





Carbon footprint assessment of hydroponic sweet Hami melon cultivation using life cycle assessment

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ABSTRACT

The increasing demand for sustainable agricultural practices has led to growing interest in evaluating the environmental impacts of hydroponic systems. This study assesses and compares the carbon footprint of hydroponic Sweet Hami melon cultivation in two commercial greenhouse systems in the Special Region of Yogyakarta, Indonesia, using a life cycle assessment (LCA) approach following ISO 14067 standards. The system boundary was defined as cradle-to-farm gate, and the functional unit was 1 kg of fresh melon. Primary data were collected from two greenhouse farms, D'Pands Agrofarm and Wanadelima Orchard, covering one full cultivation cycle (October 2024 to January 2025). Life cycle inventory (LCI) data included electricity, water, fertilizers, and material inputs, while background processes were obtained from the Agribalyse 3.0 database. The impact assessment was conducted using the IPCC GWP100 method. Uncertainty analysis was performed using Monte Carlo simulation with 1000 iterations. The results show that D'Pands Agrofarm has a higher carbon footprint (1.619 kg CO₂-eq per kg of melon) compared to Wanadelima Orchard (1.238 kg CO₂-eq per kg of melon). Electricity consumption was identified as the dominant contributor, followed by fertilizer inputs. Contribution analysis indicates that differences in resource use, particularly energy demand and water treatment efficiency, significantly influence total emissions. Monte Carlo simulation supports the reliability of the results and confirms a clear distinction between the two systems. This study provides empirical evidence from tropical hydroponic greenhouse systems and demonstrates that variations in structural and operational characteristics significantly influence carbon footprint outcomes. The findings suggest that improving energy efficiency and optimizing resource management are key strategies for reducing environmental impacts in hydroponic cultivation systems.

Keywords: agricultural environment, carbon footprint, green productivity, life cycle assessment, sustainability supply chain.

INTRODUCTION

Melon (*Cucumis melo* L.) is a fruit plant belonging to the Cucurbitaceae family. Melons originate from the Mediterranean region, which borders West Asia with Europe and Africa. They can spread widely throughout the Middle East into Europe, including Denmark, the Netherlands, and Germany. From Europe, melons were brought to the Americas in the 14th century and were widely cultivated in Colorado, California, and Texas. Eventually, melons spread throughout the world, particularly in tropical and subtropical regions,

including Japan, China, Taiwan, Korea, Australia, and even develop in Indonesia (Supriyanta et al., 2022). Melon is a high-value horticultural crop in Indonesia, favoured for its sweetness and nutritional value, including high water content (>90%), vitamins (A, C, D, E, K) and natural sugars (Narayanan et al., 2024). In Indonesia, there has been a growing demand for high-quality melon fruit characterized by high sugar content, firm texture, long shelf life, vibrant peel and flesh color, and a round shape (Setiawan et al., 2025).

Hydroponic cultivation is gaining popularity among melon farmers in Indonesia. Hydroponics

is a method of plant cultivation that uses water or other growing media instead of soil such as cocopeat, rice husk charcoal, rockwall, or gravel (Radinka et al., 2023). Hydroponic farming requires special care in controlling water level and acidity of nutrient solution. To achieve good crop yields until harvest, farmers must maintain these levels through daily monitoring (Supriyanta et al., 2022). Hydroponic cultivation is generally carried out in greenhouses. Greenhouse cultivation is considered to optimize resource utilization and microclimate conditions, allowing for monitoring of melon quality. Greenhouses allowed for a reduction in resource use, such as water and chemical inputs, by optimizing microclimate conditions suitable for plant growth (Abdurahman et al., 2022). Controllable microclimate conditions include sunlight, air temperature, air humidity, nutrient supply, wind speed, and carbon dioxide concentration (Ernawati et al., 2021). The energy consumption to control the microclimate conditions can increase greenhouse gas (GHG) emissions if not managed properly.

Life cycle assessment (LCA) can be used to measure environmental impact from the product life cycle. The term “carbon footprint” is used to measure GHG emissions environmental impact produced by particular product or service over its lifetime expressed in CO₂-eq which consists of CO₂, CH₄ and N₂O emissions (Chłopek et al., 2021). Carbon footprint is calculated by measuring the entire product life cycle from start to finish (Muthu, 2016). Previous studies have reported carbon footprint values for melon cultivation in conventional systems, such as 0.882 kg CO₂-eq in Costa Rica (Suppen-Reynaga et al., 2024) and 0.751 kg CO₂-eq in Brazil (Barros et al., 2019) with cultivation stages identified as the main contributors to emissions.

Despite these advancements, limited attention has been given to hydroponic greenhouse systems, particularly under tropical conditions. Moreover, existing LCA studies often rely on single-case analyses or generalized assumptions, which may not adequately capture variations in environmental performance arising from differences in greenhouse structure and operational practices. In particular, the influence of structural characteristics and resource management strategies on carbon emissions remains insufficiently explored.

Therefore, this study aims to assess the carbon footprint of hydroponically grown Sweet Hami melon using a cradle-to-gate LCA approach based

on empirical data collected from two commercial greenhouse farms with differing structural and operational characteristics in a tropical region. In addition to quantifying carbon emissions, this study investigates how variations in greenhouse configuration and resource use contribute to differences in environmental performance, thereby identifying key emission drivers in controlled-environment agriculture systems. This study corresponds with the aims of sustainable development goals (SDGs) 12 (Shaikh et al., 2024) and SDG 13 (Chaurasiya et al., 2025) by promoting low-emission agriculture systems and sustainable production practices in the horticultural sector.

MATERIAL AND METHODS

Study area and system description

The research was conducted at two commercial hydroponic greenhouse farms located in the Special Region of Yogyakarta, Indonesia: D’Pands Agrofarm (Bantul Regency) and Wanadelima Orchard (Kulonprogo Regency). Both sites cultivate Sweet Hami melon using hydroponic systems under controlled greenhouse conditions. The study period covered one full cultivation cycle from October 2024 to January 2025, representing typical operational conditions during the rainy season in the region, which may influence water use and environmental control requirements in greenhouse systems. Figure 1 shows the greenhouse system at D’Pands Agrofarm, while Figure 2 shows the greenhouse system at Wanadelima Orchard.

Despite cultivating the same crop, the two greenhouses differ in structural and operational characteristics, including greenhouse size, altitude, number of exhaust fans, planting density, and total number of plants. These differences may influence environmental conditions such as temperature, humidity, and airflow, thereby affecting energy use and GHG emissions (Kurniawan et al., 2020). Table 1 shows the structural and operational differences between D’Pands Agrofarm and Wanadelima Orchard.

Goal and scope definition

A comparative LCA was conducted following ISO 14067 standards to evaluate the carbon footprint, which include four main phases:



Figure 1. D'Pands Agrofarm



Figure 2. Wanadelima Orchard

(1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation for carbon footprint.

The hydroponic cultivation consists of five main stages: (1) seeding, (2) plant media preparation, (3) plant care, (4) harvesting, and (5) consumption. The seeding stage includes seed incubation, nursery activities, and seedling monitoring. The plant media preparation stage involves cocopeat sterilization, desalination, filling into polybags, washing, and arrangement within the greenhouse. The plant care stage includes transplanting, nutrient application, pruning, pollination, fruit selection, and general crop maintenance. The harvesting stage involves harvesting and greenhouse cleaning. The consumption stage

involves consumption and disposal. Figure 3 shows cradle-to-farm gate system boundary.

The system boundary was defined as cradle-to-farm gate, encompassing all processes from seeding stage to harvesting stage. Processes included within the system boundary comprise the production and use of agricultural inputs, such as seeds, peatmoss, cocopeat, fertilizers, and pesticides, water consumption, electrical energy use, fuel use, and on-site greenhouse cultivation activities. Outputs include the main product (sweet Hami melon) and by-products such as plant residues, used growing media, polybag waste, and wastewater.

Processes excluded from the system boundary include consumption stages. Infrastructure construction and capital goods (greenhouse structures) were also excluded due to data limitations

Table 1. Structural and operational differences between D’Pands Agrofarm and Wanadelima Orchard

Parameter	D’Pands Agrofarm	Wanadelima Orchard
Greenhouse length	27.9 m	24.5 m
Greenhouse width	14.3 m	9.5 m
Greenhouse height	6 m	6 m
Total area	398.97 m ²	242.75 m ²
Altitude	30 m asl	78 m asl
Number of exhaust fans	6 units	3 units
Number of planting lines	10 lines	7 lines
Total number of plants	1,200 plants	700 plants
Planting density	3.01 plants/m ²	2.88 plants/m ²

and their relatively minor contribution over the system lifetime.

Functional unit

The functional unit is defined as 1 kg of harvested sweet Hami melon at the farm gate. All input and output data collected during one cultivation cycle were normalized to this functional unit to ensure comparability between the two greenhouse systems.

Life cycle inventory (LCI)

The LCI was developed based on mass and energy flows within the defined system boundary. Inventory data were categorized into four main groups: (1) raw materials, (2) supporting materials (liquid and solid), (3) energy uses, and (4) outputs (main product and by-products).

Primary data were collected through direct measurement, operational records, and field observations at both greenhouse sites. Secondary data, including emission factors of material and energy, were obtained from the Agribalyse 3.0 database.

The inventory includes detailed inputs such as water consumption, fertilizer application, electricity use, fuel consumption, and supporting materials used throughout the cultivation stages. Outputs include the harvested melon and various waste streams generated during the process. The complete inventory data for both study sites are presented in Table 2 and Table 3.

Water use was recorded across all cultivation stages. In D’Pands Agrofarm, total water consumption reached 258069 L per cultivation cycle, consisting of 577 L for seeding, 7260 L for plant media preparation, and 250232 L for plant care and harvesting. In contrast, Wanadelima Orchard used significantly less water, with a total of 118899.8 L per cycle, including 384.8 L for seeding, 6534 L for plant media preparation, and 111981 L for plant care and harvesting.

The high water consumption during the plant care stage was mainly influenced by the efficiency of the reverse osmosis (RO) system used for water treatment. The RO efficiency in D’Pands Agrofarm was approximately 25%, whereas Wanadelima Orchard achieved a higher efficiency of 33.33%. Lower RO efficiency resulted in higher water input requirements due to increased reject water generation.

All input water was sourced from groundwater wells at each greenhouse site. Treated water was used for irrigation after mixing with nutrient solutions according to standard operating

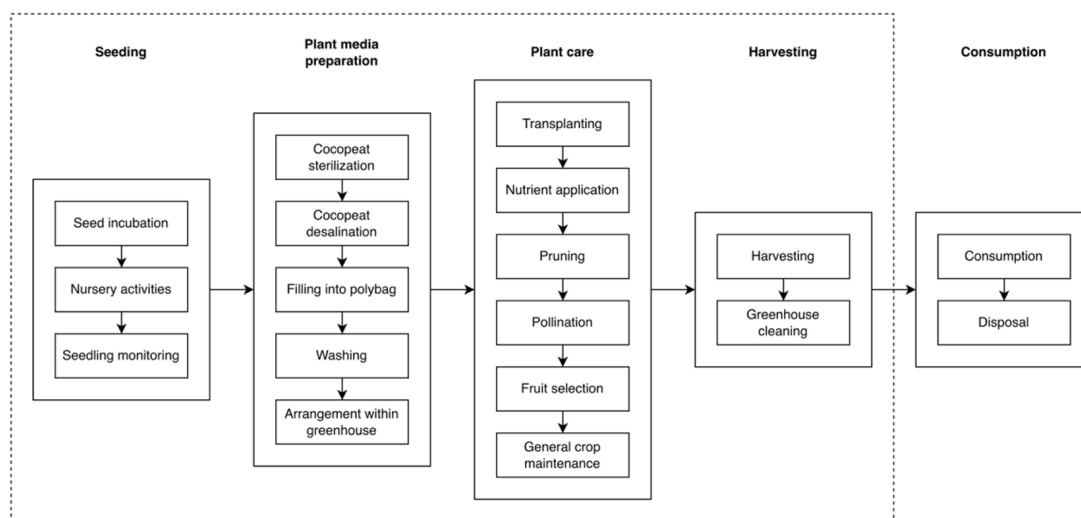


Figure 3. System boundary

Table 2. D’Pands Agrofarm’s life cycle inventory

Input/Output	Total/planting period	Unit	Functional unit	Unit	%	Majority process
Sweet Hami melon	1449.4887	kg	1	kg		
Input: main raw material						
Melon seed	0.0630	kg	0.00004	kg	0.00418%	Seeding
Peatmoss	88.8750	kg	0.06131	kg	5.90308%	Seeding
Cocopeat	1416.6326	kg	0.97733	kg	94.09274%	Plant media preparation
Input: liquid supporting raw material						
Water	258069.0000	L	178.04141	L	99.99953%	Plant care
H ₂ O ₂	0.0240	L	0.00002	L	0.00001%	Plant media preparation
Pesticide	1.1780	L	0.00081	L	0.00046%	Plant care
Input: solid supporting raw material						
Onion	0.0140	kg	0.00001	kg	0.00581%	Seeding
Polybag	13.2000	kg	0.00911	kg	5.47931%	Plant care
N fertilizer	45.2414	kg	0.03121	kg	18.77968%	Plant care
CaO fertilizer	46.0875	kg	0.03180	kg	19.13089%	Plant care
K ₂ O fertilizer	89.0713	kg	0.06145	kg	36.97343%	Plant care
S fertilizer	13.3823	kg	0.00923	kg	5.55500%	Plant care
P ₂ O ₅ fertilizer	22.3719	kg	0.01543	kg	9.28658%	Plant care
MgO fertilizer	11.5377	kg	0.00796	kg	4.78929%	Plant care
Input: energy						
Electrical energy	2675.0182	kWh	1.84549	kWh	100%	Plant care
Input: fuel						
Gasoline	17.2000	L	0.01187	L	100%	Plant care
Output: main/side product						
Sweet Hami melon	1449.4887	kg	1.00000	kg		
Peatmoss waste	87.6552	kg	0.06047	kg		
Seedling waste	18.0000	item	0.04139	item		
Cocopeat waste	1416.6326	kg	0.97733	kg		
Plant waste	326.4000	kg	0.22518	kg		
Polybag waste	13.2000	kg	0.00911	kg		
Wastewater	194935.0000	L	5.00935	L		

procedures, while reject water was discharged as wastewater. Table 4 shows water consumption across cultivation stages.

Electricity consumption was calculated based on the operation of all equipment used during the cultivation process, including water pumps, reverse osmosis systems, exhaust fans, and sprayers. In D’Pands Agrofarm, total electricity consumption reached 2675.02 kWh per cultivation cycle, consisting of 0.01 kWh for seeding, 1.21 kWh for media preparation, and 2673.80 kWh for plant care and harvesting. In Wanadelima Orchard, total electricity consumption was lower at 1508.15 kWh per cycle, including 0.01 kWh for seeding, 1.09 kWh for media preparation, and 1507.05 kWh for plant care.

The majority of electricity consumption occurred during the plant stage, reflecting the continuous operation of irrigation systems, water treatment, and environmental control equipment. Table 5 shows electricity consumption across cultivation stages.

Fertilizer inputs were applied through fertigation using stock solutions A and B. The fertilizers used included calcium nitrate, potassium nitrate, micro-Fe, potassium sulfate, Vitaflex, mono potassium phosphate, and magnesium sulfate. The total fertilizer input was 453.50 kg per cultivation cycle for D’Pands Agrofarm and 300.00 kg for Wanadelima Orchard. The application rates were calculated based on the nutrient composition specified on product labels and

Table 3. Wanadelima Orchard’s life cycle inventory

Input/Output	Total/planting period	Unit	Functional unit	Unit	%	Majority process
Sweet Hami melon	1127.7360	kg	1	kg		
Input: main raw material						
Melon seed	0.0368	kg	0.00003	kg	0.00423%	Seeding
Peatmoss	51.3280	kg	0.04551	kg	5.90293%	Seeding
Cocopeat	818.1700	kg	0.72550	kg	94.09258%	Plant media preparation
Input: liquid supporting raw material						
Water	118899.8000	L	39.23418	L	99.99948%	Plant care
H ₂ O ₂	0.0216	L	0.00002	L	0.00001%	Plant media preparation
Pesticide	0.5940	L	0.00053	L	0.00050%	Plant care
Input: solid supporting raw material						
Onion	0.0070	kg	0.00001	kg	0.00446%	Seeding
Polybag	7.7000	kg	0.00683	kg	4.90128%	Plant care
N fertilizer	29.4671	kg	0.02613	kg	18.77968%	Plant care
CaO fertilizer	29.7145	kg	0.02635	kg	18.91416%	Plant care
K ₂ O fertilizer	58.9249	kg	0.05225	kg	37.50748%	Plant care
S fertilizer	8.8527	kg	0.00785	kg	5.63501%	Plant care
P ₂ O ₅ fertilizer	14.8031	kg	0.01313	kg	9.42264%	Plant care
MgO fertilizer	7.6324	kg	0.00677	kg	4.85827%	Plant care
Input: energy						
Electrical energy	1508.1537	kWh	0.70144	kWh	100%	Plant care
Input: fuel						
Gasoline	10.8000	L	0.00958	L	100%	Plant care
Output: main/side product						
Sweet Hami melon	1127.7360	kg	1.00000	kg		
Peatmoss waste	50.6235	kg	0.04489	kg		
Seedling waste	15.0000	item	0.03192	item		
Cocopeat waste	826.3690	kg	0.73277	kg		
Plant waste	136.0000	kg	0.12060	kg		
Polybag waste	7.7000	kg	0.00693	kg		
Wastewater	6534.8000	L	5.79462	L		

standard operating procedures. Table 6 shows fertilizer input by type.

Life cycle impact assessment (LCIA)

The LCIA was conducted to quantify the environmental impact of hydroponic melon production in terms of carbon footprint. The assessment focused on the global warming potential (GWP) over a 100-year time horizon (GWP100), expressed in kg CO₂-eq. The LCIA was performed using openLCA 2.1.0 software, with background data obtained from the Agribalyse 3.0 database. The IPCC GWP100 method was applied to calculate greenhouse gas emissions associated with all

input flows included in the system boundary. The result of the LCIA were calculated based on the LCI data and normalized to the functional unit of 1 kg of melon.

Sensitivity and uncertainty analysis

Uncertainty analysis was performed using Monte Carlo simulation with 1000 iterations to evaluate the variability in carbon footprint results between the two greenhouse systems. The simulation was conducted using openLCA software.

Input parameters were assigned probability distributions based on data type and availability. Measured primary data, such as electricity

Table 4. Water consumption across cultivation stages

Stage	D’Pands Agrofarm (L)	Wanadelima Orchard (L)
Seeding	577.000	384.800
Plant media preparation	7260.000	6534.000
Plant care & harvesting	250232.000	111981.000
Total	258069.000	118899.800

Table 5. Electricity consumption across cultivation stages

Stage	D’Pands Agrofarm (kWh)	Wanadelima Orchard
Seeding	0.0120	0.0120
Plant media preparation	1.2100	1.0890
Plant care & harvesting	2673.7962	1507.0527
Total	2675.0182	1508.1537

consumption, water use, and material inputs) were modeled using normal distributions. Secondary data derived from the Agribalyse 3.0 database were treated using the default uncertainty distributions provided within the database. For parameters with limited data availability, assumptions were applied based on field observations and standard practices reported in the literature. The result of the uncertainty analysis were expressed as 95% confidence intervals, providing an estimate of the variability and reliability of the calculated carbon footprint values.

RESULTS AND DISCUSSION

Carbon footprint result

The carbon footprint of hydroponically grown Sweet Hami melon was calculated based on the LCI data presented in Table 2 and Table 3. The results

show that the total carbon footprint per 1 kg of melon was 1.619 kg CO₂-eq for D’Pands Agrofarm and 1.238 kg CO₂-eq for Wanadelima Orchard.

The difference in carbon footprint between the two greenhouse systems indicates that variations in structural and operational characteristics significantly influence GHG emissions. Factors such as electricity consumption, water use, and material inputs contribute to these differences.

Contribution analysis and hotspot identification

The contribution analysis was conducted to identify the main sources of GHG emissions in hydroponic melon cultivation. The contribution of major input categories to the total carbon footprint is presented in Figure 4.

The result show that electricity consumption is the dominant contributor to total emissions in both greenhouse systems. In D’Pands Agrofarm, electricity-related processes contributed approximately 0.692 kg CO₂-eq per kg of melon, while in Wanadelima Orchard the contribution was lower at approximately 0.502 kg CO₂-eq. This reflects the higher electricity demand in D’Pands Agrofarm, particularly for water treatment, irrigation, and environmental control systems.

Fertilizer inputs, calcium nitrate, were identified as the second largest contributor, contributing around 0.369 kg CO₂-eq in D’Pands Agrofarm and 0.305 kg CO₂-eq in Wanadelima Orchard. This is mainly due to the energy-intensive production of nitrogen-based fertilizers.

Other contributing factors include transport processes, plastic materials (polyethylene), and fuel-based electricity and fertilizer inputs. It should be noted that transport-related emissions presented in this study originate from background processes in the life cycle inventory database

Table 6. Fertilizer input by type

Fertilizer type	D’Pands Agrofarm (kg)	Wanadelima Orchard (kg)
Calcium nitrate	177.2596	114.2865
Potassium nitrate	136.6628	90.4054
Micro-Fe	0.5107	0.3378
Potassium sulfate	22.2664	14.7297
Vitaflex	7.9669	5.2703
Mono potassium phosphate	43.0230	27.5676
Magnesium sulfate	72.1106	47.7027
Total	453.5000	300.0000

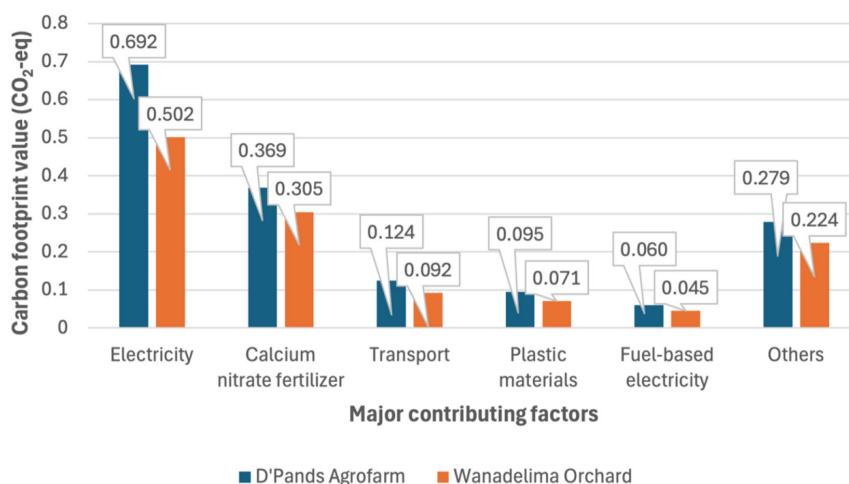


Figure 4. Major contributing factors

(Agribalyse 3.0), representing upstream transportation associated with the production and supply of inputs, rather than on-site transportation within the greenhouse systems.

Overall, the result indicate that electricity use and fertilizer inputs are the primary emission hotspot in hydroponic greenhouse systems. Therefore, improving energy efficiency and optimizing fertilizer management are critical strategies for reducing the carbon footprint of hydroponic melon cultivation.

Comparison between greenhouse systems

The comparison between D'Pands Agrofarm and Wanadelima Orchard reveals significant differences in carbon footprint, despite both systems cultivating the same crop under controlled greenhouse conditions. These differences are primarily driven by variations in resource consumption. D'Pands Agrofarm showed substantially higher electricity use (2675.02 kWh per cycle) compared to Wanadelima Orchard (1508.15 kWh per cycle). Similarly, water consumption in D'Pands Agrofarm (258069 L per cycle) was considerably higher than in Wanadelima Orchard (118899.8 L per cycle). Fertilizer inputs also differed, with total usage of 453.50 kg in D'Pands Agrofarm and 300.00 kg in Wanadelima Orchard.

The higher water consumption in D'Pands Agrofarm is closely related to the lower efficiency of its reverse osmosis systems, which increase the volume of raw water required to produce irrigation water. This leads to higher electricity demand for water treatment and distribution. Electricity is the dominant emission source, amplifying the

impact of increased resource use on total carbon footprint. Differences in greenhouse structure and operational practices, such as environmental control systems and input management, further contribute to variations in resource efficiency between the two systems.

These findings demonstrate that carbon footprint in hydroponic greenhouse systems is not solely determined by the type of crop or cultivation method, but is highly influenced by system-specific characteristics. Therefore, optimizing greenhouse design and operational efficiency is essential to reduce environmental impacts.

Uncertainty analysis result

Uncertainty analysis was performed using Monte Carlo simulation with 1000 iterations to evaluate the variability of carbon footprint result for both greenhouse systems. The distribution of simulation results in D'Pands Agrofarm is presented in Figure 5, while in Wanadelima Orchard is presented in Figure 6.

The results show that the mean carbon footprint obtained from the Monte Carlo simulation was lower than the deterministic results for both systems. For D'Pands Agrofarm, the mean value was 1.174 kg CO₂-eq per kg of melon, compared to the deterministic result of 1.619 kg CO₂-eq. Similarly, for Wanadelima Orchard, the Monte Carlo mean was 0.928 kg CO₂-eq, compared to 1.238 kg CO₂-eq from the deterministic calculation.

This difference indicates variability in input parameters. The deterministic approach uses fixed input values, whereas the probabilistic approach incorporates variability, providing a more

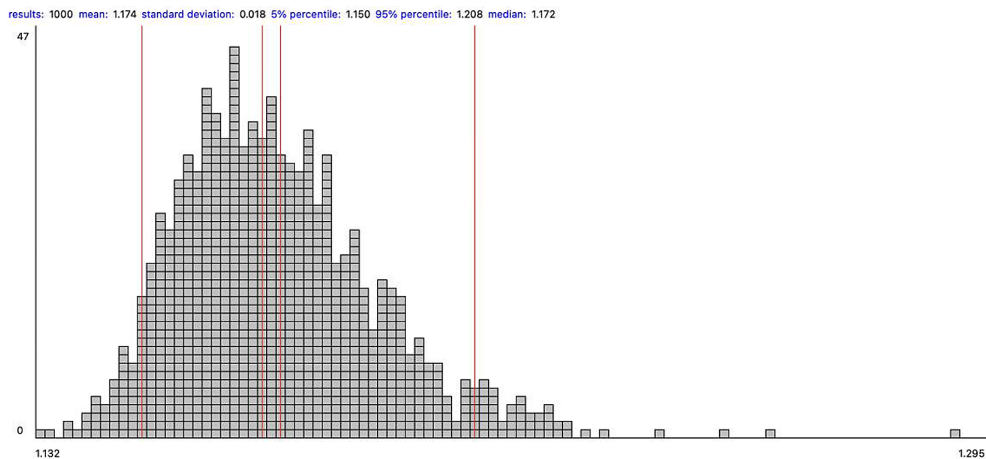


Figure 5. Monte Carlo simulation at D'Pands Agrofarm

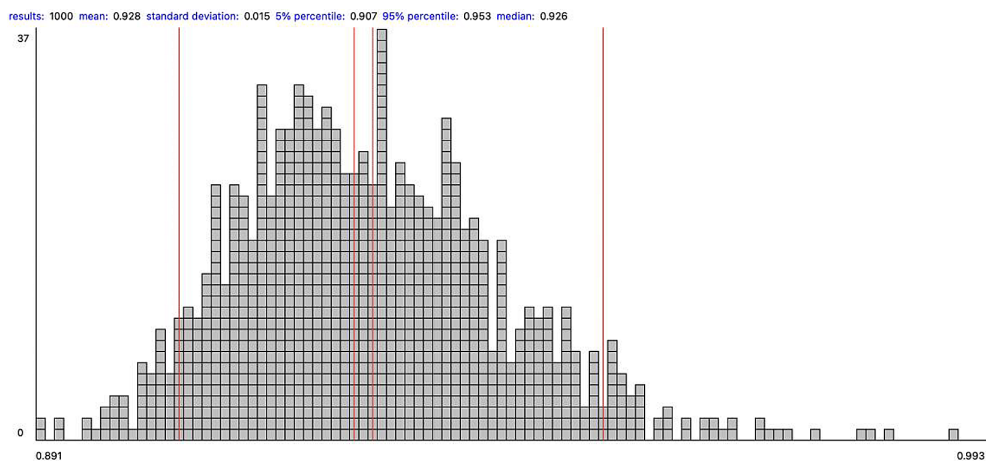


Figure 6. Monte Carlo simulation at Wanadelima Orchard

realistic representation of the result. The simulation results also show relatively narrow distributions, indicating low variability in the model outputs. Furthermore, the distributions of the two systems do not overlap, suggesting that the difference in carbon footprint between D'Pands Agrofarm and Wanadelima Orchard is statistically significant and not due to random variation. Overall, the uncertainty analysis confirms the robustness and reliability of the results and strengthens the validity of the comparative findings between the two greenhouse systems.

DISCUSSION

The result indicate that energy consumption is the dominant contributor to total carbon emission in hydroponic Sweet Hami melon cultivation. This highlights the critical role of energy use

in Controlled Environment Agriculture (CEA), where electricity is required to maintain controlled growing conditions (Ng et al., 2026). Previous studies have also emphasized the strong linkage between energy use and carbon emission in agricultural systems, particularly in energy-intensive processes such as irrigation and water supply (Qin et al., 2024).

Previous LCA studies on greenhouse melon production have identified different emission hotspot depending on system configuration. Supriyanto et al., (2025) reported that cultivation media such as cocopeat and rice husk charcoal were the main contributors to environmental impacts. In contrast, the present study identified electricity use as the dominant contributor. This difference suggests that variations in input composition and system design can significantly influence the distribution of environmental burdens in hydroponic cultivation systems.

In conventional melon cultivation systems, such as those reported in Costa Rica (Suppen-Reynaga et al., 2024) and Brazil (Barros et al., 2019), cultivation stages have been identified as the primary contributors to emissions. These stages typically involve field operations and input the characteristic of open-field agriculture. In contrast, hydroponic greenhouse systems rely more heavily on continuous energy input to maintain controlled growing conditions, which explains the dominance of energy-related emissions observed in this study. This comparison highlight that emission hotspot are highly dependent on the cultivation system.

CONCLUSIONS

The result showed that energy consumption, particularly electricity use, is the dominant contributor to total carbon emission in hydroponic Sweet Hami melon cultivation. This finding is consistent with the general understanding of energy use as a critical factor in controlled-environment agriculture.

Furthermore, this study demonstrated that variations in operational parameters, such as energy use and water treatment efficiency, significantly influence emission levels, even with similar cultivation systems. This finding substantiates the sensitivity of carbon footprint outcomes to system-specific configurations. Importantly, this study provides empirical evidence from a tropical hydroponic greenhouse system, contributing to the limited body of knowledge on carbon footprint assessment in such contexts. These findings reinforce the importance of system design in determining emission hotspot in agricultural production systems.

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