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Carbon Footprint Calculation of Net CO_2 in Agroforestry and Agroindustry of Gayo Arabica Coffee, Indonesia

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Abstract

Carbon dioxide (CO_2) in the atmosphere occurs as the result of various chemical, physical, and biological processes. The presence of CO_2 around atmosphere greatly affects the agroforestry and agroindustry of coffee. This study aimed to describe the CO_2 cycle in agroforestry and agroindustry of Gayo Arabica coffee (*Coffea arabica*) and net CO_2 ha^{-1} of coffee plantation. CO_2 cycle was analyzed based on the movement of CO_2 around the agroforestry and agroindustry of coffee. CO_2 cycle model describes net CO_2, CO_2 emission, CO_2 reduction, and CO_2 sequestration. Net CO_2 ha^{-1} of coffee plantation was 162.75×10^{-2} t CO_2 *e* ha^{-1}, with CO_2 emission was 203.84×10^{-2} t CO_2 *e* ha^{-1}, CO_2 reduction was 3.10×10^{-2} t CO_2 *e* ha^{-1}, and CO_2 sequestration was 363.49×10^{-2} t CO_2 *e* ha^{-1}. This research formulates the calculation of equivalent carbon emissions in the arabica coffee production system in the field and primary processing, using various methods (remote sensing analysis and calculation of direct and indirect equivalent carbon emissions). The CO_2 cycle positively impacts the sustainability of agroforestry and agroindustry of Gayo Arabica coffee.

Keywords: Climate change, Environmentally-friendly, Global warming, Green coffee industry, Greenhouse gases, Life cycle assessment, Life cycle thinking, Waste utilization

1. Introduction

Coffee is one of the most important agricultural commodities commercialized worldwide (Sachs *et al.*, 2019), supplied by approximately 25×10^6 farmers living in around 50 developing countries (ICO, 2022). Drinking coffee, particularly arabica coffee (*Coffea arabica* L.), is considered a lifestyle thanks to its distinct and unique sensory characteristics while serving as beverage (Cheng *et al.*, 2016). Meanwhile, its waste materials (*e.g.,* pulp, husk, silver skin, and parchment) can also potentially be recycled to produce value-added products (Damat *et al.*, 2019; Reichembach and de Oliveira Petkowicz, 2020; Serna-Jiménez *et al.*, 2022; Setyobudi *et al.*, 2018, 2019).

Arabica coffee production is based on primary processing methods (Sanz-Uribe *et al.*, 2017). Farmers' reasons for developing plantation types and processing methods follow the availability of production factors and value chain institutions (*e.g.,* certification). Coffee production from major producing countries such as Brazil and Vietnam applies intensive coffee cultivation without other vegetation and post-harvest using agricultural mechanization. This system contrasts with Indonesia and other countries in the neotropical region, such as Mexico, Guatemala, and Costa Rica. In the latter countries, coffee production is based on various plantation models, *e.g.,* semi-intensive and agroforestry. The complexity of the production model of the agricultural sector causes the assessment of sustainability and environmental performance to have opportunities to develop measurement and assessment methods.

Currently, the priority of sustainable agriculture is essential due to the challenges ahead, where consumers are likely to demand coffee beans produced with sustainability principles (Bockel and Schiettecatte, 2018). From 2008 to 2016, conventional coffee production decreased by 8 % and certified sustainable coffee increased by 24 % (Voora *et al.*, 2019). Sustainable agriculture in coffee production uses Weil's terminology (Abbasi *et al.*, 2014; Sudrajat, 2019; Weil, 1990) as agriculture that maintains the quality of the garden and landscape environment and is based on available resources. Sustainable agriculture has economic viability, and provides welfare for farmers and society as a

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whole. Hence, sustainable studies require a holistic approach, using and integrating knowledge–action–methods that become solutions to problems (Sala *et al.*, 2013). One agricultural model promoted based on a comprehensive study of ecosystem services in the coffee plantation landscape is agroforestry.

The agroforestry model of arabica coffee production as compared with monoculture coffee has many ecological benefits. The advantages involve providing ecosystem services and maintaining biodiversity (Sala *et al.*, 2013), storing carbon in coffee biomass and shading plants (Negash *et al*, 2013), increasing soil carbon stocks (Tumwebaze *et al.*, 2016), and supplying plant nutrients through mineralization (Sauvadet *et al.*, 2019) and N fixation (Munroe and Isaac, 2014). The study of bee-pollination ecosystem services on coffee plants mentions the economic value range of (USD 16.5 to USD 129.6) ha^{-1} of coffee plantation based on pollination value modeling (Bravo-Monroy *et al.*, 2015). However, many coffee bean products are traded in accordance with environmentally friendly coffee standards. Calculation of the carbon footprint indicates the source of GHG emissions from several activities, namely chemicals used on plantations, fossil fuels used on plantations and primary and secondary processing, fossil fuels used on transportation, and electricity used.

Hotspots that impacted the environment (midpoint and endpoint) are determined based on potential global warming indicators. The parameter used is CO_2 *e* (carbon dioxide equivalent) (BSI, 2011). The first step in the carbon emissions study of coffee was to calculate the carbon footprint of the entire activity (Motta, 2022). Carbon footprint indicators were used to compare the production models between organic and conventional cultivation (Trinh *et al.*, 2020), variations in carbon stock and plantation management in coffee agroforestry (van Rikxoort *et al.*, 2014), and productivity level of coffee grounds (Maina *et al.*, 2015). Calculating the carbon footprint has different assessment results and depends on the evaluated production model.

Carbon footprint studies are based on life cycle thinking (LCT). LCT provides benefits and calculates the trade-offs of all activities throughout the life cycle of products and services and then identifies opportunities for environmental improvement in each activity (Nazir, 2017). Therefore, the studies of carbon footprint can be expanded to include multidisciplinary considerations (ecological and socio-economic) and interdisciplinary considerations (engineering and environmental) for agricultural sustainability purposes (Henriksson *et al.*, 2015).

Several studies of coffee production's carbon footprint include agroforestry's potential to mitigate climate change (van Rikxoort *et al*., 2014). Agroforestry of coffee has the potential for carbon sequestration (Goodall *et al.*, 2015) and provides socio-economic advantages from wood and fruit plants (Pinoargote *et al.*, 2016). Harsono *et al*. (2021) utilize energy balance and green house gas emission calculation and found the potential measures to replacing gasoline with biofuel, utilising liquid waste with chemical processing, and solid wastes (briquettes and bio-pellets) of coffee production for renewable energy. Another study evaluated the net balance of GHG by including agroforestry potential in N mineralization and N fixation (Hergoualc'h *et al.*, 2012). Bockel and Schiettecatte (2018) review the LCA method and the calculation of carbon footprints in the production models of various coffee in producer countries and then formulate a calculation of carbon footprint in agricultural production based on carbon balance. The development of knowledge and modeling of the carbon cycle is required to calculate the carbon footprint in controlling agricultural activities under climate change mitigation.

The most significant Arabica coffee production in Indonesia comes from Aceh Province of Indonesia. The province reportedly had moderate to low environmental conditions compared to other provinces in Indonesia (Hariyanti *et al.*, 2021). Gayo arabica coffee is known as Sumatran coffee. This type of coffee has a geographical indication certificate from the Indonesian government in 2008 (Damayanti and Setiadi, 2019) and received geographical indication recognition from the European Union in 2021 as an agricultural commodity from a specific geographical area – Gayo highlands and major river basins in Aceh province 3°45'0" to 4°59'0" North latitude and 96°16'10" to 97°55'10" East longitude (Ellyanti *et al*., 2012). Gayo Arabica coffee has a unique and strong cupping character (body, aroma and flavor image of dark chocolate, clean). Gayo Arabica coffee cultivation has a shade plant of the lamtoro species [*Leucaena leucocephala* (Lam.) De Wit] and the cultivation is done organically (Siahaan *et al*., 2023). Organic materials from primary processing waste, *i.e.* pulper and huller, are used (Setyobudi, 2022). Most farmers in cooperative organizations follow organic certification institutions and fair trade practices. Some of them become farmers who have rainforest alliance certificates. The main exports of Gayo Arabica coffee beans are to the European Union and the United States. Currently, an assessment of the carbon footprint that includes the potential for carbon sequestration of plants has not been carried out, so calculating the carbon balance per unit area (ha) is impossible. Thus, it is considered necessary to carry out a thorough calculation of the carbon balance in the form of a CO_2 balance. This study aims to describe the CO_2 cycle in agroforestry and Gayo Arabica coffee agro-industry and uses carbon footprint calculations using the reference unit of each coffee plantation area (ha).

2. Materials and Methods

2.1. Study area

This study was conducted in Gayo Highlands at Bener Meriah and Central Aceh Regency, Aceh Province, Indonesia as shown Figure 1. The study lasted for 9 mo, starting from December 2016 to August 2017.

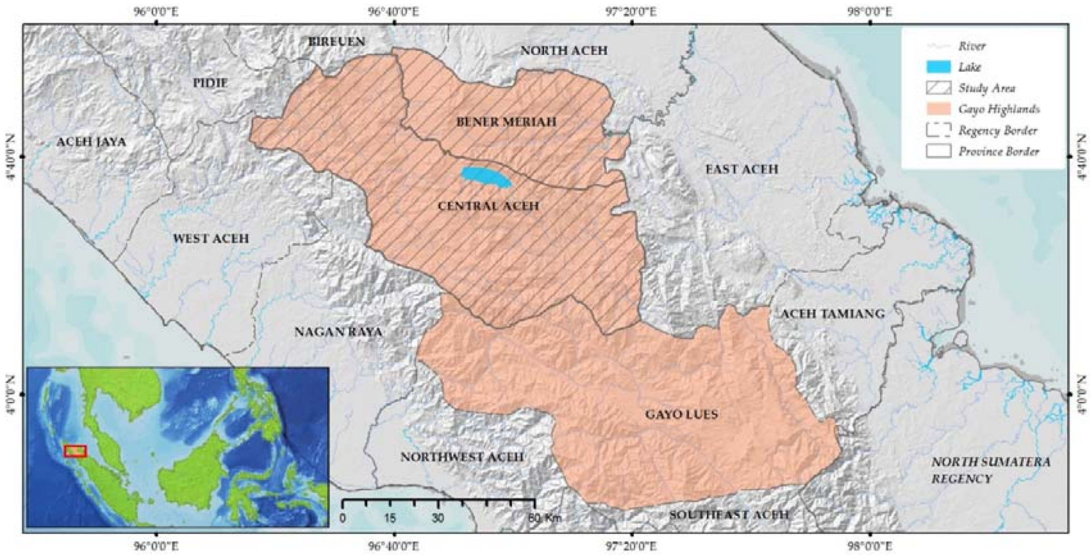

Figure 1. Location of study site

2.2. CO_2 cycle model

The CO_2 cycle explains the movement of CO_2 from various sources connecting the biosphere, atmosphere, geosphere, and hydrosphere (Grace, 2013) through photosynthesis, decomposition, respiration, and mineralization (Marchi *et al.*, 2015). Sources of CO_2 come from natural processes and human activities that are dynamic and temporal (Prentice *et al*., 2011). Increasing the concentration of CO_2 in the atmosphere will cause an increase in the earth's surface temperature which has the potential to global warming. A controlled CO_2 cycle should be able to reduce deforestation, obtain alternative energy, and implement geo engineering (Grace, 2013).

The CO_2 cycle in this study was analyzed based on GHG's potential for storage and production (sink and sources). Calculating net CO_2 sourced from direct and indirect GHG emissions throughout coffee production activities, estimates of carbon sequestration (above and below biomass) in coffee agroforestry, and potential reduction of direct emissions through GHG conversion from waste. CO_2 is emitted from activities in plantations, transportation, primary processing, and final handling in coffee agroforestry and agroindustry cooperatives. CO_2 reduction in agroforestry and agroindustry of coffee is sourced from energy estimates from by-products. CO_2 sequestration in agroforestry and agroindustry of coffee sourced from CO_2 sequestration activities by plants.

2.3. Net CO_2

The net CO_2 analyzed is based on the net CO_2 present in the agroforestry and agroindustry of coffee [Equation (1)] as follow (Lacis *et al*., 2010):

$$\text{Net } CO_2 = [CO_2 \text{ emissions} - CO_2 \text{ reduction} - CO_2 \text{ sequestration}] \quad (1)$$

Note:
Net CO_2: Total CO_2 who entering and leaving in the systems of agroforestry and agroindustry of coffee calculated based on CO_2 cycle.
CO_2 emissions: Total CO_2 determined from fuel and electricity used and the decomposition of organic matter.
CO_2 reduction: Total CO_2 from converting of wastewater, pulp, and parchment were producing in the agroforestry and agroindustry of coffee.
CO_2 sequestration: Total CO_2 sequestrated during photosynthesis and respiration process.

The "plus" value of CO_2 accumulation in the agroforestry and agroindustry of coffee is expressed as CO_2 net.

2.3.1. CO_2 emissions

The CO_2 emissions are estimated by multiplying the amount of material by the value of the conversion factor (IPCC, 2006) in Equation (2).

$$CO_2 \text{ emissions} = [M] \times [CF] \quad (2)$$

Note:
CO_2 emissions: Total of CO_2 emissions (t CO_2 *e* ha^{-1})
M: Total of materials (t C ha^{-1})
CF: Conversion factor of materials (IPCC, 2006)

2.3.2. CO_2 reduction

CO_2 reduction is estimated by calculating the potential of electrical energy multiplied by the electric emission and conversion factors (IPCC, 2006) in Equation (3).

$$CO_2 \text{ reduction} = [E] \times [EF] \times [CF] \quad (3)$$

Note:
CO_2 reduction: Total of CO_2 reduction (t CO_2 *e* ha^{-1})
E: Total electric potential from the conversion of waste (kWh)
EF: Emission factor from the production of electricity kWh^{-1} in Indonesia = 0.867 CO_2-e
CF: Conversion factor of materials (IPCC, 2006)

2.3.3. CO_2 sequestration

CO_2 sequestration is estimated using Equation (4) (Guillaume *et al*, 2018).

$$CO_2 \text{ sequestration} = [C_n] \times [3.67] \quad (4)$$

Note:

CO_2 sequestration: Total of CO_2 sequestration (t CO_2 *e* ha^{-1})

C_n: C content per unit area (t C ha^{-1})

3.67: The equivalent number or the conversion of element C to CO_2

3. Results and Discussion

3.1. CO_2 cycle model

In the CO_2 cycle, four main reservoirs of carbon are connected by exchange pathways. These reservoirs are the atmosphere, the terrestrial biosphere (including freshwater systems and non-biological material such as soil carbon), the oceans (including dissolved inorganic carbon and biological and non-biological marine biota), and sediments (including fossil fuels). The movement or exchange of CO_2 between reservoirs occurs due to various chemical, physical, geological, and biological processes. The oceans contain the largest pools of activated carbon close to the earth's surface, but the slow exchange of CO_2 between the ocean and the atmosphere.

The results of these studies showed the CO_2 cycle in agroforestry and agroindustry of Gayo Arabica coffee contains several sources of CO_2. The sources include the decomposition of organic matters, coffee processing industries, coffee transportation, and CO_2 in the atmosphere, which will later be absorbed by coffee and shading plants (*L. leucocephala*) to photosynthetic and respiratory processes (Figure 2).

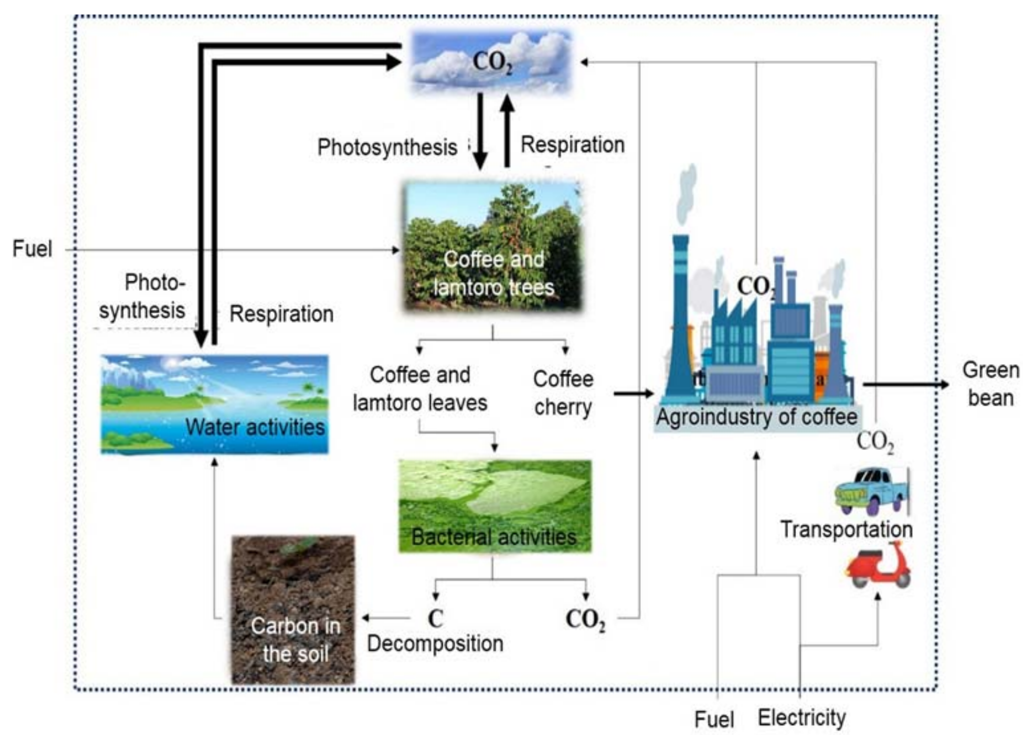

Figure 2 . CO_2 cycle in agroforestry and agroindustry of coffee

3.2. Net CO_2

Estimation of net CO_2 based on data obtained from 41 farmers; whom the cooperative members that possess 46.1 ha of agroforestry plantations in different locations in the Gayo area. The consideration factors in coffee agroforestry and agroindustry are the emitted, diminished, and sequestered CO_2 quantities. The estimated net CO_2 can be seen in Table 1.

The net CO_2 estimates based on Table 1 showed a positive CO_2 equilibrium. This indicates that the total CO_2 sequestration under coffee agroforestry was more prominent than its emissions from agroforestry and agroindustry.

Table 1. Net CO_2 in agroforestry and agroindustry of coffee

CO_2 cycle	Amounts (t CO_2 *e* ha^{-1})	Percentages
<u>CO_2 emissions</u>		
Atmosphere:		
(i) Land clearing activities	4.52×10^{-2}	2.22 %
(ii) Primary processing activities	20.54×10^{-2}	10.08 %
(iii) Transportation activities	0.57×10^{-2}	0.28 %
(iv) Decomposition activity	178.22×10^{-2}	87.43 %
Total of CO_2 emission	203.84×10^{-2}	
<u>CO_2 reduction</u>		
Electrical energy production potential from:		
(i) Wastewater	1.84×10^{-2}	59.35 %
(ii) Pulps	1.25×10^{-2}	40.32 %
(iii) Parchments	0.01×10^{-2}	0.32 %
Total CO_2 reduction	3.10×10^{-2}	
<u>CO_2 sequestration</u>		
Agroforestry of coffee:		
(i) Conversion of carbon stocks from coffee agroforestry	363.49×10^{-2}	100 %
Total of CO_2 sequestration	363.49×10^{-2}	
Net CO_2	162.75×10^{-2}	

CO_2 emissions are determined from emission sources that can be controlled from land clearing activities, indirect emissions from using fuel and electricity in primary processing and transportation machines, and indirect emissions that occur on-site. Oppositely, it cannot be controlled by the decomposition of coffee and *L. leucocephala* leaves. The emission data for 1 kg of green beans was determined from the calculation of the carbon footprint of Gayo Arabica coffee production in 2016.

Land clearing is an activity to clear the weeds on the coffee plantation using a pruning machine with 88 % iso-octane fuel (premium fuel). Cleaning is done thrice yearly, requiring a 7 L fuel ha^{-1}. The emission factor of 1 L of premium was 2.152 kg CO_2*e*. Total land clearing emissions ha^{-1} yr^{-1} was 2.1515 × 21 L = 45.18 kg CO_2 *e* ha^{-1} yr^{-1}

Primary processing changes cherry coffee into green beans through various activities by farmers, collectors, huller owners, and cooperatives. Its activities include preparing water requirements for pulping in the plantation, using pulper and huller machines with diesel fuel, completion of green bean handling in cooperatives, disposal of waste that causes decomposition, and burning of parchment at huller facilities. The emissions from all primary processing activities were calculated from the carbon footprint of Gayo Arabica coffee production in 2016. The emissions from activities per hectare are determined from the emission value of primary processing activities multiplied by the productivity.

Emissions from each preparation of water requirements, use of pulper machines, use of huller machines, final handling in cooperatives, decomposition of wastewater and pulp, and burning of parchment were (1.3×10^{-2}, 3×10^{-3}, 10^{-3}, 2.3×10^{-2}, 12.5×10^{-2}, 14.3×10^{-2}, and 5×10^{-3}) kg CO_2 e kg^{-1} green bean, respectively. Thus, the emission from the activities ha^{-1} were (13.9, 2.98, 0.81, 23.93, 2.90, 148.70, and 12.55) kg CO_2e ha^{-1}, respectively. The total emission from primary processing was 205.35 kg CO_2e ha^{-1} yr^{-1}.

Transportation is an activity of moving materials (coffee beans processed by pulpers and hullers) with four routes: farmers to collectors, collectors to huller owners, huller owners to collectors, and collectors to the cooperative. Transportation uses premium and diesel fuels so that it produces direct emissions. The calculation of emissions from all transportation was determined from the carbon footprint of Gayo Arabica coffee production in 2016. Emissions from each route were (10^{-3}, 10^{-3}, 10^{-3}, and 2×10^{-3}) kg CO_2e ha^{-1}, respectively. Hence, emissions from each route per ha were (1.22, 1.40, 1.22, and 1.86) kg CO_2e ha^{-1}. The total emission from kg CO_2e ha^{-1} was 5.697 kg CO_2e ha^{-1} yr^{-1}.

The decomposition of coffee and *L. leucocephala* leaves breaks down the organic matter from coffee and *L. leucocephala* leaves that fall on the surface of the coffee fields. The emission factor of biomass from the plantation is 0.44 kg CO_2e. The fallen coffee and *L. leucocephala* leaves were estimated to be weighed at 248.969 kg ha^{-1} (using 75 % dry base ha^{-1}). Thus, 1 782.210 kg CO_2e ha^{-1} yr^{-1} were totally emitted from the decomposition of both biomass components.

Reducing energy usage in the primary process of green bean production is a challenge for green bean producers. Minimizing energy usage in the primary process of green bean production will positively impact reducing CO_2 emissions because the highest energy usage will be contributed to CO_2 emissions. Energy reduction can be made in several ways by increasing efficiency in energy usage and using the energy from waste (Harsono *et al*., 2015; Siregar *et al*., 2020, Setyobudi *et al*., 2021a, 2022; Yandri *et al*., 2021a).

The efficiency of energy usage during the primary process of green bean production can be done by optimizing energy usage. All its stages depend primarily on energy. Therefore, optimization of energy usage can be carried out at every step. Optimizing energy usage during the process can be done by: i) reducing the distribution distance, ii) reducing water usage, and iii) reducing electricity usage (Novita *et al*., 2021; Yandri *et al*., 2020, 2021b).

Energy production from the waste of primary green bean production is one technological innovation to improve the company's performance based on an environmental management system. Several wastes, such as pulp, wastewater, and parchment, can be used as raw materials for energy production. All mentioned wastes can be used as raw material for biogas production through anaerobic fermentation (Adinurani *et al*. 2013; Novita *et al*., 2021; Setyobudi *et al*., 2018, 2021b, 2022; Syarief *et al*., 2012) and bio briquettes through pyrolysis processes (Harsono *et al*., 2019; Tandiono and Endah, 2020; Yandri *et al*., 2021b), which can be used directly as fuels.

Recycling coffee waste into bio briquettes and biogas has advantages and disadvantages. Bio briquette requires resources and funds to make it happen. However, bio briquettes are energy materials that can be transported to generate energy in other locations. Biogas also requires financial resources, but relatively zero in terms of resources. However, biogas's weakness is relative energy that cannot be transported, especially small and medium-scale biogas digesters (Adinurani *et al*. 2014, 2017). The advantage of the biogas digester is that it can simultaneously handle liquid and solid coffee waste (Setyobudi, 2022).

Biogas technology is recommended because the volume of coffee processing liquid waste is more significant than solid waste (Setyobudi *et al*. 2022). With a biogas digester, a double benefit is obtained, namely obtaining renewable energy —clean energy, minimizing the release of CO_2 into the air, minimizing environmental pollution in water and soil, and producing solid and liquid organic fertilizers (Abdullah *et al*., 2020; Setyobudi, 2022; Susanto *et al*., 2020a). Besides being able to generate electricity, biogas energy can also be used as drying energy in the coffee bean process, as a substitute for sunlight, or as a substitute for fossil drying energy, for example, liquid propane gas (LPG).

In order to increase the quantity of biogas production and the quality of the environment, several researchers recommend the combination of the biogas digester with the latrine system for the disposal of excreta from each household (Susanto *et al*., 2020a, 2020b; Zhou *et al*., 2022). Further research can be applied using renewable hybrid energy, *i.e*. biogas and solar panels, such as heating/drying energy in the coffee bean process (Novianto *et al.,* 2020; Setyobudi, 2022). Through this hybrid energy, coffee agroforestry and agroindustry can maximise CO_2 reduction.

Similarly, research on sustainable coffee production requires hybrid methods, one of which is remote sensing and geospatial methodologies (Hunt *et al*., 2020) linked to life cycle thinking systems (Bockel and Schiettecatte 2018, Pramulya *et al*., 2022). The renewable hybrid method aims to analyse several parameters of sustainability and provide implications for improving coffee production and supply chains (Hamdan *et al*., 2018; Pramulya *et al*., 2021). In addition, the hybrid method addresses coffee production that is sensitive to deforestation and land expansion.

The carbon footprint calculation in this study succeeded in calculating the actual carbon emissions from Arabica coffee production activities in the farm and primary processing using the land reference unit. The use of the land reference unit is necessary to estimate the amount of carbon emissions produced on each farmer's farm. This helps to formulate mitigation strategies for each farmer. Referring to the Land-based Carbon Dioxide Removal method (Gvein *et al*. 2023), calculating carbon footprint at farm level helps to understand the choice of mitigation scenarios in local environmental and social contexts.

4. Conclusion

The CO_2 cycle in agroforestry and agroindustry of Gayo Arabica coffee contains several sources of CO_2, such as the decomposition of organic matters, coffee processing industries, coffee transportation, and CO_2 in the atmosphere, which later will be absorbed by coffee and shading plants (*L. leucocephala*) to photosynthetic and respiratory process.

When comparing with the carbon stock calculations of Solis *et al* (2020) in two regions in Peru, the carbon sequestration data of agroforestry coffee plantations in the Gayo highlands is lower. This is because the vegetation type of the study site is relatively small (2 to 3 species) compared to the Peruvian region (18 species). Meanwhile, there was an additional soil carbon calculation in the Peruvian research.

However, the calculation of the overall carbon footprint of the coffee production system with the restriction from farm to processing stage shows that the carbon emissions of one kilo gram of green bean in the Gayo Highlands are lower (Pramulya *et al* 2021) than the carbon emissions of coffee produced in Costa Rica at 1.93 kg CO2-e (Killian *et al*. 2013), Mesoamerica at (6.2 to 10.8) kg CO2-e (van Rikxoort *et al*. 2014) and Kenya at 4 kg CO2-e (Maina *et al*. 2015).

Estimation of net CO_2 showed that the CO_2 equilibrium is positive. This indicates that the total CO_2 emissions in coffee agroforestry and agroindustry were smaller than the total CO_2 sequestration in coffee agroforestry. Net CO_2 ha^{-1} in the coffee plantation was 162.75×10^{-2} t CO_2 ha^{-1}, with CO_2 emission, reduction, and sequestration being (203.84×10^{-2}, 3.10×10^{-2}, and 363.49×10^{-2}) t CO_2 ha^{-1}. The CO_2 cycle positively impacts the sustainability of agroforestry and agroindustry of Gayo Arabica coffee.

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