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Biofertilizers for Sustainable Agriculture: a Life Cycle Assessment of Upstream Manufacturing to Carbon Reduction

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Agriculture contributes to 22 % of global anthropogenic greenhouse gas emissions, of which fertilizer represents 10.6 % of agricultural greenhouse gas emissions. While there is increasing concern about the impact of chemical fertilizers on climate change, the impact of biofertilizers, especially their manufacturing, has not been addressed extensively. This study quantifies the upstream emissions of a biofertilizer manufacturing plant in Malaysia using the Life Cycle Assessment (LCA) methodology, where electricity consumption (64.2 %) is the biggest source of carbon emissions. The emissions are compared with other fertilizers to determine the environmental advantages of biofertilizers. Compared to other chemical fertilizers, biofertilizer manufacturing emits 23.2 times less carbon emissions than nitrogen fertilizer manufacturing. Chemical fertilizer manufacturing emissions come from various factors, especially energy-intensive processes and direct carbon emissions from material reactions (e.g., carbonate dissolution and material decomposition). Organic fertilizers, such as manure, digestates, and compost, emit up to 10,666 times more carbon emissions due to organic decomposition, which releases carbon dioxide and methane.

1. Introduction

Climate change is an alarming issue that causes adverse changes to global economic, ecological, resource, and food security (Woon et al., 2023). Among the contributors to climate change, agriculture contributes to 22 % of global anthropogenic emissions (OECD, 2022). Fertilizers supply nutrients that increase crop yield, but chemical fertilizers emit 10.6 % of all agricultural emissions (Menegat et al., 2022). The fertilizer industry is prominent in countries like Indonesia and China, where it is among the top three most energy-consuming industrial sectors (Adiansyah et al., 2021). Fertilizer manufacturing contributes to 39 % of the product's life cycle emissions (Nozaki, 2022). Fertilizer carbon emissions can be reduced using more sustainable alternatives, including biofertilizers, which can reduce emissions to varying degrees depending on the available microbe (Hu et al., 2024). Biofertilizers utilize microbes that act as biostimulants and have various climate-beneficial functions, such as nitrogen-fixing properties (Rohela and Saini, 2022). Biofertilizers have been found to substitute between 23 – 52 % of nitrogen fertilizers without yield loss (Rose et al., 2014).
Several studies have examined the emissions associated with upstream biofertilizer processes. Styles et al. (2018) observed the life cycle environmental impacts of biofertilizers from treated liquid digestates and found that approximately 70 – 98 % of upstream carbon emissions stem from chemical inputs needed for the treatment. Alengebawy et al. (2022) evaluated four digestate-treated biofertilizers and found that heat contributes to over 90 % of GHG emissions for three scenarios, and 90 % of the emissions from the biocompost scenario stem from chemical inputs. Studies examining single-cultured biofertilizers commonly utilize microalgae. Arashiro et al. (2022) utilized microalgae cultivated from a wastewater treatment plant, industrial wastewater treatment, and high-rate algal ponds. They found that approximately 25 – 70 % of greenhouse gas (GHG) emissions stem from electricity consumption, and roughly 60 % of the GHG emissions are from chemical inputs required for algal

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ponds with added nutrients from standard growth mediums. Other studies often consider organic fertilizers, like compost, as biofertilizers due to their inherent microbes that can benefit the crops (Manciulea et al., 2018). Previous literature quantified the emissions of biofertilizers sourced from microalgae, digestate, or compost, but only the study by Rose et al. (2014) observed biofertilizers containing cultivated bacteria, which does not include upstream emissions in their assessment.

This study quantifies the emissions of the upstream processes of biofertilizer containing cultivated bacteria using the Life Cycle Assessment (LCA) methodology. The results are separated in a hotspot analysis and compared with chemical, organic, and microalgae fertilizers to determine the environmental advantages of biofertilizer manufacturing (Phuang et al., 2021). Recommendations are provided for further environmental improvement of the biofertilizer manufacturing process.

2. Methodology

The integrated framework combines the LCA methodology to quantify all the environmental impacts associated with biofertilizer manufacturing (ISO 14040:2006; ISO 14044:2006).

2.1 Goal and scope definition

This study observes the upstream processes of biofertilizer containing cultivated bacteria from IBG Manufacturing Sdn. Bhd. in Malaysia and quantifies emissions in 2023. The functional unit is 1 L of manufactured biofertilizer as the product is prepared in liquid form. A secondary functional unit of 1 kg of manufactured fertilizer is utilized for the comparative analysis with other fertilizers. The system boundary is "cradle-to-gate", which begins with the extraction of raw materials from suppliers until the distribution of the biofertilizer products to consumers (see Figure 1). The transportation of biofertilizers to customers is considered an upstream process that generates carbon emissions by the manufacturer and is included in the system boundary (Barrow et al., 2013). Microorganisms (*Bacillus subtilis* for nitrogen-fixation, *Bacillus amyloliquefaciens* for phosphate solubilization, and *Bacillus mycoides* for potassium solubilization) are cultivated and fermented in a bioreactor before being mixed with organic materials and packaged for distribution. Most ingredients are sourced locally with a few overseas suppliers and shipments to customers are mostly overseas. Material emissions from the cultivation process are assumed to be negligible as the material inputs are low in quantity and are not carbon-intensive compared to the electricity consumption of the bioreactor (Järviö et al., 2021).

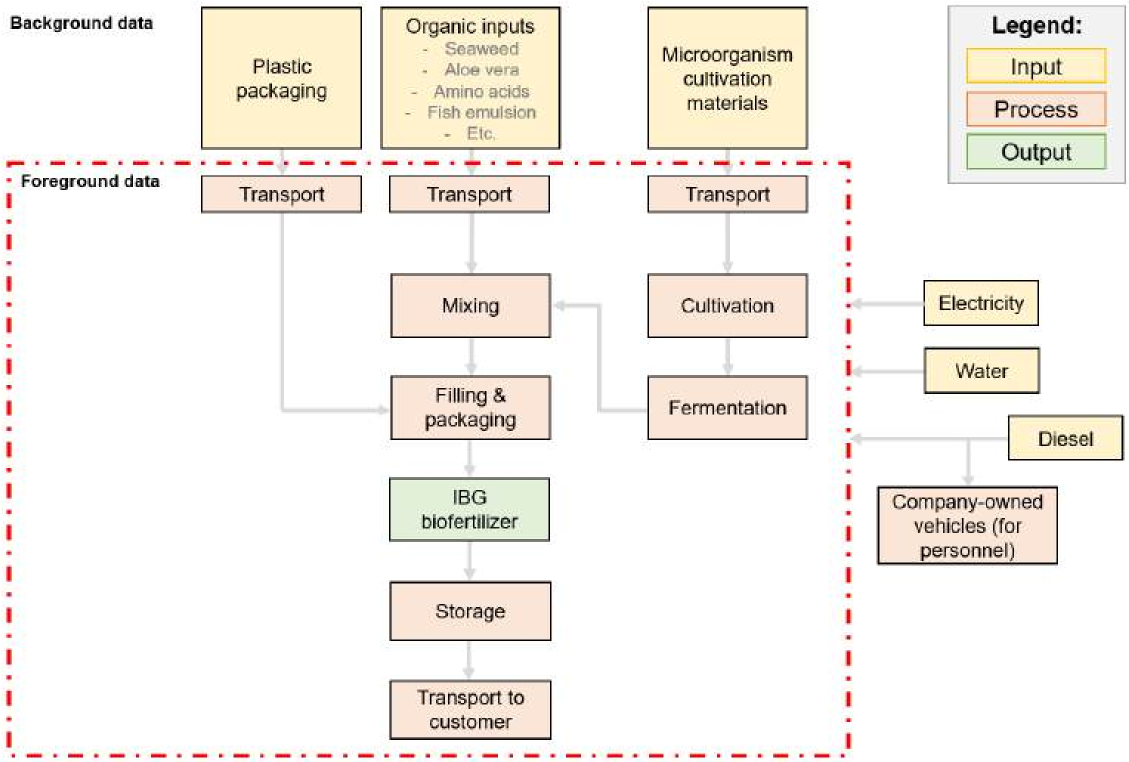

Figure 1: The "cradle-to-gate" system boundary of the biofertilizer manufacturing plant

2.2 Life cycle inventory

Key input and output data defined in the system boundary are systematically collected. The plant owner provides data such as electricity, water, and diesel consumption, transportation distances, the process flow diagram, and ingredient inputs. Emission factors are taken from the most recent Malaysian governmental reports. All data are listed in Table 1. Background data includes organic materials, plastic packaging, microorganism cultivation materials, electricity (e.g., emissions for infrastructure), water, and diesel. These data are collected in similar years to the foreground data and are cross-validated by the on-site operators to enhance the data accuracy and reliability. Most of the water input is consumed during mixing to dissolve the materials and generates negligible quantities of wastewater.

Table 1: Life cycle inventory inputs for the annual production of 1 L of IBG biofertilizer

Process / materials	Quantity	Unit	Source
Ingredient transportation (to manufacturing plant)			
Land transport; lorry	0.175	tkm	Plant
Sea transport; sea freight	0.981	tkm	Plant
Packaging transportation (to manufacturing plant)			
Land transport; lorry	1.7×10^{-3}	tkm	Plant
Sea transport; sea freight	0.225	tkm	Plant
Operational process			
Electricity consumption	0.452	kWh	Plant
Water consumption	6.72×10^{-3}	m^3	Plant
Diesel consumption			
Forklift and other operational machinery	3.72×10^{-8}	m^3	Plant
Transportation of diesel (for machinery) to plant	1.13×10^{-5}	tkm	Plant
Vehicles for personnel and non-production uses	2.33×10^{-6}	m^3	Plant
Product transportation (to customers)			
Land transport; lorry	0.715	tkm	Plant
Sea transport; sea freight	2.011	tkm	Plant
Emission Factors			
Land transport	1.065×10^{-4}	kg CO_{2eq}/t/km	CIDB (2021)
Sea transport	1.614×10^{-2}	kg CO_{2eq}/t/km	CIDB (2021)
Electricity generation	0.55	kg CO_{2eq}/kWh	TNB (2022)
Water processing	0.586	kg CO_{2eq}/m^3	AS (2022)
Diesel combustion	2.697×10^3	kg CO_{2eq}/m^3	USEPA (2023)

2.3 Life cycle impact assessment

Upstream carbon emissions are quantified by multiplying the activity data with emission factors. The emission factors have different units depending on the activity data. For example, transportation emissions are quantified by utilizing the mass and distance of the transported products (in tkm), and electricity emissions are quantified by calculating annual consumption (in kWh). The formula is shown in Eq (1).

$$GHG\ emissions = Activity\ data \times Emission\ factor \tag{1}$$

The calculated emissions are compiled into a graph displaying the disaggregated emissions of each process involved in manufacturing the biofertilizer.

2.4 Life cycle interpretation

A hotspot analysis is conducted to determine processes contributing to the highest emissions, and recommendations are provided to reduce carbon emissions. The results are compared with other fertilizers to determine whether IBG's biofertilizer manufacturing is more eco-friendly than other fertilizer production processes.

3. Results and Discussion

Figure 2 shows the upstream emissions of the biofertilizer manufacturing process. Most emissions stem from electricity consumption, primarily for the bioreactor in cultivation and fermentation, mixing, filling, and packaging processes, contributing to 64.2 % of the manufacturing carbon emissions. Customer transportation is the next largest emitter, contributing 28.1 % of the emissions, as the biofertilizer product is frequently shipped to overseas customers. The large difference in ingredient and packaging transportation with customer transportation is caused by the latter covering a greater distance than the ingredient transportation, resulting in approximately 5.6 times larger emissions. Other emissions contribute less than 5 % of the total emissions each. Diesel consumption for forklifts and other operational uses, along with its transportation from stations to the manufacturing plant, combine to less than 0.1 % of the total emissions due to the low quantities used and the utilization of several electrical forklifts that further reduce diesel consumption for operation.

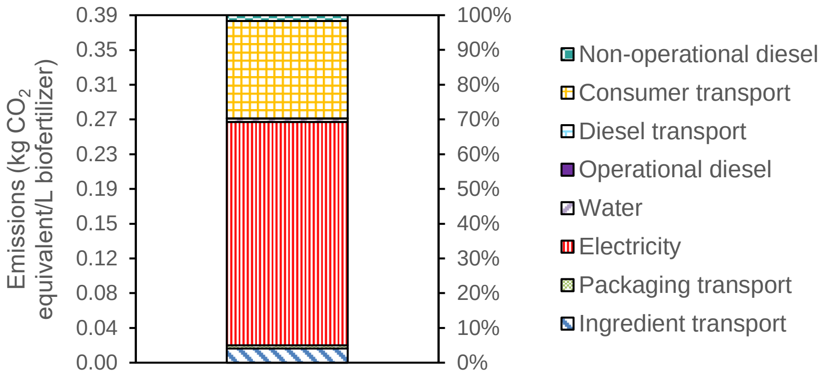

Figure 2: IBG biofertilizer manufacturing emissions for 1 L of biofertilizer

Most emissions associated with biofertilizer manufacturing stem from electricity consumption due to Malaysia's use of coal and natural gas as primary energy sources (TNB, 2022). Malaysia is increasing its renewable energy mix to 70 % by 2050, which can significantly reduce fossil fuel-induced electricity emissions once implemented (MOE, 2023). Alternatively, energy consumption can be reduced by utilizing more energy-efficient equipment or installing rooftop solar panels to reduce the emissions from electricity consumption.
The emissions of biofertilizer manufacturing are compared with other forms of fertilizer manufacturing from various studies to determine the degree of environmental improvement. The review study by Walling and Vaneeckhaute (2020) benchmarked multiple types of organic and inorganic fertilizers from around the globe and assessed common emission hotspots. Figure 3 compares the lowest and highest values of manufacturing emissions of their assessed chemical fertilizers based on the benchmark by Walling and Vaneeckhaute (2020).

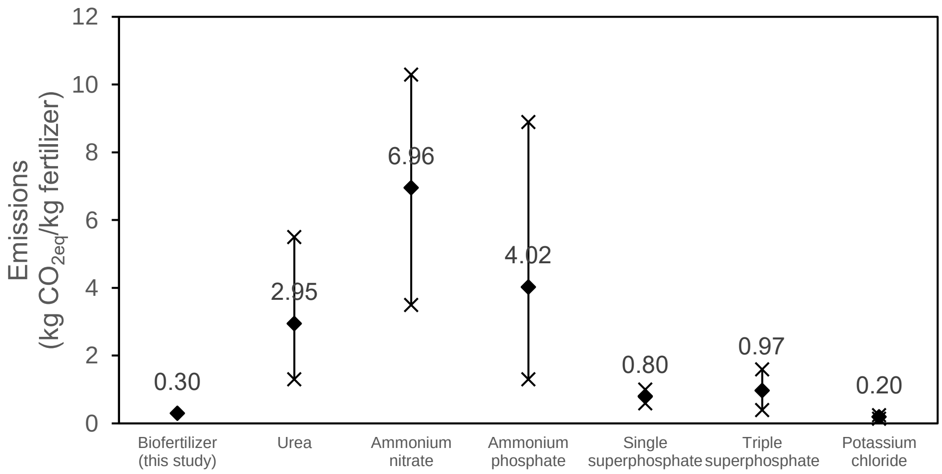

Figure 3: Manufacturing emissions comparison of IBG biofertilizer with other chemical fertilizers based on a functional unit of 1 kg of fertilizer

Based on the benchmark, the manufacturing emissions of biofertilizers are 9.8 – 23.2 times lower than chemical fertilizers containing nitrogen (i.e., urea, ammonium nitrate, and ammonium phosphate), but are comparable with potassium and phosphorous fertilizers. Nitrogen fertilizers require ammonia commonly produced from the Haber-Bosch process, which requires hydrogen generated from the steam reforming of hydrogen and nitrogen, co-generating carbon dioxide and methane (Menegat et al., 2022). The Haber-Bosch process can create ammonia but is an energy-intensive process that dominates the emissions from its manufacturing (Walling and Vaneeckhaute, 2020). Fertilizers with high energy consumption can have a wide range of emissions, as shown by the nitrogen fertilizers in Figure 3, as utilizing cleaner energy sources (e.g., renewables instead of coal) can reduce emissions.

According to Walling and Vaneeckhaute (2020), organic fertilizers, including manure, compost, and digestates, have highly variable production emissions between 230 – 3,200 kg CO_{2eq}/kg fertilizer depending on variables, such as the source of the organic material and processing conditions (e.g., composting temperature), but they always result in magnitudes of higher emissions compared to other fertilizers due to material decomposition, which primarily generates carbon dioxide with some methane and nitrous oxide (through ammonium oxidation or denitrification). The study further elaborates that the variability in manure emissions is caused by factors including the status (age, type, and weight) of the animal variability in production operations, as well as the season and the time of day. Operating parameter variations (e.g., temperature, moisture content, C:N ratio) cause variability in compost and digestate emissions, affecting methane and nitrous oxide emissions. Studies observing microalgae cultivation for biofertilizers are rare, but one study by Castro et al. (2020) produced biofertilizers containing microalgae from a high rate algal pond resulting in emissions of 3.17 kg CO_{2eq}/ kg fertilizer, most of which is due to energy consumption for cultivation and drying.

To offset the high emissions from nitrogen fertilizer production and use, biofertilizers can be mixed with other fertilizers to reduce agricultural emissions. One study by Sun et al. (2020) discovered that nitrogen-fixing biofertilizers can reduce nitrogen losses by 54 %, increase nitrogen uptake efficiency by 11.2 %, and increase crop yields by 5 %, by substituting 50 % of urea with biofertilizers. The ability to offset nitrogen fertilizer and the low emissions associated with producing biofertilizers offer an opportunity to reduce agricultural carbon footprint.

4. Conclusions

Biofertilizer upstream emissions quantified through the LCA methodology have shown beneficial impacts on climate change compared to manufacturing other fertilizers. Electricity is the biggest contributor to carbon emissions (64.2 %), primarily due to energy requirements for powering the bioreactor, mixing, and filling machines. Compared with other fertilizer manufacturing, biofertilizers emit up to 23.2 times less carbon than nitrogen fertilizers, up to 10,666 times less carbon than organic fertilizers, and approximately 10 times less carbon than biofertilizers containing microalgae. The upstream emissions of biofertilizer containing bacteria are comparable to those of phosphorous and potassium fertilizers, but biofertilizers can substitute nitrogen fertilizers, significantly reducing global fertilizer emissions. The high electricity consumption used for manufacturing biofertilizers can be reduced by utilizing cleaner energy sources such as solar panels. It is recommended that future studies observe the downstream emissions of biofertilizer applications to quantify the life cycle emissions.

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