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Life Cycle Assessment of Melon (*Cucumis Melo* L) Production in Tropical Greenhouse, Indonesia

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ABSTRACT

Recently, melon cultivation in controlled environments such as greenhouse are popular to improve productivity and quality. However, environmentally friendly productions are necessary for preserving ecosystems and reducing environmental impact. This research aimed to evaluate the environmental impact using a life cycle assessment approach. Research was conducted using a life cycle assessment with six categories evaluated such as Global Warming Potential (GWP), Stratospheric Ozone Depletion (SOD), Terrestrial Acidification (TAC), Freshwater Eutrophication (FEU), Terrestrial Ecotoxicity (TEC), and Human Carcinogenic Toxicity (HCT) for kilograms of fresh melon. The result of GWP was 2.137 kg CO_2 eq; SOD at 0.39(10^{-5}) kg CFC-11 eq; TAC at 3.93(10^{-3}) kg SO_2 eq; FEU at 0.44(10^{-3}) kg P eq; TEC at 4.62 kg 1.4-DCB eq; and HCT at 0.13 kg 1.4-DCB eq. Furthermore, the main contribution of environmental impact was cultivating media such as cocopeat and rice husk charcoal. The result of this research is important to improve greenhouse-based melon production.

1. INTRODUCTION

Food and Agriculture Organization (FAO) reports that by 2050, the global population will reach 10 billion, leading to a 50% increase in food demand, especially in developing countries (Usman *et al*., 2020). Organic farming is a widely adopted system based on sustainable agriculture. Meanwhile, conventional farming is a system where synthetic fertilizers, pesticides, and herbicides are commonly used. Using these substances can lead to the loss of soil organic carbon, environmental pollution, and climate change (Allam *et al*., 2022).

The increasing demand for food in Indonesia indicates the importance of intensification in the agricultural system. Melon plants (*Cucumis melo* L.) have high economic value and good nutritional content (Istiningdyah *et al*., 2013). In 2022, melon production in Indonesia decreased by 8%, from 129,000 fruits to 118,000 fruits. Melon plants are sensitive to climate change and susceptible to diseases. Cultivating melons in greenhouses at the Agribusiness Technology Park (ATP) is one of the methods to increase the production of quality melons. Greenhouse production technology has proven its efficiency in global vegetable supply, with more than 27 countries using it to sustain vegetable production (Aznar-Sánchez *et al*., 2020). Life Cycle Assessment (LCA) is a comprehensive method for measuring the environmental impact of a process, product, or service.

However, one of the main challenges in LCA is data acquisition. Indonesian Life Cycle Inventory (IDN-LCI) database has been developed to facilitate an inventory system (Siregar *et al*., 2020a). However, there are still limitations due to the need for dataset input to the database. Research on LCA analysis for melon production in greenhouse in

Indonesia are important to conduct to enhance the content of Indonesian LCI Databases. There are several related research conducted in several countries, such as tomatoes in Iran (Khoshnevisan *et al*., 2014), agricultural products in Italia and other countries for several products (Cellura *et al*., 2012; Kalboussi *et al*., 2022). Various agricultural activities such as fertilizer, pesticide use, and machine operation require energy and contribute to greenhouse gas emissions (Charles *et al*., 2006). Greenhouse gases have effects, such as chemical changes in the atmosphere, leading to climate change. Research by Frankowska *et al*. (2019) discusses UK fruit cultivation emissions using the LCA approach. One is melon fruit, with emissions of 0.91 kg CO_2 eq per kilogram using the ReCiPe 2008 method.

In Indonesia, LCA also applied for several products such as coffee (Rahmah *et al*., 2022; Cammarata *et al*., 2023), oil palm (Siregar *et al*., 2020b), and other plantation products. However, there still needs to be more data on life cycle assessment for melon cultivation using greenhouses in Indonesia. There are several research conducted on melon production in smart greenhouses to improve the quality data of life cycle inventory (Erniati *et al*., 2023, 2024; Lourenço *et al*., 2024). This gap is evident as limited studies have been conducted to quantify the emissions and overall environmental footprint of melon production in Indonesia using a greenhouse. Consequently, evaluating the environmental impact of melon cultivation in greenhouses using various methods is crucial to providing insights into the most sustainable practices. Alternative scenarios that consider environmental factors are necessary to achieve sustainable cultivation outcomes. The objective of the study was to evaluate the environmental impact of the scope of gate-to-gate melon cultivation in greenhouses using hydroponic systems with drip irrigations.

2. MATERIALS AND METHODS

2.1. Research Location

Data collection and research were conducted in Agribusiness and Technology Park (ATP) in Cikarawang, Bogor Regency, from August to December 2023. Data was collected from melon production in a greenhouse with dimensions 8 x 24 meters and 600 individual plants.

2.2. Goal and Scope Definition

This study focuses on melon cultivation in greenhouses consisting of several activities such as media preparation, cultivation, and customer distribution (Figure 1). Life cycle inventory data was collected from the Agribusiness and

Figure 1. Melon condition at 32 days after planting in Agribusiness and Technology Park IPB University greenhouse

Technology Park IPB University greenhouse using gate-to-gate boundaries as depicted in Figure 2. This scope was chosen because melon cultivation is a relatively straightforward process. This study does not include production processes such as melon seed preparation, cocopeat processing, and rice husk charcoal processing as they are carried out outside the ATP environment. There is no product life cycle process in melon cultivation because melon fruits are distributed directly to consumers.

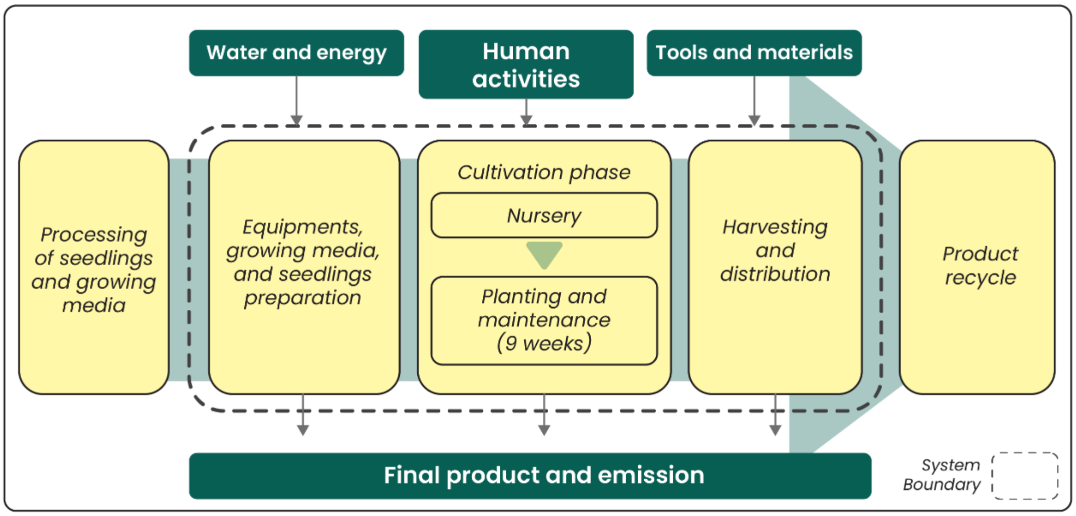

Figure 2. System boundary of melon production in greenhouse

2.3. Life Cycle Inventory

In this study, the inventory analysis stage identifies and collects inventory data consisting of inputs and outputs in the process flow of melon cultivation (Figure 3). Inventory data collection is conducted using two methods: primary data obtained through direct data collection in melon greenhouses and interviews with staff and workers at ATP, Cikarawang, Dramaga, West Java. Meanwhile, secondary data is obtained from literature studies and previous cultivation data. Data was collected by the objectives and boundaries determined in the previous stages. Based on the flowchart above in Figure 3, data collection starts from the cultivation preparation to the product sales stage. Inventory data quantification can be seen in Table 1.

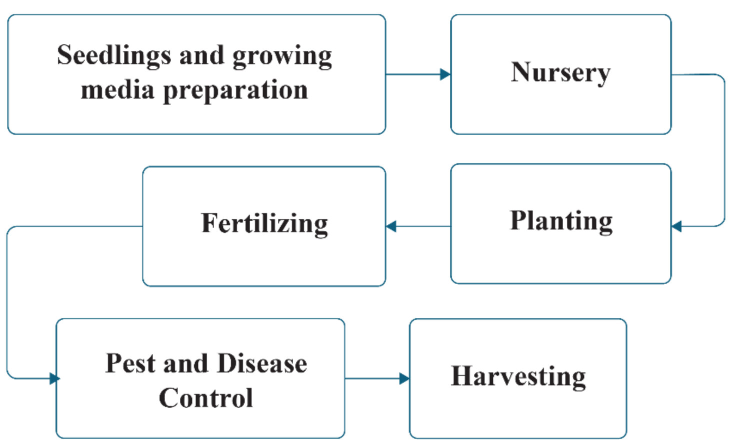

Figure 3. The Melon cultivation process consists of seedling, growing media preparation, nursery, planting, fertilizing, pest control, disease control, and harvesting.

Table 1. Inventory quantification process

Inputs and outputs	**Unit**
1. Preparation of seeds and growing media	
Water	L
Cocopeat	kilogram
Waste treatment	
Wastewater from cocopeat soaking	L
2. Nursery	
Melon seeds	buah
3. Planting	
Rice husk charcoals	kilogram
Polyethylene bag	kilogram
4. Fertilization	
Calcium nitrate	gram
Potassium nitrate	gram
FeEDTA	gram
FeEDDHA	gram
Potassium sulfate	gram
MKP	gram
Magnesium sulfate	gram
ZA	gram
H3BO3	gram
Zinc EDTA	gram
Mangan EDTA	gram
Cuprum EDTA	gram
Na Molibdat	gram
Water	liter
Water pump electricity	kWh
5. Pest and diesease management	
Water	liter
Insecticide	ml
Fungicide	gram
6. Harvesting	
Melon fruit	kilogram
Waste	
Biomass waste	kilogram

2.4. Life Cycle Impact Assessment

The environmental impact of melon cultivation was assessed using SimaPro 9.5.0.2 software with the ReCiPe 2016 characterization method. This method was chosen because it is the most used LCA analysis method and provides universal characteristic factors that can be applied in Indonesia. A study by Frankowska *et al*. (2019b) on the impact assessment of various fruits in the UK used the ReCiPe 2008 method for calculations. Based on PROPER regulations (Kementrian LHK RI, 2019) regarding mandatory environmental impact assessment, this study will focus on six impact categories out of the 18 available in ReCiPe 2016 midpoint (H) which are global warming potential (GWP), stratospheric ozone depletion (SOD), freshwater eutrophication (FEU), terrestrial acidification (TAC), terrestrial ecotoxicity (TEC), dan human carcinogenic toxicity (HCT).

2.5. Interpretation: The Final Stage of LCA

Life Cycle Assessment (LCA) is a comprehensive framework for evaluating the environmental impacts of products, processes, or services throughout their life cycle. Interpretation, the final stage of LCA, involves analyzing the results obtained from the inventory analysis and impact assessment phases to identify opportunities for reducing environmental impacts. Interpretation is a crucial step in LCA as it transforms the quantitative data from inventory analysis and impact assessment into meaningful insights that can guide decision-making and inform sustainability strategies. By identifying critical processes, exploring improvement scenarios, and drawing conclusions, LCA interpretation helps organizations reduce their environmental footprint and contribute to a more sustainable future.

3. RESULTS AND DISCUSSION

3.1. Inventory Analysis

Inventory analysis in melon cultivation consists of data sources, literature, and inventory. It will cover all quantification of input and output data. This research obtained 16 datasets, 14 input and 2 output datasets, from the SimaPro database. This data will be used to compile the inventory classification for the melon cultivation stage. The most used databases are the Ecoinvent 3 database, with nine datasets, and the Agri-footprint database, with seven datasets. Tables 2 and 3 show the input and output data sources: the overall input and output calculations accumulation and the dataset type used. The input and output calculations are obtained from the accumulation per melon cultivation season, which is 70 days. For example, the amount of water used for one cultivation season is 40.3 kL, consisting of 150 L/season for the cultivation preparation process, 8,906.64 L/season for the preparation of melon seeds and planting media, 31,080 L/season for the fertilization process, and 300 L/season for the Pest and disease control process. The need for insecticides and fungicides is 600 ml and 800 grams, respectively, which are only used in the Pest and disease control process.

Table 2. Input data sources

Inputs	Qty	Unit	Dataset	Database
Calcium nitrate	6.81	kg	Calcium nitrate {RoW}| market for calcium nitrate | Cut-off, S	Ecoinvent 3
Potassium nitrate	1.23	kg	Potassium nitrate {RoW}| market for potassium nitrate | Cut-off, S	Ecoinvent 3
Magnesium sulfate	0.8	kg	Magnesium sulfate {GLO}| market for magnesium sulfate | Cut-off, S	Ecoinvent 3
Potassium sulfate	2.99	kg	Potassium sulfate {RoW}| market for potassium sulfate | Cut-off, S	Ecoinvent 3
Water	40.3	kL	Water pump operation, electric {MY}| Cut-off, S	Ecoinvent 3
	14.16	kWh	Water pump operation, electric {MY}| Cut-off, S	Ecoinvent 3
Rice husk charcoal	512	kg	Charcoal {GLO}| market for charcoal | Cut-off, S	Agri-footprint
Cocopeat	2040	kg	Coconut husks, at processing {ID} Economic, S	Agri-footprint
Fungicide	0.72	kg	Fungicide, at plant {RER} Economic, S	Agri-footprint
Insecticide	0.12	liter	Insecticide, at plant {RER} Economic, S	Agri-footprint
Electricity	22.1	kWh	Electricity, medium voltage {ID}| market for electricity, medium voltage | Cut-off, S	Ecoinvent 3
Polyethylene bag	7.5	kg	Polyethylene, linear low density, granulate {GLO}| market for polyethylene, linear low density, granulate | Cut-off, S	Ecoinvent 3
Cocopeat's transport	760.92	ton km	Transport, truck <10t, EURO3, 50%LF, empty return {GLO} Economic, U	Agri-footprint
Rice husk charcoal's transport	0.7168	ton km	Transport, truck <10t, EURO3, 20%LF, empty return {GLO} Economic, S	Agri-footprint

RoW = Rest of World; GLO = Global; MY = Malaysia; ID = Indonesia; RER = Region Europe.

Table 3. Output data sources

Output	Qty	Unit	Dataset	Database
Cocopeat soaking wastewater	8.91	kL	Wastewater, unpolluted {RoW}| market for wastewater, unpolluted | Cut-off, S	Ecoinvent 3
Biomass waste	317.79	kg	Biowaste, garden waste {GLO}| market for biowaste, garden waste | Cut-off, S	Ecoinvent 3

Determining the dataset used is based on the allocation model, geography, and library processes. In the Ecoinvent 3 database, all datasets use the cut-off allocation model. The life cycle process of melon cultivation ends with the purchase of the product by the consumer, so the selection of the cut-off model is considered appropriate because the life cycle does not involve product recycling (Steubing *et al.*, 2016). In determining the geographic location of each dataset, there are local and global geographies. Meanwhile, there are only two datasets from Indonesia because the inventory datasets from Indonesia could be more extensive.

The inventory of melon cultivation consists of upstream, core process, and downstream inventories. Inventory quantification is done based on input and output categories. Table 4 shows the input and output quantities inventory for each component per cultivation season of 70 days and per functional unit (FU), which is the kilogram of melon. The quantity per kg of melon is obtained by dividing the total quantity of each component per cultivation season by the total number of melons per season (1032.48 kg). The land size used for the greenhouse is 500 m^2.

Table 4. Overall inventory analysis

Input/Output	Total/season	Unit	Total/kg	Unit	Dominant Process
Melon fruits	1032.48	kg			Harvesting
Melon seeds	1200	pcs	2.14		Nursery
Water	40438	kL	72.21	L	Fertilizing
Insecticide	600	ml	1.07	ml	Pest and diesease management
Cocopeat	2040	kg	3642.8	gram	Preparation
Arang sekam	512	kg	914.28	gram	Planting
Polybag	7.5	kg	13.4	gram	Planting
Fungisida	800	gram	1.429	gram	Pest and diesease management
Calcium nitrate	1403.2	gram	2.506	gram	Fertilizing
Potassium nitrate	1228	gram	2.193	gram	Fertilizing
FeEDTA	31.24	gram	0.056	gram	Fertilizing
FeEDDHA	15.66	gram	0.028	gram	Fertilizing
Potassium sulfate	85.48	gram	0.153	gram	Fertilizing
MKP	350.32	gram	0.626	gram	Fertilizing
Magnesium sulfate	802.16	gram	1.432	gram	Fertilizing
ZA	158.56	gram	0.283	gram	Fertilizing
H3BO3	7.48	gram	0.013	gram	Fertilizing
ZnEDTA	1.74	gram	0.003	gram	Fertilizing
MnEDTA	10.04	gram	0.018	gram	Fertilizing
CuEDTA	0.94	gram	0.002	gram	Fertilizing
NaMolibdat	0.34	gram	0.001	gram	Fertilizing
Calcium nitrate	5406.3	gram	9.654	gram	Fertilizing
FeEDTA	156.90	gram	0.280	gram	Fertilizing
FeEDDHA	83.40	gram	0.149	gram	Fertilizing
Potassium sulfate	2913.7	gram	5.203	gram	Fertilizing
MKP	862.32	gram	1.540	gram	Fertilizing
H3BO3	17.94	gram	0.032	gram	Fertilizing
ZnEDTA	2.10	gram	0.004	gram	Fertilizing
MnEDTA	25.38	gram	0.045	gram	Fertilizing
CuEDTA	0.90	gram	0.002	gram	Fertilizing
NaMolibdat	0.18	gram	0.0003	gram	Fertilizing
Water pump	19.1	kWh	0.034	kWh	Fertilizing
Rice husk charcoals	0.717	ton km	13 x10^{-4}	ton km	Preparation
Cocopeat	760.92	ton km	1.358	ton km	Preparation
Luas greenhouse	500	m^2	0.893	m^2	Preparation
Melon fruit	1032.48	kg			
Wastewater from cocopeat soaking	2671.9	L	4,61	L	Preparation
Biomass waste	317.79	kg	0.548	kg	Harvesting
Distribution	0	ton km	0	ton km	Downstream

The inventory of main raw material inputs is shown in Table 4 (point 1), which is 1200 melon seedlings/season or 2.14 seedlings/kg of melon. This indicates that to produce 1032.48 kg of melon in one cultivation period, 1200 seedlings are needed, and the production per kilogram of melon requires 2.14 seedlings. Table 4 (point 2) shows the inventory of supporting liquid raw materials dominated using water. The water needed is 40.328 kL/season or 72.01 L/kg of melon. The most dominant process for water usage is the fertilization process, which amounts to 31.08 kL/season, followed by the cultivation preparation process at 8.9 kL/season and the pest and diseases management process at 300 liters. Another liquid supporting material is an insecticide, which amounts to 600 ml for pest and disease management.

In the third point, it shows the inventory of solid supporting materials. The largest contributor used is cocopeat, totaling 2040 kg/season or 3642 g/kg of melon, and husk charcoal, totaling 512 kg/season or 914 g/kg of melon. Additionally, there are several other materials, including 800 g/season of fungicide and a mixture of vegetable AB Mix and fruit AB Mix, with total masses of 4.095 kg/season and 9.469 kg/season, respectively. In the vegetable and fruit AB Mix mixture, the composition with the largest percentage is calcium nitrate with a total of 6.8 kg/season, followed by potassium sulfate at 3 kg/season and potassium nitrate at 1.2 kg/season. All solid supporting raw material inventories are used in growing media preparation, planting, fertilization, and Pest and disease control.

The use of electricity is shown in Table 4 (point 4). The total electricity consumption is 19.1 kWh/season or 0.034 kWh/kg melon. This indicates that only 0.034 kWh of electricity is required to produce 1 kilogram of melon. Electricity usage only occurs while providing AB mix nutrients with a water pump. The water pump's electricity consumption is 19.1 kWh (100%), with a total usage duration of 14 hours.

Table 5 (point 5) shows the transportation of materials for purchasing husk charcoal and cocopeat. Husk charcoal is purchased at Penggilingan, Situgede, 1.4 km. With a total load of 0.512 tons, the transport-distance load of purchasing husk charcoal is 0.717 ton-km. Meanwhile, the purchase of cocopeat is done at Pangandaran with 373 km and a total load of 2.04 tons. The transport-distance load of purchasing cocopeat is 750.92 ton-km.

Table 5 (point 8) shows the melon fruit's main product output, totaling 1032.48 kg/season. Furthermore, the output in waste treatment or handling is indicated in Table 5 (point 9). The liquid waste produced is from cocopeat immersion, totaling 2.67 kL/season or 4.61 L/kg of melon produced during the growing media preparation stage. Meanwhile, the solid waste produced is biomass waste, totaling 317.79 kg/season or 0.548 kg/kg of melon produced after harvesting.

In the final point, there are two groups of inventory distribution data, namely the purchase of husk charcoal and cocopeat, as shown in Table 5 (point 5). The purchase of husk charcoal and cocopeat has transport loads of 0.716 tons.km/season and 760.92 tons.km/season, respectively. The distance for purchasing husk charcoal is 1.2 km (Penggilingan, Situgede—Cikarawang, Dramaga), and for purchasing cocopeat, it is 373 km (Pangandaran, West Java—Dramaga, Bogor).

3.2. Life Cycle Impact Analysis

The environmental impact assessment results for melon cultivation were obtained from the characterization analysis. Table 5 and Figure 4 show the total environmental impact characterization of the melon cultivation process per season and kg. Each total was calculated with SimaPro 9.5.0.2 by adding all the inventory through the processing menu.

Table 5. Impact characterization per season and kilogram of melon

Impact categories	Unit	Total/period	Total/kg
Global warming potential (GWP)	kg CO_2 eq	2201.44	2.132
Stratospheric ozone depletion (SOD)	kg CFC-11 eq	405×10^{-5}	0.392×10^{-5}
Terrestrial acidification (TAC)	kg SO_2 eq	4.04	3.92×10^{-3}
Freshwater eutrophication (FEU)	kg P eq	404×10^{-3}	0.432×10^{-3}
Terrestrial ecotoxicity (TEC)	kg 1.4-DCB eq	4763.303	4.613
Human carcinogenic toxicity (HCT)	kg 1.4-DCB eq	130.8	0.126

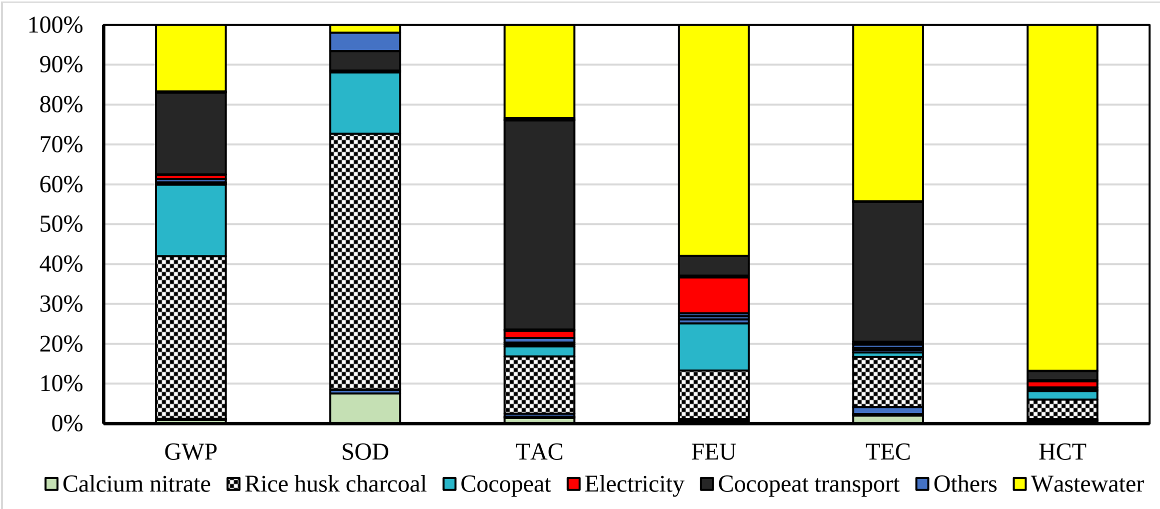

Figure 4. Graph of impact characterization of each inventory in melon cultivation per season

3.3. Global warming potential (GWP)

Melon cultivation contributes to global warming potential (GWP) by 2201.44 kg CO_2eq/season or 2.132 kg CO_2eq/kg of melon (Figure 5). The environmental impact is primarily caused by husk charcoal and cocopeat transportation, with GWP contributions of 897.7kg CO_2eq and 449.86 kg CO_2eq, respectively. Other major GWP contributors in melon cultivation include the use of cocopeat at 394.73 kg CO_2eq; wastewater from cocopeat immersion at 366.53 kg CO_2eq; electricity usage at 26.15 kg CO_2eq; and calcium nitrate usage at 20.13 kg CO_2eq. Husk charcoal usage has the highest contribution to GWP. Based on the LCA analysis in SimaPro, every kilogram of husk charcoal contributes 1.753 kg CO_2eq to GWP. Additionally, the husk charcoal dataset used emits the most emissions in the form of methane (biogenic), carbon dioxide (fossil), and nitrous oxide, at 1.34 kg CO_2eq, 0.24 kg CO_2eq, and 0.137 kg CO_2eq, respectively. Furthermore, the cocopeat transportation process provides the second-highest contribution to GWP due to the long delivery distance, resulting in vehicle pollution that impacts the environment. The distance between the cocopeat processing location and the ATP is 373 km with a load of 2.04 ton. Every ton-km of cocopeat transportation process emits 0.59 kg CO_2eq to GWP, with 86.5% coming from vehicles and 13.5% from diesel fuel usage. The largest emission released is carbon dioxide, at 0.508 kg CO_2eq.

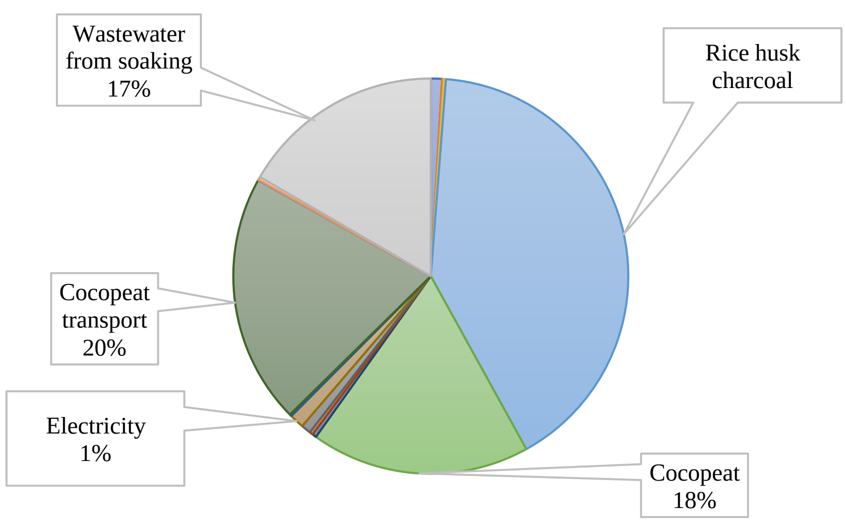

Figure 5. Major GWP contributors

Meanwhile, cocopeat has a significant GWP contribution because the amount of cocopeat used in each growing season is 2.04 ton. Every kilogram of cocopeat has a GWP contribution of 0.193 kg CO_2eq with emissions entirely stemming from the cocopeat processing process, releasing predominantly carbon dioxide emissions at 0.154 kg CO_2eq. Furthermore, in cocopeat immersion wastewater, every 1 liter of wastewater contributes 0.137 kg CO_2eq to GWP due to the presence of soluble tannins in the immersion wastewater with a large volume.

Regarding electricity consumption, the medium voltage dataset covers transforming electrical energy after production from high voltage to medium voltage, air emissions, and energy loss throughout transmission. Based on the LCA analysis in SimaPro, every kWh generated contributes 1.183 kg CO_2eq to GWP. The dominant emissions released are carbon dioxide (fossil) and methane (fossil), at 1.13 kg CO_2eq and 0.036 kg CO_2eq, respectively.

According to research by Frankowska *et al.* (2019), melon cultivation in the United Kingdom contributes 0.9 kg CO_{2eq}/kg of melon in terms of GWP. Meanwhile, yellow melon production in Jaguaribe, Brazil, contributes 0.5 kg CO_{2eq}/kg (Figueirêdo *et al.*, 2013). The most significant difference in GWP between these two cultivations and melon cultivation in the ATP lies in using cocopeat and rice husk charcoal as growing media. Cocopeat has a considerable contribution and involves a soaking process that generates waste. Additionally, using AB Mix as a liquid fertilizer has a significant contribution compared to the study by Figueirêdo *et al.* (2013), which only used organic fertilizer.

3.4. Stratospheric ozone depletion (SOD)

The contribution of stratospheric ozone depletion (SOD) in melon cultivation can be seen in Figure 6. The contribution of SOD is $405(10^{-5})$ kg CFC-11eq/season or $0.392(10^{-5})$ kg CFC-11eq/kg of melon. The use of cocopeat and charcoal causes a significant environmental impact. The use of cocopeat and charcoal contributes to SOD by $25.9(10^{-4})$ kg CFC-11 eq and $6.2(10^{-4})$ kg CFC-11 eq, respectively. According to Figure 6, other major contributors to SOD in melon cultivation (from the highest) are calcium nitrate at $3(10^{-4})$ kg CFC-11eq, cocopeat transportation of $1.9(10^{-4})$ kg CFC-11eq, and biomass waste at $1.8(10^{-4})$ kg CFC-11eq.

The use of cocopeat and charcoal contributes to SOD because their processing releases dominant emissions of ozone-depleting substances (ODS) such as CFCs and HCFCs. The processing of cocopeat involves pyrolysis processes that release CO_2 emissions into the air, contributing to ozone depletion. Based on the LCA analysis in SimaPro, every kilogram of cocopeat and charcoal contributes to SOD by 50.7 (10^{-7}) kg CFC-11eq and $3.06(10^{-7})$ kg CFC-11eq. Furthermore, in the transportation of cocopeat, every on-km of transportation contributes to SOD by $2.58(10^{-7})$ kg CFC-11eq, with 43.2% coming from vehicles and 56.8% from the use of diesel as vehicle fuel. Vehicles release dominant

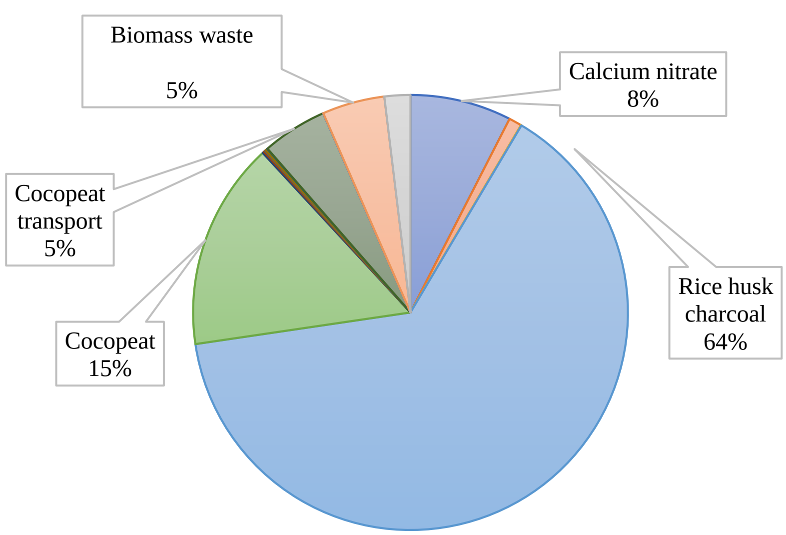

Figure 6. Major SOD contributors

nitric oxide emissions at 1.11(10^{-7}) kg CFC-11eq, while diesel use releases dominant methane emissions at 1.22(10^{-7}) kg CFC-11eq. The emissions from the transportation dataset of cocopeat are high due to the large load and considerable transportation distance.

Additionally, calcium nitrate ($Ca(NO_3)_2$) is an inorganic substance used as one of the components in the AB Mix liquid fertilizer. The use of calcium nitrate contributes to SOD because the dataset in SimaPro includes the production and transportation processes of calcium nitrate. Based on the LCA analysis in SimaPro, a kilogram of calcium nitrate contributes to SOD by 4.48(10^{-5}) kg CFC-11eq, with dominant emissions of nitric oxide at 4.48(10^{-5}).

Lastly, in biomass waste, every kilogram of waste produced contributes to SOD by 1.5(10^{-7}) kg CFC-11eq. In melon cultivation, biomass waste is generated after harvesting from leftover plants such as roots, stems, and leaves. Due to the absence of organic waste processing, all plant waste becomes trash. Based on the Ecoinvent 3 dataset in SimaPro, biomass waste emissions include nitric oxide at 5.92(10^{-7}).

3.5. Terrestrial acidification (TAC)

The contribution of terrestrial acidification (TAC) in melon cultivation can be seen in Figure 7. The TAC contribution is 4.062 kg SO_2eq/season or 3.93(10^{-3}) kg SO_2eq/kg of melon. The significant environmental impact is caused by the transportation of cocopeat, which contributes 2.122 kg SO_2eq to TAC. In the transportation of cocopeat, every 1 ton km of transportation contributes 2.79(10^{-3}) kg SO_2eq to TAC. The transportation of cocopeat generates dominant emissions of nitrogen oxides and ammonia, amounting to 0.002 kg SO_2eq and 1.15(10^{-5}) kg SO_2eq, respectively. The transportation of cocopeat has a significant contribution due to the considerable distance traveled, resulting in more emissions during the journey. According to Figure 7, other major contributors to TAC in melon cultivation include wastewater from soaking cocopeat at 0.945 kg SO_2eq, charcoal at 0.582 kg SO_2eq, cocopeat at 0.102 kg SO_2eq, and electricity consumption at 0.085 kg SO_2eq.

Regarding wastewater from cocopeat soaking, the contribution to TAC is 3.54(10^{-4}) kg SO_2eq/L. The dominant emissions released are sulfur oxides at 23(10^{-5}) kg SO_2eq and nitrogen oxides at 11.2(10^{-5}) kg SO_2eq. An explanation of the wastewater from cocopeat soaking has been provided in the previous GWP impact explanation. Meanwhile, the use of charcoal and cocopeat contributes to TAC due to the production, processing, and significant use. Based on the LCA analysis in SimaPro, every kilogram of charcoal and kilogram of cocopeat contribute to TAC by 1.14(10^{-3}) kg SO_2eq and 5.01(10^{-5}) kg SO_2eq, respectively, with dominant emissions of sulfur oxides at 66(10^{-5}) kg SO_2eq and 3.2(10^{-5}) kg SO_2eq. Lastly, electricity consumption contributes to TAC at 0.004 kg SO_2eq/kWh. The emissions produced are sulfur oxides and nitrogen oxides, totaling 0.0027 kg SO_2eq and 0.001 kg SO_2eq, respectively. Electricity consumption has a significant contribution due to several processes involved, with process descriptions provided in the previous GWP impact explanation.

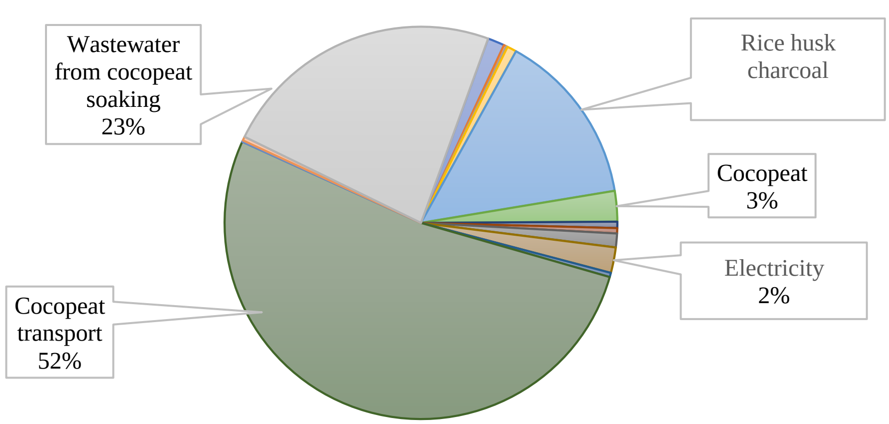

Figure 7. Major TAC contributors

3.6. Freshwater eutrophication (FEU)

The contribution of freshwater eutrophication (FEU) in melon cultivation can be seen in Figure 8. The FEU contribution as phosphor equivalent (Peq) is 454(10^{-3}) kg Peq/season or 0.440(10^{-3}) kg Peq/kg of melon. The significant environmental impact is caused by wastewater from soaking cocopeat, which contributes 0.258 kg Peq to FEU. According to Figure 8, other major contributors to FEU in melon cultivation include charcoal at 0.054 kg Peq, cocopeat at 0.053 kg Peq, electricity consumption at 0.046 kg Peq, and transportation of cocopeat at 0.022 kg Peq.

Wastewater from soaking cocopeat contributes the most to FEU due to the soluble tannin content in the soaking water. Based on the LCA analysis in SimaPro, every liter of wastewater from soaking cocopeat contributes 9.67(10^{-5}) kg Peq to FEU. The emissions generated from soaking wastewater include phosphate at 3.46(10^{-5}) kg Peq. Phosphate is a chemical substance containing phosphorus that causes freshwater eutrophication. Meanwhile, charcoal, cocopeat, electricity consumption, and transportation of cocopeat each contribute 0.0001 kg Peq, 0.00003 kg Peq, 0.002 kg Peq, and 0.00003 kg Peq per unit, respectively. Using charcoal and cocopeat generates phosphate emissions of 7.04(10^{-5}) kg Peq and 1.81(10^{-5}) kg Peq. Explanations for each component same as in the previous explanation of GWP.

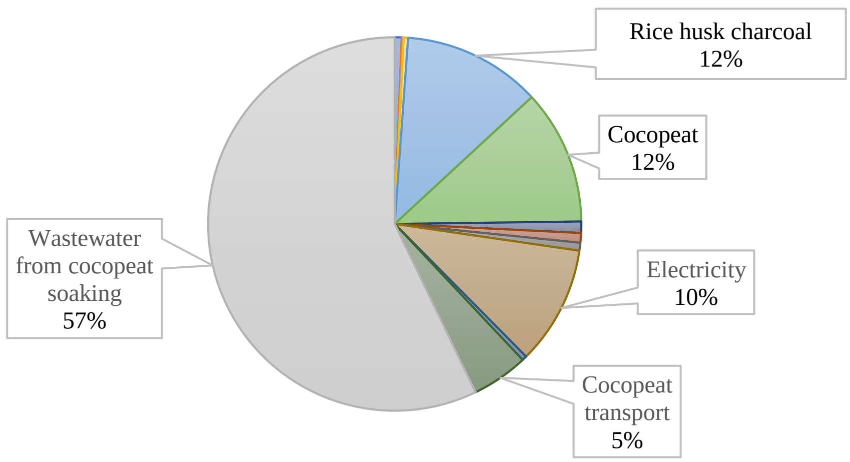

Figure 8. Major FEU contributors

3.7. Terrestrial ecotoxicity (TEC)

The contribution of terrestrial ecotoxicity (TEC) in melon cultivation can be seen in Figure 9. The TEC contribution is 4768.303 kg 1.4-DCBeq/season or 4.618 kg 1.4-DCBeq/kg of melon. The significant environmental impact in the media preparation and planting processes is caused by wastewater from soaking cocopeat and the transportation of cocopeat, which contribute 2106.2 kg 1.4-DCBeq and 1668.7 kg 1.4-DCBeq, respectively. According to Table 13, other major contributors to TEC in melon cultivation include charcoal at 598.34 kg 1.4-DCBeq; calcium nitrate at 95.35 kg 1.4-DCBeq; and potassium sulfate at 81.53 kg 1.4-DCBeq.

Based on the LCA analysis in SimaPro, every 1 L of wastewater from soaking cocopeat contributes 0.788 kg 1.4-DCBeq to TEC. The dominant emissions from soaking wastewater include copper, chromium (III), zinc (II), and nickel (II) at 0.42 kg 1.4-DCBeq; 0.14 kg 1.4-DCBeq; 0.06 kg 1.4-DCBeq; and 0.04 kg 1.4-DCBeq, respectively. Exposure to all these substances can damage ecosystems and increase the potential loss of species (ReCiPe 2016). Furthermore, in the transportation process of cocopeat, every 1 ton-km contributes 2.193 kg 1.4-DCBeq to TEC, with 87.6% coming from the vehicles used and 12.4% from diesel fuel. The emissions generated for every 1 ton-km of transportation of cocopeat include copper and nickel at 1.93 kg 1.4-DCBeq and 0.06 kg 1.4-DCBeq, respectively.

Lastly, for calcium nitrate and potassium sulfate, every kilogram produces 0.13 kg 1.4-DCB eq and 0.1 kilograms 1.4-DCBeq. Based on the dataset in SimaPro, the dominant emissions from calcium nitrate include chromium and nickel at 0.12 kg 1.4-DCBeq and 0.002 kg 1.4-DCBeq. Explanations regarding the TEC contribution of calcium nitrate have been provided in the previous explanation of SOD. Meanwhile, potassium sulfate (K_2SO_4) is the second largest liquid fertilizer mixture AB Mix component. The dominant emissions from potassium sulfate include copper and nickel at 8.9 kg 1.4-DCBeq and 0.83 kg 1.4-DCBeq. In the TEC characterization analysis, there is one component that does not have an impact on terrestrial ecotoxicity, which is biomass waste. This is because biomass waste does not generate emissions that can contribute to TEC.

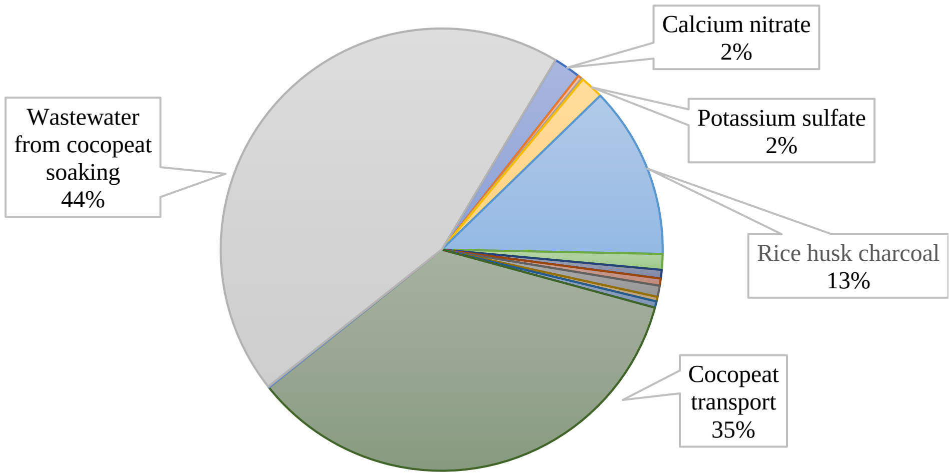

Figure 9. Highest terrestrial ecotoxicity (TE) contributors

3.8. Human Carcinogenic Toxicity (HCT)

The contribution of human carcinogenic toxicity (HCT) in melon cultivation can be seen in Figure 10. The HCT contribution is 131.216 kg 1.4-DCBeq/season or 0.127 kg 1.4-DCBeq per kilogram of melon. A large amount of wastewater causes a significant environmental impact in the media preparation process from soaking cocopeat, contributing 113.5 kilogram 1.4-DCBeq to HCT. According to Figure 10, other major contributors to HCT in melon cultivation include charcoal at 6.34 kg 1.4-DCBeq; transportation of cocopeat at 2.98 kg 1.4-DCBeq; cocopeat at 2.794 kg 1.4-DCBeq; electricity consumption at 2.37 kg 1.4-DCBeq; and calcium nitrate at 0.89 kg 1.4-DCBeq.

Based on the LCA analysis in SimaPro, every liter of wastewater from soaking cocopeat contributes to HCT at 0.042 kg 1.4-DCBeq. The dominant emissions from soaking wastewater contribute to HCT, including nickel in water at $25(10^{-5})$ kg 1.4-DCBeq and in air at $6.3(10^{-5})$ kg 1.4-DCBeq. The previous explanation of TEC provides explanations for the contribution of HCT to wastewater from soaking cocopeat. Lastly, every 1 kWh generates 0.12 kg 1.4-DCBeq

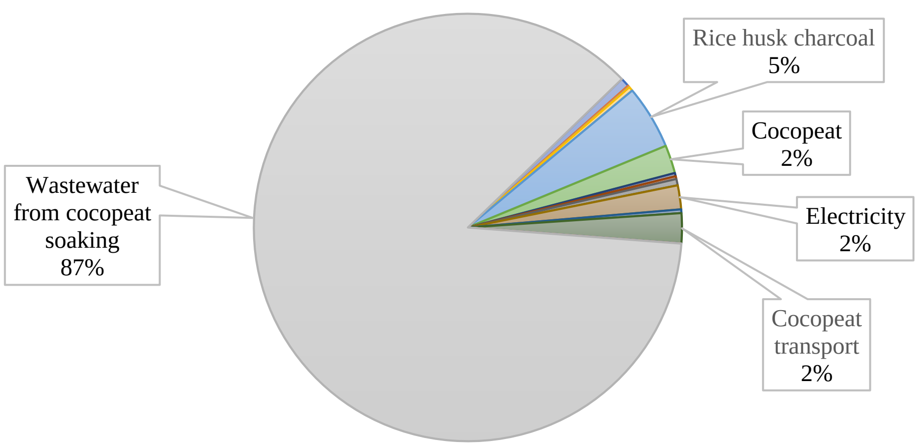

Figure 10. Highest human carcinogenic toxicity (HCT) contributors

for electricity consumption in HCT. The emissions produced per 1 kWh include chromium and nickel at 0.1 kg 1.4-DCBeq and 0.004 kg 1.4-DCBeq, respectively. Explanations regarding the contribution of HCT to electricity consumption have been provided in the previous explanation of GWP.

4. CONCLUSION

The result of this study was that the environmental impact of melon production was global warming potential was 2.137 kg CO_2eq; SOD was 0.392(10^{-5}) kg CFC-11eq; TAC was 3.93(10^{-3}) kg SO_2eq; FEU was 0.440(10^{-3}) kg Peq; TEC of 4.618 kg 1.4-DCBeq; and HCT of 0.127 kg 1.4-DCBeq. The largest contributors to the impact are preparing the growing media and the planting process. Meanwhile, the inputs and outputs with the largest impact contributions are the use of rice husk charcoal, transportation of cocopeat, and the use of cocopeat. The benefit of this study was knowledge to improve the low environmental impact of melons produced in greenhouses.

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