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Carbon Storage and Greenhouse Gas Emissions from Corporate Social Responsibility-Based Sustainability Projects in Semarang Regency, Indonesia

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Abstract. This study evaluates the environmental impacts of four Corporate Social Responsibility (CSR)-based sustainability projects implemented by a private company producing traditional herbal products in Bergas Kidul Village, Central Java, Indonesia. These CSR projects were intended to mitigate climate change by sequestering carbon in relatively solid forms, thus reducing the emission of greenhouse gases. Reduction of carbon emissions was the main goal to be fulfilled in order to prove that the CSR projects were in line with the corporate commitment to sustainability. The implemented projects included avocado tree plantations, communal cattle farming, organic fertilizer application, and the reuse of high-density polyethylene (HDPE) drums. This research aimed to assess and estimate the carbon balance of these four practices based on the potential greenhouse gases stored and emitted by each practice. Supporting data were collected through surveys, interviews, and literature studies. Data were then analyzed using the 2006 and 2019 IPCC Guidelines for National Greenhouse Gas Inventories, specifically using the Tier 1 method. The Tier 1 approach employs the basic method and the default emission factors provided in the IPCC Guidelines (Workbook and Reference Manual). Based on this analysis, avocado plantations were estimated to sequester 79.850 ton per year of CO_2 eq but cattle farming generated 19.91 ton per year of CO_2 eq. The use of organic fertilizer in paddy fields was estimated to emit around 0.0005 kg of N2O per hectare (0.1325 kg of CO2 eq per hectare), and this seemed to be drastically reduced compared to the application of chemical fertilizers. Applying liquid organic fertilizer was estimated to reduce approximately 74.518 kg of CO_2 eq per hectare. Meanwhile, reusing 46 HDPE drums as planting medium for the household food security project in the studied area, instead of burning them, was predicted to store approximately 1.583 tons of CO_2 eq in the solid form. While we couldn't conclude a single net carbon balance resulted from these projects due to methodological limitations, these results could depict the potential and risks of environmental impacts of the claimed sustainability interventions for a longer period.

Keywords: carbon assessment; CSR projects; greenhouse gases; sustainable agriculture

1. Introduction

The Corporate Social Responsibility (CSR) program has evolved as an integrated model for private sector participation in sustainable rural development in Indonesia. CSR is a form of corporate commitment to support sustainable development through environmentally friendly, socially relevant, and economically beneficial programs. An Indonesian private company producing traditional herbal beverages has been working on several CSR projects in Bergas Kidul Village of Semarang Regency in Central Java, Indonesia (Figure 1). These initiatives were part of this company's long-term commitment to align its operations with global sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs) and Intergovernmental Panel on Climate Change (IPCC). In both frameworks, urgent action to mitigate climate change by reducing the emission of greenhouse gases into the atmosphere and sequestering carbon was advocated. Many technical actions can be feasible for this purpose, such as keeping carbon in soils, plant biomass, and solid materials for a relatively long period. Based on these frameworks and knowledge, the company has been implementing four various CSR projects for the last 3-4 years. However, the potential carbon storage and emission resulted from these projects are not yet known.

The project's focus on empowering local farmers and residents to these particular

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activities: 1) avocado cultivation in farmlands and yards, 2) communal cattle husbandry and manure management, 3) application of liquid organic fertilizer produced from the waste of herbal beverage production, and 4) reuse of HDPE drums as planting mediums for nearby household home gardens instead of burning them. These initiatives were taken due to their strong relevance to carbon balance in the soil and atmosphere. Carbon is one of the major greenhouse gases (GHGs); its excessive accumulation, especially in the form of carbon dioxide (CO2) and methane (CH4), in the atmosphere contributes to global warming (Seydewitz et al., 2023). Through photosynthesis, this gas is captured, converted into plant biomass, and thus stored in a more stable form. When avocado trees are grown, this gas would not be that easy to release, as the trees remain on the land for a long period. Avocado trees contributed significantly to the local carbon stock (Wijayanto & Prasetyo, 2021). At the landscape level, planting avocado trees along the water basin of River Citarum in Indonesia has shown multiple benefits for soil conservation, ecosystem rehabilitation, and soil carbon storage (Sudibyo et al., 2019).

Livestock husbandry emits CH_4 during digestion in cattle's rumen when methanogenic microbes ferment the fibres contained in cattle feeds. An average dairy cow releases around 0.16 tons per year of methane, of which more than 80% of the CH_4 is expelled from the mouth during belching or eructation (Thacharodi et al., 2024). Depending on its on-site management, cattle manure could emit a certain amount of CH_4 and N_2O. An anaerobic environment, such as a lagoon or a wet manure pile, results in CH_4 emission, while an aerobic condition allows nitrification and denitrification, thus resulting in N_2O emission (Pauzan et al., 2024; Syarifuddin et al., 2019). Biological factors (age, weight, physiological status), feed (fibre quality, proportion, additives), and cattle management (barn types, manure storage, and local climate) affects the amount of GHGs released into the atmosphere. Higher bodyweight in cattle indicates higher amount of enteric emission and nitrogen excretion (Hasnarani & Hasanah, 2025).

(Seydewitz et al., 2023; Zhen et al., 2023) emphasized that organic-based systems play an essential role in transforming atmospheric carbon into terrestrial stocks, thereby reducing net emissions and improving ecosystem function. The integrated management of improved fertilizer and livestock can significantly reduce greenhouse gas emissions, while waste reuse may minimize carbon losses (Hartoyo et al., 2022; Mboyerwa et al., 2022; Wihardjaka, 2021). The use of organic fertilizer has resulted in better soil structure, water holding capacity, and carbon sequestration.

Burning HDPE plastic will emit CO_2, CH_4, and N_2O into the air. The emission of CO_2 gas results from carbon oxidation, while the release of N_2O emerges from the oxidation of nitrogen under high temperatures. The production of CH_4 gas occurs due to incomplete incineration (Mentes et al., 2023). Instead of burning plastic and releasing various GHGs into the atmosphere, reusing industrial plastic waste reduces indirect CO_2 emissions from incineration (Castillo-Díaz et al., 2021). Despite the potential or risk of each practice to sequester carbon, there has not been any study on the carbon balance resulting from all these practices in Bergas Kidul Village. *To the best of our knowledge, this is the first study to estimate and elaborate on the potential carbon storage as well as emission of different CSR interventions using the IPCC Tier 1 method.* This study aims to estimate and evaluate the potential carbon storage and emission resulted from CSR projects in the studied region.

2. Materials and Methods

2.1 Data Collection

The study was conducted in Bergas Kidul Village, located within the industrial vicinity (Ring I) of the Bergas area in Semarang Regency of Central Java (**Figure *1***). The area represents a mixed rural–

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industrial landscape. It is characterized by the high population density, smallholder agricultural plots, and mixed livestock–crop systems.

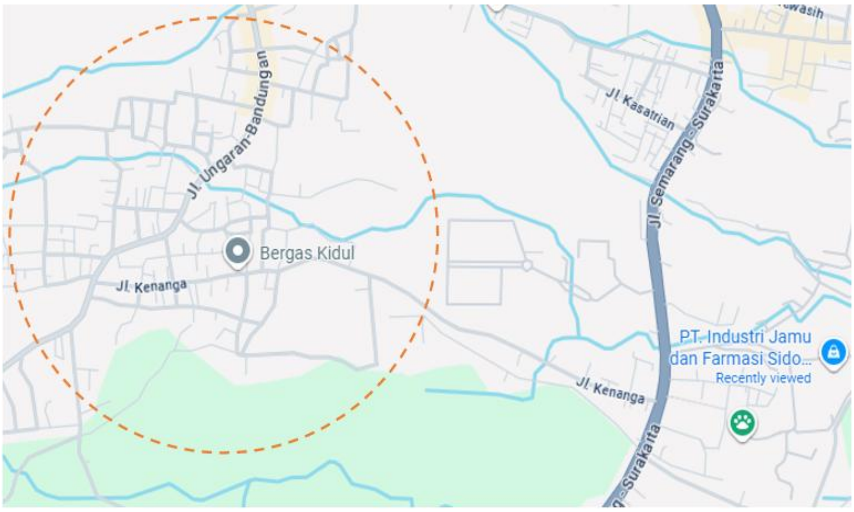

Figure 1. The location of CSR programs in Semarang Regency of Central Java, Indonesia

Data was collected in September 2025 through on-site measurement, interviews, and secondary data compilation from CSR documentation. The greenhouse gas (GHG) emission and mitigation potential of each sustainability project were analyzed using IPCC protocols (Eggleston et al., 2006a, 2006b). Within the avocado plantation program, 500 trees were identified, with 35% classified as productive. A total of 50 trees (10%) were randomly selected and grouped into productive and non-productive categories, followed by diameter at breast height (DBH) measurement. This sampling proportion is considered adequate for relatively homogeneous populations in field-based studies, as it captures variability while maintaining efficiency, and randomization helps minimize sampling bias. Supporting data were collected through structured interviews, including plant variety, age, productivity status, and cultivation practices, to strengthen the interpretation of biomass and carbon estimates.

In the communal cattle pen, all 16 livestock (five dairy and eleven beef cattle) were measured using chest girth to estimate emissions. In three paddy field demonstration plots, N_2O emissions were calculated based on nitrogen input across four fertilizer treatments using the IPCC indirect emission method. Meanwhile, the stored GHG due to reusing the HDPE drum was estimated using the IPCC Waste Sector approach. This was carried out by comparing reuse scenarios to the open-burning system. Overall, the study quantified CO_2 storage in avocado tree biomass and HDPE drums, CH_4 and N_2O emissions from cattle farming and manure management, as well as N_2O emissions from organic fertilizer application.

2.2 General Calculation Framework

In this study, a distinction is made between carbon stock and GHG emission within the carbon balance framework. Carbon stock, such as the CO_2 stored in avocado tree biomass and N_2O kept in solid form by using HDPE drums, represents the accumulated carbon at a given point in time, reflecting long-term sequestration. In contrast, GHG emissions from cattle and organic fertilizer use were treated as flow variables, expressed as GHG (CO_2, CH_4, and/or N_2O) emissions. All GHG data were then converted into CO_2 equivalent (CO_2 eq) using the conversion standard from Global Warming Potential (GWP) IPCC (Table 1).

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Table 1. Conversion standard of GHG

Conversions of CO_2 eq	
Formula	GWP
CO_2	1
CH_4	28
N_2O	265

Source: IPCC

2.3 Estimation of Carbon Storage in Avocado Trees

The carbon stock of avocado trees was estimated through the non-destructive allometric equation, which relates tree diameter to its total aboveground biomass (AGB). The formulas used for this estimation were (Kuyah et al., 2024):

AGB of nonproductive avocado trees = $0.0638 \times (DBH)^{2.5435}$ ... (1)

AGB of productive avocado trees = $(0.0638 \times (DBH)^{2.5435}) \times 96\%$ ... (2)

The carbon content (C) was assumptively 47% of the total biomass (on Climate Change, 2006), thus the corresponding CO_2 eq of an individual tree was obtained by multiplying its C content with the molecular weight ratio of CO_2 to C (3.67). The formula was:

$$CO2\ eq_{tree} = AGB \times 0.47 \times 3.67 \ldots (3)$$

Total CO_2 sequestration was:

$$CO2\ eq_{total} = \sum CO2\ eq_{tree} \ldots (4)$$

2.4 Estimation of GHG Emissions from Cattle

The enteric CH_4, manure CH_4, and manure N_2O in cattle management were estimated based on chest girth data using the following calculations.

a. Body weight and Livestock Unit
Body weight was estimated using Schoorl's formula:

$$\text{Body weight (in kg)} = \frac{(chest\ girth\ (in\ cm) + 22)^2}{100} \ldots (5)$$

Livestock Unit (AU) was estimated using the following equation:

$$AU = \frac{\Sigma\ Body\ Weight\ (in\ kg)}{453\ kg} \ldots (6)$$

a. Enteric methane
Enteric methane emission (CH_4) was calculated using IPCC Tier-1 method:

$$\text{Enteric } CH_4 \text{ (ton per year)} = N(AU)x\ EF\ x\ 21‰ \ldots (7)$$

where:

- N(AU) = total livestock units per category
- EF = emission factor (dairy ≈ 68 kg of CH_4 per year; other cattle ≈ 47 kg of CH_4 per year)

b. CH_4 from manure management
Manure methane emission was estimated using the Tier-1 IPCC, 2006 formula:

$$\text{Manure } CH_4 \text{ (Gg per year)} = \sum \frac{EF_{(T)} \times N(AU)}{10^6} \ldots (8)$$

where:

- $EF_{(T)}$ = 29 kg of CH_4/head/year for dairy cattle; 1 kg/CH_4/head/year for other cattle (based on temperature; Bergas Kidul has the average temperature of 24°C - 32°C)

c. N_2O from manure management
Direct N_2O is estimated using Tier-1 IPCC, 2006 formula:

$$N2OD(MM) = [\sum S\ [\sum T\ (NT \times NexT \times MST,S \times EF3,S)] \times \frac{44}{28} \ldots (9)$$

where:

- N_T = number of animals in category T (head)
- Nex_T = nitrogen excretion per head per year (kg N/head per year)
- $MS_{T,S}$ = fraction of excreted N entering manure management system S
- $EF_{3,S}$ = emission factor for direct N_2O from manure management (kg N_2O-N kg^{-1} N)

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2.5 Estimation of N_2O Emission from Organic Fertilizer Use

The emission of N_2O associated with fertilizer use was estimated using the protocol of IPCC "Indirect N_2O Emissions from Agriculture". As livestock volatilization was excluded from the measurement, thus the emission was estimated using the simplified equation:

$$N_2O - N = (N_{FERT}\ x\ FRACGAS_F)x\ E_{F4} \ldots (10)$$

where:

- N_{FERT} = inorganic (synthetic) fertilizer used in the studied field (kg N per year)
- $FRAC_{GASF}$ = fraction of applied inorganic N that volatilizes to NH_3 + NO_x (IPCC default = 0.10)
- EF_4 = emission factor that converts deposited/volatilized N to N_2O-N (kg N_2O-N per kg N deposited; IPCC EF_4 default = 0.01)

The value of N_2O-N then was converted to N_2O emission using the following formula:

$$N_2O = N_2O - N\ x\frac{44}{28} \ldots (11)$$

2.6 Sequestered CO_2 from Reusing HDPE Drums

The emission from plastic waste management (incineration/open burning) was estimated following the Tier-1 IPCC waste approach. The simplified formula will be used because the 200 L-HDPE drums were in a dry condition (dm ≈ 1); thus, the carbon is almost entirely fossil carbon. The calculations used were:

a. CO_2 from HDPE

$$E\ CO_2 = W \times CF \times FCF \times OF \times \frac{44}{12} \ldots (12)$$

b. CH_4 from incomplete combustion

$$E\ CH_4 = W \times CF \times FCF \times OF \times \frac{16}{12} \ldots (13)$$

Where:

- W = dry mass of the HDPE waste (kg)
- CF = fraction of carbon in dry matter (for HDPE CF ≈ 0.856281, i.e., 85.6281%)
- FCF = fossil carbon fraction (FCF = 1 for HDPE since polymer carbon is fossil-derived)
- OF_{CO2} = oxidation factor for CO_2 (default OF ≈ 0.99 for near-complete combustion)
- OF_{CH4} = effective fraction forming CH_4 under imperfect combustion (default OF ≈ 0.01 for CH_4 as "small" fraction)

3. Results and Discussion

Values presented in this study are purely descriptive and predictive due to some technical limitations in collecting statistically appropriate data. Carbon storage in solid form (tree biomass and HDPE drums) represents the sequestered carbon from CSR interventions. In contrast, carbon emissions from cattle and organic fertilizer represent the potential GHG input into the atmosphere due to the projects. The stored or emitted CO_2 (or CO_2 eq) is elaborated under each CSR project.

3.1 CO_2 Storage in Avocado Trees Vegetation

An individual productive avocado tree stored an average of 0.395 tons of CO_2; thus, approximately 69.07 tons of CO_2 were stored within the biomass of all productive avocado trees in the village. Individual nonproductive trees sequestered around 0.033 tons of CO_2; therefore, around 10.84 tons of CO_2 were stored within all nonproductive avocado trees in the village. In total, CO_2 sequestered by the avocado plantation in this project reached 79.91 tons (Table 2).

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Table 2. The estimated CO_2 storage by avocado trees due to CSR intervention in the studied area

Vegetation CO2 Storage			
Category	The average CO_2 stored in one tree (ton)	Number of avocado trees	Total CO_2 stored in avocado trees (ton)
Productive trees	0.395	175	69.125
Nonproductive trees	0.033	325	10.725
Total			79.850

CO_2 storage in the avocado vegetation reached a total of 79.850 ton of CO_2, with productive trees contributing 0.395 tons of CO_2 per tree (69.125 ton of CO_2 in total) and nonproductive trees contributing 0.033 tons of CO_2 per tree (10.725 ton of CO_2 in total). This clear disparity reflects the strong influence of tree maturity and biomass accumulation on carbon storage, consistent with findings that larger and older trees dominate carbon pools in smallholder systems (Wijayanto & Prasetyo, 2021). Quantitatively, the estimated carbon stock per tree in this study appears relatively high compared to other tropical fruit tree systems, which commonly report lower per-tree sequestration depending on species, stand density, and management intensity (Gelaye & Getahun, 2024). This indicates that the avocado trees in Bergas Kidul may have reached a more advanced growth stage or benefited from favorable site conditions. However, this interpretation should be approached critically, as allometric equations, while practical, can introduce uncertainty and potential overestimation when applied beyond their original calibration context (Kuyah et al., 2024).

Despite the promising carbon storage potential, several limitations and contrasting findings must be acknowledged. Studies on Indonesian home garden systems demonstrate that carbon stocks in smallholder agroforestry are often substantially lower than those in natural forests and highly variable depending on species composition and management practices (Roshetko et al., 2002). This suggests that the relatively high sequestration observed in this study may not be directly generalizable across similar systems. Furthermore, recent literature highlights methodological gaps and uncertainties in carbon accounting within agroforestry systems, including variability in tree architecture, biomass allocation, and site-specific conditions, which may influence the robustness of carbon estimates (Gelaye & Getahun, 2024). Ecologically, while avocado trees are associated with soil stabilization, increased organic matter input, and improved microhabitat conditions, these ecosystem services are often inferred rather than directly measured, and their magnitude can vary significantly depending on local environmental factors (Idris et al., 2025). Therefore, although the Bergas Kidul avocado program demonstrates meaningful potential for community-level climate change mitigation, its scalability and long-term effectiveness require cautious interpretation, improved methodological rigor, and consistent agronomic management practices (Aulia & Ermawati, 2023).

3.2 Greenhouse Gas Emissions from Cattle Farming

Annual greenhouse gas emissions from the communal cattle farming system in Bergas Kidul Village were estimated at 0.676 ton/year of CH_4 and 0.0037 ton/year of N_2O (Table 3) corresponding to approximately 19.91 tons/year of CO_2 eq. Dairy cows contributed the largest share (18.93 tons of CO_2 eq), primarily due to higher enteric fermentation rates and methane yield per

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animal unit compared to beef cattle (Syarifuddin et al., 2019). This total emission appears relatively low compared to the 176.58 tons/year of CO_2 eq reported by (Hasnarani & Hasanah, 2025). When normalized per animal, the emission intensity of the communal cattle system was approximately 1.24 ton of CO_2 eq head^{-1} per year, slightly higher than the 1.06 ton of CO_2 eq head^{-1} per year for semi-intensive buffalo farming. This indicates that, although total emissions in this study are lower due to a smaller herd size, the per-animal emission intensity is relatively comparable and may even be slightly higher, potentially reflecting differences in livestock type, feeding practices, and manure management systems.

Table 3. The estimation of GHG emissions from cattle farming in the sustainability project

Estimation of CO2 emissions from cattle farming					
Type	Livestock Unit (AU)	Number of cattle	CH_4 (ton/year)	N_2O (ton/year)	CO_2 eq total (ton/year)
Dairy cows	3.747	5	0.363	0.00116	18.934
Beef cattle	6.514	11	0.312	0.00252	0.975
Total			0.676	0.00368	19.910

The estimated emission of 19.91 tons of CO_2 eq was primarily driven by enteric methane as well as manure-related CH_4 and N_2O emissions. Ruminant livestock are a dominant source of agricultural GHG emissions due to the enteric fermentation and manure management processes (Syarifuddin et al., 2019). The existing management system, characterized by indoor housing and solid manure storage, may contribute to emission formation through partially anaerobic conditions, although it may still perform better than less controlled systems such as dry-lot management (Eggleston et al., 2006a; Pauzan et al., 2024). The manure management method employed under the CSR program plays a significant role in shaping GHG emissions. Farmers in Bergas Kidul Village apply a solid storage system, where manure is piled with straw for several months. Under such conditions, partially anaerobic environments are likely to develop within the pile, supporting CH_4 formation in inner layers, while aerobic-anaerobic interfaces may facilitate N_2O production through coupled nitrification-denitrification processes (Pauzan et al., 2024). Compared to the commonly practiced dry-lot system, which exposes manure directly to air and can increase nitrogen losses, solid storage systems are associated with lower N_2O emission factors. According to IPCC default values (Eggleston et al., 2006a), the emission factor for solid storage (0.005) is substantially lower than that of dry-lot systems (0.02), indicating a potential relative reduction in emissions under improved manure handling practices. However, it is important to note that these estimates are based on generalized emission factors and not direct measurements from the study site.

Local environmental conditions also influence emission dynamics. With average temperatures ranging from 24-32 °C, Bergas Kidul falls within a warm tropical climate, which can enhance methane production by increasing manure methane conversion factors (MCF) (Eggleston et al., 2006a). For example, under such conditions, methane emissions may reach up to 29 kg of CH_4 per head per year. Nevertheless, practices such as composting and nutrient recycling implemented in the communal system may help moderate these emissions, although the extent of mitigation was not directly quantified in this study. Previous studies

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(Niles et al., 2022; Uvarov et al., 2020) have shown that improved manure management strategies can reduce N_2O emissions by 30–40%, suggesting that similar practices could contribute to emission reduction in this system.

Overall, while the communal cattle farming system contributes to greenhouse gas emissions, the adoption of improved manure management practices indicates a potential pathway for mitigation. However, the magnitude of emission reduction remains uncertain due to the reliance on Tier-1 IPCC methods and the absence of site-specific emission measurements. Future improvements, such as the implementation of aerobic composting systems, biogas digesters (Hidayati et al., 2020), or vegetative buffer zones (Firdaus, 2023), could further reduce emissions while enhancing nutrient recycling and system sustainability.

3.3 N_2O Emissions from Organic Fertilizers

As can be seen in Table 4, nitrogen inputs varied considerably across treatments. Despite contributing less than 1% of the nitrogen supplied by synthetic fertilizers, the full-organic fertilizer treatment achieved a comparable yield (5.04 ton ha^{-1}). This observation suggests that the liquid organic fertilizer may enhance nutrient use efficiency and soil biological processes rather than primarily acting as a direct nitrogen source. This interpretation is consistent with Wihardjaka (2021), who highlighted the role of organic amendments in improving microbial activity, root development, and nutrient mineralization under low external nitrogen inputs. Similarly, Mulyani et al. (2025) reported that integrated organic-based fertilization systems in irrigated rice fields can sustain productivity while improving soil quality, particularly when organic inputs are combined with reduced inorganic fertilizer rates. However, it should be noted that this comparison is based on a single observation without reported variability or statistical testing, and therefore should be interpreted with caution.

Table 4. Estimation of N_2O and CO2 eq Emissions from CSR Intervention (Improved Practice) Compared to Common practice

Fertilization treatment	Yield (ton ha^{-1})	N input (kg ha^{-1})	Total N_2O-N (kg ha^{-1})	Total N_2O (kg ha^{-1})	Total CO_2 eq (kg ha^{-1})
T1-Improved practice *(8 L of organic fertilizer + 125 kg of urea + 200 kg of NPK)*	5.68	89.63	0.0896	0.1408	37.3120
T2-Improved practice *(16 L of organic fertilizer + 125 kg of urea + 200 kg of NPK)*	6.88	89.76	0.0897	0.1410	37.3650
T3-Common practice *(250 kg of urea + 400 kg of NPK)*	5.04	179.00	0.179	0.2812	74.5180
T4-Improved practice *(21.8 L of organic fertilizer)*	5.04	0.36	0.0003	0.0005	0.1325

The full-inorganic treatment commonly practiced by adjacent farmers produced 0.281 kg of N_2O per hectare (74.51 kg of CO_2 eq per hectare), whereas the full-organic treatment advocated by CSR interventions emitted only 0.0005 kg of N_2O per hectare (0.13 kg of CO_2 eq per hectare). This represents a substantial difference in emission reduction, yet the

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magnitude should be interpreted as an indicative estimate rather than a direct field measurement. Recent studies have shown that IPCC default emission factors may overestimate actual N_2O emissions under certain agricultural conditions, particularly in managed systems with controlled nitrogen inputs and water regimes (Wu et al., 2024). More broadly, uncertainty in greenhouse gas accounting remains a critical challenge, as emission estimates are highly sensitive to methodological assumptions, system boundaries, and emission factor selection (Schulte et al., 2024). Therefore, the observed difference in emissions should be seen as a model-based approximation rather than an absolute reduction. Using the Tier-1 IPCC approach (default emission factor of 1% of applied N and volatilization fraction of 10%), liquid organic fertilizer can still be categorized as a relatively low-emission input in irrigated rice systems (Hanarisanty & Pratama, 2022).

The lower estimated emissions from organic fertilizer are associated with reduced nitrogen availability for nitrification and denitrification processes, which are the primary pathways for N_2O formation. The substitution of chemical fertilizers with liquid organic fertilizer (POC) reduces nitrogen inputs and associated N_2O emissions while improving nutrient-use efficiency (Purwanto et al., 2023; Wihardjaka, 2021). Process-based studies have demonstrated that N_2O emissions are strongly regulated by localized "hotspots" of microbial activity, where the interaction between organic substrates, oxygen availability, and mineral nitrogen controls coupled nitrification–denitrification processes (Zhang et al., 2023). In this context, organic amendments may alter these micro-environmental conditions by gradually releasing nitrogen and enhancing microbial immobilization, thereby reducing instantaneous N_2O fluxes. Furthermore, a recent review by (Dăncilă et al., 2025) emphasized that excessive nitrogen application from synthetic fertilizers significantly increases N_2O emissions, while optimized or reduced nitrogen inputs—including organic-based systems—can effectively mitigate emissions without necessarily compromising yield. However, these results should not be generalized without considering site-specific factors such as soil properties, water management, and long-term nutrient dynamics.

While integrating organic and inorganic fertilizers appears to offer a balance between productivity and emission mitigation, further multi-season observations are required to assess yield stability and cumulative greenhouse gas impacts over time. Long-term studies indicate that sustained application of organic inputs can improve soil organic carbon (SOC), nutrient retention, and overall system resilience, contributing to more stable production systems under variable environmental conditions (Mulyani et al., 2025). However, the magnitude of these benefits depends on consistent management practices and environmental context. Therefore, the findings of this study highlight the potential of organic-based fertilization as a climate-smart practice, while emphasizing the need for more robust, long-term, and site-specific evaluation.

3.4 GHG Sequestered from the Reuse of HDPE Drums

The estimated reduction of greenhouse gas (GHG) emissions from reusing 46 high-density polyethylene (HDPE) drums, each weighing 10 kg, suggests that avoiding open burning could prevent the release of approximately 1.436 tons of CO_2 and 0.005 tons of CH_4, equivalent to 1.583 tons of CO_2 eq. These calculations were based on emission factors from the 2006 IPCC Guidelines and the 2019 Refinement (Eggleston et al., 2006b). When expressed per unit mass, the resulting emission rate is approximately 3.43 tons of CO_2 eq per ton of plastic. This value is slightly higher than the range of 2.7–3.1 tons of CO_2 eq reported by (Mentes et al., 2023) for mixed plastic combustion. This discrepancy may be attributed to differences in plastic composition (pure HDPE versus mixed

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plastics), combustion assumptions, and the use of default oxidation factors, which can influence emission estimates. Therefore, while the calculated value falls within a comparable order of magnitude, it should be interpreted with caution rather than as a direct equivalence.

It is also important to acknowledge the uncertainty associated with these estimates. The calculations rely on Tier-1 IPCC default parameters, including carbon fraction and oxidation rates, which may not fully capture site-specific combustion conditions. Variability in burning efficiency, moisture content, and incomplete combustion could lead to deviations from the estimated values. As such, the reported emission reduction should be considered an approximate indication of mitigation potential rather than a precise quantification. Although the total plastic mass analyzed (460 kg) is relatively small, the results remain relevant as a proof-of-concept for localized mitigation strategies. At the community scale, such interventions demonstrate how simple waste management practices can contribute to emission reduction, even if the absolute magnitude is limited. The significance of this approach lies not in the immediate scale of reduction, but in its scalability and replicability across larger waste streams and similar rural-industrial contexts.

From an environmental perspective, the management pathway of plastic waste has important implications. Open burning of HDPE releases greenhouse gases along with hazardous pollutants such as dioxins and furans (Eggleston et al., 2006b). In contrast, alternative pathways such as recycling or reuse can reduce these emissions. In this study, reusing HDPE drums as planting containers eliminates direct combustion-related emissions and extends the functional lifespan of the material. However, the broader environmental benefits of reuse should be interpreted within a life-cycle perspective, as different waste management options involve trade-offs in energy use and emissions (Castillo-Díaz et al., 2021).

Overall, while the avoided emissions of 1.583 tons of CO_2 eq are modest in absolute terms, the findings highlight the potential contribution of small-scale circular practices to climate change mitigation. When implemented consistently and at larger scales, such reuse strategies could provide cumulative environmental benefits, particularly when integrated into broader waste management and sustainable agriculture systems.

These findings highlight the importance of methodological consistency in carbon accounting. The use of Tier-1 IPCC emission factors, generalized allometric equations, and default parameters introduces uncertainty into the estimation (Hanarisanty & Pratama, 2022; Nihayah et al., 2021). Livestock emissions and fertilizer-related N_2O fluxes represent continuous annual emissions (flow), whereas carbon stored in avocado biomass represents accumulated stock over multiple years. Similarly, avoided emissions from plastic reuse constitute one-time offsets rather than recurring annual reductions. To address this inconsistency, the results can be interpreted from two complementary perspectives. From a static carbon balance perspective, the integrated CSR initiatives demonstrate a substantial overall mitigation potential when all components are combined. However, from a dynamic annual perspective, the actual recurring mitigation effect is likely lower, as only a subset of interventions contributes to yearly emission reductions. Therefore, the reported estimation should be understood as an indicative upper-bound estimate rather than a strictly annual mitigation value. As emphasized in recent literature, emission estimates are highly sensitive to system boundaries, emission factors, and methodological assumptions, which may influence the robustness of CO_2 eq calculations (Schulte et al., 2024). Furthermore, studies have shown that default emission factors may overestimate actual emissions under certain managed agricultural

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conditions (Wu et al., 2024), reinforcing the need for cautious interpretation.

From a systems perspective, livestock activities remain the primary emission hotspot within the CSR framework, indicating that targeted mitigation strategies should prioritize improvements in manure management. Transitioning from open or semi-anaerobic storage systems to aerobic composting or biogas technologies could significantly reduce CH_4 emissions while simultaneously generating renewable energy and improving nutrient recycling (Hidayati et al., 2020; Maulana et al., 2025). At the same time, agroforestry expansion, optimized fertilizer management, and circular waste reuse represent complementary pathways that enhance carbon sequestration, reduce emissions, and support resource efficiency.

Beyond environmental impacts, these integrated interventions also generate socio-economic benefits, including improved household income, enhanced food security, and reduced dependence on external agricultural inputs (Ardana & Kalsum, 2023). Nevertheless, the long-term effectiveness of such systems depends on consistent management, technical capacity, and institutional support. Based on the results of this study, several improvements are recommended: (1) standardizing carbon accounting into annualized fluxes to resolve stock–flow inconsistencies, (2) implementing site-specific GHG measurements to reduce uncertainty associated with Tier-1 approaches, (3) applying life cycle assessment (LCA) to capture the full impact of waste management strategies, and (4) conducting scenario-based modeling to evaluate the scalability of CSR interventions.

Overall, the findings demonstrate that the four CSR projects represent a promising integrated approach to climate change mitigation at the community level. By combining emission reduction, carbon sequestration, and circular resource management, the program illustrates how agricultural systems can transition toward more sustainable and climate-resilient models. However, achieving reliable and scalable mitigation outcomes requires improved methodological rigor, temporal consistency in carbon accounting, and long-term monitoring frameworks.

4. Limitations and Future Directions

Technical on-field factors limited this study. These include the limited number of samples (such as found in organic fertilizer trials and avocado trees), the absence of actual on-field GHG emission measurements, and the temporal-spatial boundary of data collection. The uncertainty of currently available methods also limited this study. These include the use of less compatible IPCC Tier-1 emission factors for the studied area as well as the limitation in the allometric equation for specific climate, soil, and avocado varieties. Therefore, there is an urgent need to address this limitation in future research concerning carbon balance, especially in the tropics.

5. Conclusion

This study evaluated the carbon storage and emission resulting from various CSR-based initiatives by assessing the emission sources and mitigation components of each project using the IPCC Tier-1 approach. The findings are presented as predictive and descriptive values to indicate the potential carbon sequestered in solid forms (plant biomass and HDPE drums) and carbon emitted to the atmosphere (cattle and organic fertilizer GHGs). At the time of this study, the estimated CO_2 stored due to avocado tree plantation and reuse of HDPE drums were respectively 69.125 and 10.725 tons. The cattle farming advocated by the CSR program was estimated to emit around 0.676 tons of CH_4 per year and 3.68 kg of N_2O per year. This was equal to 19.910 tons of CO_2 per year. The use of organic fertilizer produced by the company was estimated to emit around 0.0005 kg of N_2O per hectare (0.13 kg of CO_2 eq per hectare). This was lower compared to the potential emission of prevalent practices in the nearby paddy field, which was

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approximately 0.2812 kg of N_2O per hectare (74.51 kg of CO_2 eq per hectare). Overall, the findings demonstrate that the four CSR interventions might deliver a promising carbon mitigation due to the potential storage in solid forms, but further methodological refinement shall be implemented for more comprehensive and consistent assessment. Future research should focus on improving methodological consistency by standardizing carbon accounting into comparable temporal units, incorporating site-specific emission measurements, and applying life cycle assessment approaches. In addition, scenario-based analysis is needed to evaluate the long-term scalability and stability of mitigation outcomes, ensuring that CSR-based sustainability initiatives can be reliably quantified and effectively integrated into broader climate mitigation strategies.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the authors did not use any AI tools.

Authorship Contribution Statement

Abner Darmawan Sigar: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft; Nurul Ardian Fitriyani: Conceptualization, Validation, Writing – review & editing; Irwan Hidayat: Consultation, Supervision, Support.; Dina Banjarnahor: Validation, Formal analysis, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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