of Green Coffee Beans Using a Computer Vision System," pp. 1–18, 2019.
- [139] L. Zampori, E. Saouter, E. Schau, J. Cristobal, V. Castellani, and S. Sala, "Guide for interpreting life cycle assessment result," *Publ. Off. Eur. Union*, p. 60, 2016, doi: 10.2788/171315.
- [140] W. Treatment, I. Guidelines, N. Greenhouse, and G. Inventories, "CHAPTER 6 WASTEWATER TREATMENT AND," 2006.

- [141] E. M. Ijanu, M. A. Kamaruddin, and F. A. Norashiddin, "Coffee processing wastewater treatment: a critical review on current treatment technologies with a proposed alternative," *Appl. Water Sci.*, vol. 10, no. 1, pp. 1–11, 2020, doi: 10.1007/s13201-019-1091-9.
- [142] R. Miller, "Review Essay: The Third Way," *Polit. Sci.*, vol. 52, no. 2, pp. 174–180, 2000, doi: 10.1177/003231870005200207.
- [143] E. Novita and M. E. Irfani, "Life Cycle Assessment of Organic Arabica Coffee Products," *J. Tek. Pertan. Lampung (Journal Agric. Eng.)*, vol. 12, no. 1, p. 186, 2023, doi: 10.23960/jtep-l.v12i1.186-200.
- [144] F. Adiwinata and M. Rahayuningsih, "Analisis Daur Hidup (Life Cycle Assessment) Pengolahan Kopi Bubuk Robusta Secara Basah Di Industri Kecil Menengah (Ikm) Beloe Klasik Lampung," vol. 15, no. 4, pp. 1175–1182, 2021, doi: 10.21107/agrointek.v15i4.1176.
- [145] K. Basavalingaiah *et al.*, "Energy flow and life cycle impact assessment of coffee-pepper production systems: An evaluation of conventional, integrated and organic farms in India," *Environ. Impact Assess. Rev.*, vol. 92, no. September 2021, p. 106687, 2022, doi: 10.1016/j.eiar.2021.106687.
- [146] M. M. Van Huijstee, M. Francken, and P. Leroy, "Partnerships for sustainable development: a review of current literature," *Environ. Sci.*, vol. 4, no. 2, pp. 75–89, 2007, doi: 10.1080/15693430701526336.
- [147] A. Fadillah, D. Indrawan, and N. A. Achsani, "Indonesian Coffee in The Global Value Chain: The Comparison of Global Partnership Sustainability Standards Implementation," *J. Manaj. dan Agribisnis*, vol. 16, no. 2, pp. 191–198, 2019, doi: 10.17358/jma.16.2.191.
- [148] ICO, "I-CIP falls back below 200 US cents / lb in July 2022," no. July, pp. 1–10, 2022.
- [149] T. Benti, "Progress in Arabica Coffee Breeding in Ethiopia: Achievements, Challenges and Prospects," *Int. J. Sci. Basic Appl. Res.*, vol. 33, no. 2, pp. 15–25, 2017, [Online]. Available: <http://gssrr.org/index.php?journal=JournalOfBasicAndApplied>.
- [150] W. Behailu, A. Sualeh, N. Mokonen, and S. Endris, "Coffee diversity and knowledge Coffee Processing and Quality Research in Ethiopia," *Researchgate.Net*, no. June, pp. 307–316, 2008, [Online]. Available: <https://www.researchgate.net/publication/341901571>.
- [151] F. Mitiku, "Dynamics of farm households on-farm and off-farm diversification: the case of coffee producing farm households in southern ethiopia fikadu mitiku abdissa," 2011.
- [152] UCDA, "Robusta coffee handbook: A sustainable coffee industry with high stakeholder value for social economic transformation," p. 148, 2019.
- [153] M. Banti and E. Abraham, "Coffee Processing Methods, Coffee Quality and Related Environmental Issues," *J. Food Nutr. Sci.*, vol. 9, no. 6, p. 144, 2021, doi: 10.11648/j.jfns.20210906.12.
- [154] R. C. Campos, V. R. A. Pinto, L. F. Melo, S. J. S. S. da Rocha, and J. S. Coimbra, "New sustainable perspectives for 'Coffee Wastewater' and other by-products: A critical review," *Futur. Foods*, vol. 4, no. June, 2021, doi: 10.1016/j.fufo.2021.100058.
- [155] W. Genanaw, G. G. Kanno, D. Derese, and M. B. Aregu, "Effect of Wastewater Discharge From Coffee Processing Plant on River Water Quality, Sidama Region, South Ethiopia," *Environ. Health Insights*, vol. 15, 2021, doi: 10.1177/11786302211061047.

- [156] N. Laili, N. S. Indrasti, and D. Wahyudi, "Design of sustainable coffee processing wastewater treatment system using K-means clustering algorithm," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 1063, no. 1, 2022, doi: 10.1088/1755-1315/1063/1/012032.
- [157] B. Chala, H. Oechsner, S. Latif, and J. Müller, "Biogas potential of coffee processing waste in Ethiopia," *Sustain.*, vol. 10, no. 8, pp. 1–14, 2018, doi: 10.3390/su10082678.
- [158] G. Corro, U. Pal, F. Bañuelos, and M. Rosas, "Generation of biogas from coffee-pulp and cow-dung co-digestion: Infrared studies of postcombustion emissions," *Energy Convers. Manag.*, vol. 74, pp. 471–481, 2013, doi: 10.1016/j.enconman.2013.07.017.
- [159] J. A. C. Olaya, J. G. M. Aroca, A. E. Garrido, and R. R. Serrezuela, "Solar Power Plant Design To Support Ecomil Lh300 At the Coffee Processing Center 'La Esperanza' in the Municipality of La Plata," *ARN J. Eng. Appl. Sci.*, vol. 15, no. 21, pp. 2375–2384, 2020.
- [160] M. R. Shaibur, H. Husain, and S. H. Arpon, "Utilization of cow dung residues of biogas plant for sustainable development of a rural community," *Curr. Res. Environ. Sustain.*, vol. 3, p. 100026, 2021, doi: 10.1016/j.crsust.2021.100026.
- [161] A. S. Adekunle *et al.*, "Production and Testing of Biogas Using Cow Dung, Jatropha and Iron Filins," *J. Bioresour. Bioprod.*, vol. 4, no. 3, pp. 143–148, 2019, doi: 10.12162/jbb.v4i3.002.
- [162] J. C. Ramirez-Perez, "A Comparison of Performance between Two Anaerobic Biodigesters Configurations for Biogas Production Una Comparación de Rendimiento entre Dos Configuraciones de Biodigestores Anaerobios para la Producción de Biogás," *Energía*, no. 14, pp. 213–223, 2018, [Online]. Available: <http://www.revistageas.org.br/ojs/index.php/geas/article/view/584>.
- [163] G. Adolfo and F. Campos, "Wet-coffee processing production wastes: Quality, Potentials, and Valorization Opportunities," 2022, [Online]. Available: <https://doi.org/10.25932/publishup-55882>.
- [164] B. V. Tangahu, A. A. Gde Kartika, K. Sambodho, S. M. Putri Marendra, and I. Arliyani, "Shallow Groundwater Pollution Index Around the Location of Griyo Mulyo Landfill (Jabon Landfill) in Jabon District, Sidoarjo Regency, East Java, Indonesia," *J. Ecol. Eng.*, vol. 22, no. 3, pp. 199–210, 2021, doi: 10.12911/22998993/132658.
- [165] A. Rifin, M. P. van Dijk, D. P. de Boer, H. Mudde, and ..., "Strengthening Indonesian Agribusiness: Rural Development and Global Market Linkages," 2016, [Online]. Available: <http://agribisnis.ipb.ac.id/wp-content/uploads/2017/04/Husnul-Khotimah-Stefan-Von-Cramon-Taubadel-dkk-VERTICAL-MARKET-INTEGRATION-PERFORMANCE-OF-INDONESIAN-RICE-MARKET-CHAIN.pdf>.
- [166] D. J. Mahushi, R. L. Machunda, E. Science, T. Nelson, and M. African, "OPTIMIZATION OF BIOGAS PRODUCTION PROCESS IN SOLID," vol. 44, no. 3, pp. 205–213, 2018.
- [167] W. dos S. Gomes *et al.*, "Changes in the Chemical and Sensory Profile of *Coffea canephora* var. Conilon Promoted by Carbonic Maceration," *Agronomy*, vol. 12, no. 10, 2022, doi: 10.3390/agronomy12102265.
- [168] B. Girma and A. Sualeh, "A Review of Coffee Processing Methods and Their Influence on Aroma," *Int. J. Food Eng. Technol.*, vol. 6, no. 1, p. 7, 2022, doi: 10.11648/j.ijfet.20220601.12.

- [169] S. S. Harsono, Salahuddin, M. Fauzi, G. S. Purwono, D. Soemarno, and Kissinger, "Second Generation Bioethanol from Arabica Coffee Waste Processing at Smallholder Plantation in Ijen Plateau Region of East Java," *Procedia Chem.*, vol. 14, pp. 408–413, 2015, doi: 10.1016/j.proche.2015.03.055.
- [170] K. C. Yadav *et al.*, "Utilizing coffee pulp and mucilage for producing alcohol-based beverage," *Fermentation*, vol. 7, no. 2, pp. 1–13, 2021, doi: 10.3390/fermentation7020053.
- [171] "DAFTAR-ALSIN-KOPI-PRIMER-converted-compressed.pdf." . source link: <https://icri.net/product-category/alat-mesin/>
- [172] A. W. Susilo, D. Nugroho, I. A. Sari, and D. F. S. Hartatri, "Katalog Produk dan Jasa Unggulan Pusat Penelitian Kopi dan Kakao Indonesia," *Pus. Penelit. Kopi dan Kakao Indones.*, pp. 1–35, 2019.
- [173] P. Data, D. A. N. Sistem, and I. Pertanian, "OUTLOOK KOMODITAS," 2022.
- [174] M. I. Sulaiman *et al.*, "Making biodiversity work for coffee production. A case study of Gayo Arabica coffee in Indonesia," *MOJ Ecol. Environ. Sci.*, vol. 6, no. 4, pp. 156–162, 2021, doi: 10.15406/mojes.2021.06.00228.
- [175] M. Ibnu, P. Glasbergen, A. Offermans, and B. Arifin, "Farmer Preferences for Coffee Certification: A Conjoint Analysis of the Indonesian Smallholders," *J. Agric. Sci.*, vol. 7, no. 6, pp. 20–35, 2015, doi: 10.5539/jas.v7n6p20.
- [176] W. For and O. Use, "Wipo for official use only," 1999.
- [177] "Auction Results - Alliance For Coffee Excellence.pdf." . Source link: <https://allianceforcoffeexcellence.org/>
- [178] G. Dunn, "Annual Review The International Coffee Organization (ICO)," *Build. Eng.*, vol. 95, no. 1, p. 36, 2022.
- [179] M. R. Spier, L. P. D. S. Vandenberghe, A. B. P. Medeiros, and C. R. Soccol, *Application of different types of bioreactors in bioprocesses*, no. February 2016. 2011.
- [180] C. Feathers, U. Liquid-, and S. A. Digestions, "Using Liquid- and Solid-State Anaerobic Digestions," 2021.
- [181] M. Várady, J. Tauchen, P. Klouček, and P. Popelka, "Effects of Total Dissolved Solids, Extraction Yield, Grinding, and Method of Preparation on Antioxidant Activity in Fermented Specialty Coffee," *Fermentation*, vol. 8, no. 8, 2022, doi: 10.3390/fermentation8080375.
- [182] SCA, "Protocols and Best Practices," p. 20, 2018, [Online]. Available: https://www.scith.coffee/wp-content/uploads/2021/03/SCA-Protocols-_Best-Practices.pdf.
- [183] R. Reta *et al.*, "Fermentation of Arabica Coffee Beans Using Ohmic Heating Technology in Producing Specialty Coffee," *Pelita Perkeb. (a Coffee Cocoa Res. Journal)*, vol. 36, no. 3, pp. 226–235, 2020, doi: 10.22302/icri.jur.pelitaperkebunan.v36i3.452.
- [184] D. Sagita *et al.*, "Experimental investigation of heating pattern, energy requirement and electrical conductivity in a batch ohmic heating system for coffee fermentation," *Innov. Food Sci. Emerg. Technol.*, vol. 76, no. November 2021, p. 102946, 2022, doi: 10.1016/j.ifset.2022.102946.

- [185] J. H. Gómez, P. Benavides, J. D. Maldonado, J. Jaramillo, F. E. Acevedo, and Z. N. Gil, "Flower-Visiting Insects Ensure Coffee Yield and Quality," *Agriculture*, vol. 13, no. 7, p. 1392, 2023, doi: 10.3390/agriculture13071392.
- [186] D. Turck *et al.*, "Safety of dried coffee husk (cascara) from *Coffea arabica* L. as a Novel food pursuant to Regulation (EU) 2015/2283," *EFSA J.*, vol. 20, no. 2, 2022, doi: 10.2903/j.efsa.2022.7085.
- [187] H. Harada, "Volatile Compounds Changes in Unfermented Robusta Coffee by Re-Fermentation Using Commercial Kefir," *Nutr. Food Sci. Int. J.*, vol. 8, no. 4, pp. 2–8, 2019, doi: 10.19080/nfsij.2019.08.555745.
- [188] Badan Pusat Statistik Indonesia, "Catalog : 1101001," *Stat. Indones. 2020*, vol. 1101001, p. 790, 2020, [Online]. Available: <https://www.bps.go.id/publication/2020/04/29/e9011b3155d45d70823c141f/statistik-indonesia-2020.html>.
- [189] M. Ibnu, A. Offermans, and P. Glasbergen, "Toward a more sustainable coffee production," *Pelita Perkeb. (a Coffee Cocoa Res. Journal)*, vol. 35, no. 3, pp. 212–229, 2020, doi: 10.22302/iccri.jur.pelitaperkebunan.v35i3.361.
- [190] F. Ashardiono, "From Commodity to Specialty Products: Three Key Concepts for a Sustainable Tea and Coffee Industry in Indonesia," *Asia-Japan Res. Acad. Bull.*, vol. 1, pp. 2019–2020, 2020, [Online]. Available: https://www.jstage.jst.go.jp/article/asiajapanbulletin/1/0/1_51/_article/-char/ja/.
- [191] W. B. Sunarharum *et al.*, "The Indonesian coffee consumers perception on coffee quality and the effect on consumption behavior," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 733, no. 1, 2021, doi: 10.1088/1755-1315/733/1/012093.
- [192] A. P. Utama, U. Sumarwan, A. I. Suroso, and M. Najib, "Roles of regulation and lifestyle on Indonesian coffee consumption behavior across generations," *Int. J. Sustain. Dev. Plan.*, vol. 16, no. 6, pp. 1153–1162, 2021, doi: 10.18280/ijstdp.160616.
- [193] U. U. S. D. of Agriculture's Agricultural Research Service, "Coffee: World Markets and Trade," *Coffee World Mark. Trade*, no. June, p. 9, 2020.
- [194] Direktorat Jenderal Perkebunan, "Statistik perkebunan unggulan nasional," *Sekr. Dirjend Perkeb. Kementeri. Pertan.*, p. 1056 pp, 2021.
- [195] USDA, "Indonesia: Coffee Annual," *USDA United States Dep. Agric.*, pp. 1–8, 2023, [Online]. Available: https://www.fas.usda.gov/data/indonesia-coffee-annual-7%0Ahttps://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Coffee Annual_Jakarta_Indonesia_ID2023-0012.pdf.
- [196] R. Hamdani Harahap, Humaizi, and I. Muda, "Sustainable management of coffee farms (case in Karo Regency, North Sumatera Indonesia)," *Int. J. Civ. Eng. Technol.*, vol. 9, no. 11, pp. 2721–2731, 2018.
- [197] J. Dawid, "Organic Fertilizers Requirement of Coffee (*Coffea arabica* L.) Review," *Int. J. Reasearch Stud. Agr. Sci.*, vol. 4, no. 7, pp. 11–18, 2018.
- [198] R. Parajuli, T. Dalgaard, and M. Birkved, "Can farmers mitigate environmental impacts through combined production of food, fuel and feed? A consequential life cycle assessment of integrated mixed

crop-livestock system with a green biorefinery,” *Sci. Total Environ.*, vol. 619–620, pp. 127–143, 2018, doi: 10.1016/j.scitotenv.2017.11.082.

[199] B. Sengupta *et al.*, “Toward sustainable and eco-friendly production of coffee: abatement of wastewater and evaluation of its potential valorization,” *Clean Technol. Environ. Policy*, vol. 22, no. 5, pp. 995–1014, 2020, doi: 10.1007/s10098-020-01841-y.

[200] S. N. Lubis, D. A. N. Hida, and L. Fauzia, “Integrated farming system of Arabica coffee in Karo District, North Sumatera,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 782, no. 2, 2021, doi: 10.1088/1755-1315/782/2/022011.

[201] J. Dawid, “Organic Fertilizers Requirement of Coffee (*Coffea Arabica* L) Review,” vol. 4, no. 7, pp. 11–18, 2018.

[202] K. C. Calvert, K. Sanh, H. Hoa, and Q. Tri, “Review of Coffee Waste Water Characteristics and Approaches To,” *J. Agric. Food Chem.*, vol. 42, no. 5, pp. 132–137, 2014, [Online]. Available: <http://dx.doi.org/10.1016/j.resconrec.2017.10.001><http://dx.doi.org/10.1016/j.carbpol.2010.07.063><http://dx.doi.org/10.1016/j.jff.2015.11.027><http://dx.doi.org/10.1016/j.wasman.2013.11.010><http://www.sbicafe.ufv.br:80/handle/123456789/6858>

[203] T. Widjaja, Nurkhamidah, A. Altway, T. Iswanto, and E. Grady, “Performance of Biogas Production from Coffee Pulp Waste with Cow Dung and Cattle Rumen Fluid as Inoculum in a Batch Reactor,” *Proc. Int. Conf. Sustain. Biomass (ICSB 2019)*, vol. 202, no. Icsb 2019, pp. 252–256, 2021, doi: 10.2991/aer.k.210603.045.

[204] Muhammad Ibnu, “Gatekeepers of sustainability,” *Maastricht*, no. 2017, 2017, doi: 10.26481/dis.20170927mi.

[205] N. L. Hal *et al.*, “Direktorat pendanaan riset dan inovasi,” 2023.

[206] F. Djufry, S. Wulandari, and R. Villano, “Climate Smart Agriculture Implementation on Coffee Smallholders in Indonesia and Strategy to Accelerate,” *Land*, vol. 11, no. 7, 2022, doi: 10.3390/land11071112.

[207] “Indonesia 2022 - Alliance For Coffee Excellence.pdf.” . source link: <https://allianceforcoffeexcellence.org/>

[208] SETAC, “Guidelines for Life-Cycle Impact Assessment: Code of Practice,” *Soc. Environ. Toxicol. Chem.*, vol. 1, no. April, p. 73, 1993, [Online]. Available: <https://www.setac.org/resource/guidelines-lca-code-practice-1993.html>https://www.setac.org/resource/resmgr/books/lca_archive/guidelines_for_life_cycle.pdf.

[209] ISO, “Environmental Management - Life Cycle Assessment - Principles and Framework (ISO 14040:2006),” *Br. Stand.*, vol. 3, no. 1, p. 32, 2004, [Online]. Available: <https://www.iso.org/standard/23151.html>.

[210] I. Standard and T. S. Preview, “ISO 14044 Environmental management-Life cycle assessment-Requirements and guidelines Management environnemental-Analyse du cycle de vie-Exigences et lignes directrices iTeh STANDARD PREVIEW,” vol. 2006, 1404.

[211] S. Fazio, F. Biganzioli, V. De Laurentiis, L. Zampori, S. Sala, and E. Diaconu, Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, version 2, from ILCD to EF 3.0. 2018.

- [212] G. Ansanelli, G. Fiorentino, R. Chifari, K. Meisterl, E. Leccisi, and A. Zucaro, "Sustainability Assessment of Coffee Silverskin Waste Management in the Metropolitan City of Naples (Italy): A Life Cycle Perspective," *Sustainability*, vol. 15, no. 23, p. 16281, 2023, doi: 10.3390/su152316281.
- [213] J. N. Cheng Hin and R. Zmeureanu, "Optimization of a residential solar combisystem for minimum life cycle cost, energy use and exergy destroyed," *Sol. Energy*, vol. 100, pp. 102–113, 2014, doi: 10.1016/j.solener.2013.12.001.
- [214] P. Dunne, C. Grady Kerrigan Sheanon Newman, M. Slevin, and K. Sheanon Newman, "Life Cycle Cost Guidance Notes (Single Column)," 2011.
- [215] A. Adell, "Experiences from the SMART SPP LCC-CO2 emissions tool LCC in public procurement webinar," no. June, 2015, [Online]. Available: <http://www.smart-spp.eu/>.
- [216] T. Mearig and L. Morris, "Life Cycle Analysis Handbook," vol. 3, p. 33, 2018.
- [217] P. Gosalvittr, R. M. Cu, R. Smith, and A. Azapagic, "An environmental and economic sustainability assessment of coffee production in the UK," vol. 465, no. March, 2023, doi: 10.1016/j.cej.2023.142793.
- [218] R. Rosmeli, "Model and strategies for the development of coffee in Jambi Province to respond the global market demand," *J. Perspekt. Pembiayaan dan Pembang. Drh.*, vol. 7, no. 3, pp. 315–326, 2019, doi: 10.22437/ppd.v7i3.8666.
- [219] I. C. Council, U. Kingdom, N. Q. Standards, and C. Rica, "Icc 122-12 23," no. August, 2018.
- [220] K. Air, "Keterangan : II . PERSYARATAN TEKNIS MINIMAL PUPUK HAYATI Mikoriza Arbuskular (MA) : Stereomikroskop," no. 1.
- [221] E. Hidayat, A. Afriliana, G. Gusmini, M. Taizo, and H. Harada, "Evaluate of Coffee Husk Compost," *Int. J. Food, Agric. Nat. Resour.*, vol. 1, no. 1, pp. 37–43, 2020, doi: 10.46676/ij-fanres.v1i1.8.
- [222] A. Skorupa, M. Worwąg, and M. Kowalczyk, "Coffee Industry and Ways of Using By-Products as Bioadsorbents for Removal of Pollutants," *Water (Switzerland)*, vol. 15, no. 1, 2023, doi: 10.3390/w15010112.
- [223] A. M. Akol, D. O. Ndolo, and F. R. Kutu, "Agroecological techniques : adoption of safe and sustainable agricultural practices among the smallholder farmers in Africa," vol. 2050, no. May, 2023, doi: 10.3389/fsufs.2023.1143061.
- [224] A. S. Wogderess, "Available information on the feeding value of coffee waste and ways to improve coffee waste for animal feed," vol. 3, no. 6, pp. 243–257, 2016.

List of Publications

Journal Papers

1. A comparison of life cycle assessment (LCA) of Andungsari Arabica coffee processing technologies towards lower environmental impact. *Journal of Cleaner Production* 447 (2024) 141561. <https://doi.org/10.1016/j.jclepro.2024.141561>
2. Developing Coffee Cherry Skin and Coffee Husk by Products as Sustainable Novel Food and Fuel. *International Journal of Technology, Food and Agriculture (TEFA)*. TEFA 2024, Vol. 1, No. 1 <https://doi.org/10.25047/tefa.v1i1.4572>
3. Life Cycle Assessment of Coffee Roasting Process Based on Two Different Energy Sources on Smallholder Coffee Farm in Jember. *Journal of Engineering Science and Technology* Vol 19, No 2. Page 60-72. https://jestec.taylors.edu.my/Special%20Issue%20ICIST%202023/ICIST_06.pdf
4. Comprehensive Environmental Impact Analysis of Dry Processing Methods for Specialty Coffee Beans in Bondowoso, Indonesia using Life Cycle Assessment. *Biomass* 2024, 4(3), 843-864; <https://doi.org/10.3390/biomass4030047>
5. Biodigester as a Useful Tool in Industrial Ecology Coffee (IEC) for Sustainable Coffee Production. (*Under Review: Waste and Biomass Valorization-Springer*).
6. Life Cycle Assessment – Explore the unique approach of evaluating the physical and sensory quality of Andungsari coffee through an innovative stainless steel reactor fermentation method. (*In preparation*).
7. Sustainable Coffee Production – Environmental Impact and Economic Sustainability of 4F (Food, Feed, Fuel and Fertilizer) towards Industrial Ecology Coffee (IEC). (*In preparation*).

Conference Papers

1. Study on biogas production from coffee wastes and cow-dung fermentation and its use towards reducing emissions from coffee roasting. *IOP Conference Series: Earth and Environmental Science*, Volume 1201, 6th International Symposium on Green Technology for Value Chains 22/11/2022 - 23/11/2022 Online, Indonesia. [Doi 10.1088/1755-1315/1201/1/012004](https://doi.org/10.1088/1755-1315/1201/1/012004).