Jurnal Teknologi Industri Pertanian 35 (1): 44-56, April 2025
DOI: https://doi.org/10.24961/j.tek.ind.pert.2025.35.1.56
ISSN: 0216-3160 EISSN: 2252-3901

Terakreditasi Peringkat 2
SK Dirjen Pendidikan Tinggi, Riset, dan Teknologi No. 158/E/KPT/2021
Tersedia online http://journal.ipb.ac.id/index.php/jurnaltin

STUDY OF GLOBAL WARMING POTENTIAL IMPACT FROM MUNICIPAL SOLID WASTE MANAGEMENT USING BIOCONVERSION OF BLACK SOLDIER FLY (*Hermetia illucens*): CASE STUDY DEPOK CITY

KAJIAN DAMPAK POTENSI PEMANASAN GLOBAL PENGELOLAAN SAMPAH PERKOTAAN MELALUI BIOKONVERSI LALAT TENTARA HITAM (Hermetia illucens): STUDI KASUS KOTA DEPOK

R. Muchamad Irchas Sukabudhi[1)], Nastiti Siswi Indrasti[2,*)], and Andes Ismayana[2)]

[1)]Agroindustrial Engineering Study Program of Graduate School, IPB University, Bogor, West Java 16680, Indonesia
[2)]Departement of Agroindustrial Technology, Faculty of Agricultural Technology, IPB University, Bogor, West Java, Indonesia
Email: nastitis@apps.ipb.ac.id

Paper: Received June 10, 2024; Revised Agust 23, 2024; Accepted October 09, 2024

ABSTRAK

Penelitian ini secara komprehensif mendiskusikan potensi dampak lingkungan yang timbul dari sistem pengelolaan sampah perkotaan dengan biokonversi lalat tentara hitam (Hermetia illucens) atau black soldier fly (BSF). Tujuan dari studi ini adalah menghitung nilai potensi dampak pemanasan global dalam jangka waktu 100 tahun (GWP100) pada sistem pengelolaan sampah perkotaan yang diimplementasikan oleh PT. XYZ Kota Depok, mengidentifikasi sumber emisi, serta menganalisis rekomendasi alternatif perbaikan dalam upaya meminimalisir dampak lingkungan yang ditimbulkan. Pengumpulan data penelitian dilakukan di PT. XYZ di Kota Depok, Provinsi Jawa Barat, pada bulan Mei hingga Juni 2022. Studi kasus ini menerapkan metodologi life cycle assessment (LCA), dibatasi pada ruang lingkup cradle-to-gate dengan unit fungsional 1 ton sampah kota. Hasil penilaian dampak menunjukkan bahwa potensi dampak GWP100 yang timbul dari sistem adalah sebesar 3,69E+02 kg CO_2 eq/ton sampah kota. Emisi GRK yang menjadi sumber utama dampak tersebut adalah CH_4 (2,47E+02 kg CO_2 eq/ton sampah kota) dan CO_2 (1,19E+02 kg CO_2 eq/ton sampah kota). Sebagian besar (67%) emisi tersebut berasal dari output limbah padat yang ditimbun secara open dumping (2,57+02 kg CO_2 eq/ton sampah kota). Skenario perbaikan yang dapat direkomendasikan adalah melakukan perlakuan awal terhadap sampah perkotaan, substitusi penggunaan listrik fotovoltaik, memilih mitra prioritas dengan jarak terdekat, serta substitusi kemasan biokomposit. Apabila seluruh skenario tersebut diimplementasikan maka dampak GWP100 dari keseluruhan sistem akan menurun sebesar 56,02%.

Kata kunci: Biokonversi BSF; Hermetia illucens; LCA; potensi pemanasan global; pengelolaan sampah perkotaan

ABSTRACT

This research comprehensively investigated the global warming potential impact of the municipal solid waste management system using bioconversion of black soldier fly (Hermetia illucens). For this purpose, the life cycle assessment methodology was applied to evaluate the global warming potential over a 100-year horizon (GWP100) for the system used by XYZ Ltd. Depok City, identify emission sources and analyze alternative strategies to mitigate environmental impacts. Data collection for this study was conducted at XYZ Ltd. in Depok City, West Java Province, between May and June 2022. This case study focused on a cradle-to-gate analysis with a functional unit of 1 ton of municipal solid waste. The impact assessment results showed that GWP100 impact from bioconversion of municipal solid waste was 3.69E+02 kg CO_2 eq. Solid waste disposed through open dumping was a dominant contributor of these emissions (2.57E+02 kg CO_2 eq). The GHG emissions that were the primary source of these impacts are CH_4 (2.47E+02 kg CO_2 eq) and CO_2 (1.19E+02 kg CO_2 eq). Ultimately, the improvement scenarios recommended in this study are the pretreatment of municipal solid waste, substituting photovoltaic electricity use, choosing priority clients with the closest distance, and substituting biocomposite packaging. Implementing these measures will reduce the GWP100 impact by 56.02%.

Keywords: BSF bioconversion; global warming potential; *Hermetia illucens*; LCA; Municipal solid waste

INTRODUCTION

The rapid population growth and varied activities of urban populations in Indonesia have significantly complicated municipal solid waste management (MSWM) (Lohri *et al.*, 2014). Based on data published by Indonesia's Ministry of Environment and Forestry (MoEF), the amount of waste from 2021 to 2023 has increased by 43%, with a total national waste generation of 19.6 million tons in 2023. Most of this waste is generated in the metropolitan regions of Java Island, especially the DKI Jakarta area, with per capita waste production averaging 0.6 kg/day or 214 kg/year (Suprihatin *et al.*, 2008). The waste composition is dominated by organic waste in the form of food waste at 41.9%, which generally comes from households. The government has established over 450 waste

*Coressponding Author

management facilities to mitigate these challenges, predominantly utilizing open dumping and landfill methods (Fatimah *et al*., 2020).

Various studies have proven that conventional waste management is a significant source of GHG emissions. In 2016, solid waste management worldwide was estimated to produce 1.6 million tons of CO_2 eq, contributing nearly 5% to global GHG emissions (Kaza *et al*., 2018). Specifically, conventional waste management methods (landfill and open dumping) produce GHG emissions approximately 400 - 969 kg CO_2 eq/ton of waste. (Paes *et al*., 2020; Xin *et al*., 2020). These conditions encourage various studies to develop low-emission and sustainable waste management methods, including bioconversion with black soldier flies (*Hermetia illucens*).

The advancement of research has further proven the advantages of bioconversion technology with black soldier flies (BSF) as a waste management method. The method is known to degrade waste volume effectively. In addition, BSF bioconversion produces outputs in the form of BSF larvae (BSFL) and BSF frass that have economic value (Yuwono dan Mentari, 2018). BSFL can be used as a source of animal protein, generally as fish feed, while the BSF frass can be used as solid organic fertilizer (Kawasaki *et al*., 2020). Furthermore, in terms of ecological aspect, waste treatment with BSF bioconversion is known to have a lower potential environmental impact than conventional methods (Guo *et al*., 2021).

Life Cycle Assessment (LCA) has been firmly established as a methodology for evaluating the environmental impact associated with the life cycle of products and services (Peña *et al*., 2021). The analysis can start from raw material input, production process, and product use to disposal (cradle-to-grave). LCA research also aims to identify areas for improvement and find alternative solutions to reduce the environmental impact (Wiloso *et al.*, 2019). The Indonesian government has adopted international standards for the implementation of LCA through SNI ISO 14040: 2016 and SNI ISO 14044: 2017. The standards explain that at least the implementation of LCA consists of four stages: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; 4) interpretation.

LCA research on waste management with BSF bioconversion mostly focuses on analyzing the environmental impact of utilizing BSFL as an output into a protein source in the form of fish feed (Smetana *et al.*, 2016; Bava *et al*., 2019; Ermolaev *et al*., 2019; Spykman *et al.*, 2021). Other research proves that the global warming impact from the waste management using BSF bioconversion method approximately (-432) – 252.08 kg CO_2 eq/ton of waste (Salomone *et al*., 2017; Ites *et al*., 2020; Guo *et al*., 2021). The BSF bioconversion method can cause differences in emissions and environmental impacts between one facility and another. This fact then becomes a gap for conducting LCA research from implementing MSWM systems using the BSF bioconversion method, especially in Indonesia.

This research is a case study conducted at XYZ Ltd. specializes in MSWM services. XYZ Ltd. located in Depok City, West Java Province, was selected as the research site due to its representative characteristics, which accurately reflect the current state implementation of MSWM using BSF bioconversion method in Indonesia. Most of the MSW collected from the metropolitan areas surrounding DKI Jakarta, Bogor, and Depok. The objectives of this research are to determine the value of the potential global warming impact in 100 years horizon (GWP100) on the MSWM system using BSF bioconversion, identify emission sources from inputs and outputs throughout the system, and analyze alternative recommendations for improvement to minimize the environmental impact caused. Ultimately, this research is expected to serve as a scientific basis for developing a MSWM system with a sustainability perspective.

RESEARCH AND METHODS

Data collection in the study was carried out at XYZ Ltd. located in Depok City, West Java Province, from May to June 2022. The environmental impacts of the MSWM system with BSF bioconversion were analyzed using the LCA method by quantifying the input-output flow (exchange flow) from the system to the environment by predetermined limits. The phases of this research refer to the LCA implementation guidelines according to the SNI ISO 14040:2016 framework (Figure 1) which consist of four stages namely: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; 4) interpretation.

Goal and Scope Definition

The definition of objectives and scope aims to ensure that the research can be carried out systematically by referring to the specified scope and system boundary. This research aims to determine the value of the global warming potential impact of the MSWM system with BSF bioconversion at XYZ Ltd. Depok City and recommend alternative improvements for stakeholders to reduce environmental impacts.

This research is conducted with a cradle-to-gate scope, starting from the collecting and transportation of MSW (transportation), mass breeding of BSF eggs (breeding), waste bioconversion process using BSFL (treatment), dried BSFL production, and organic fertilizer production. Figure 2 shows the system boundary of this research schematically. Furthermore, the scope of this research area is limited to the Jakarta Metropolitan Area (Depok, Jakarta, and Bogor). The functional unit determined in this study is 1 ton of MSW as the amount defined in the impact assessment.

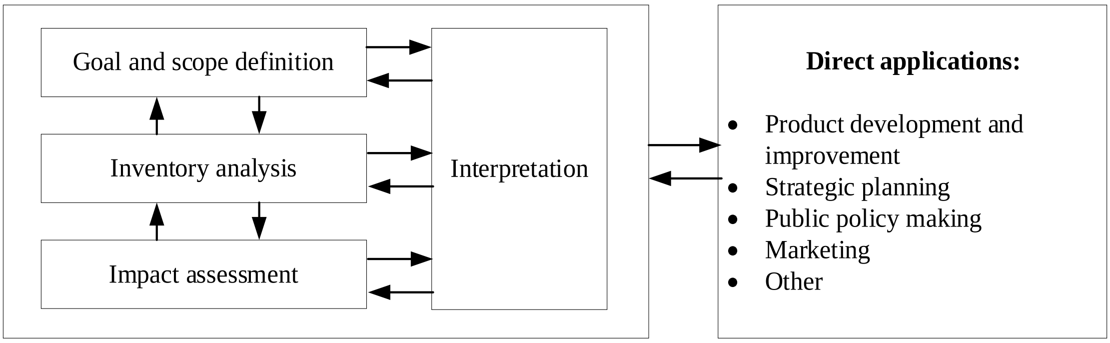


Figure 1. LCA framework according to SNI ISO 14040:2016

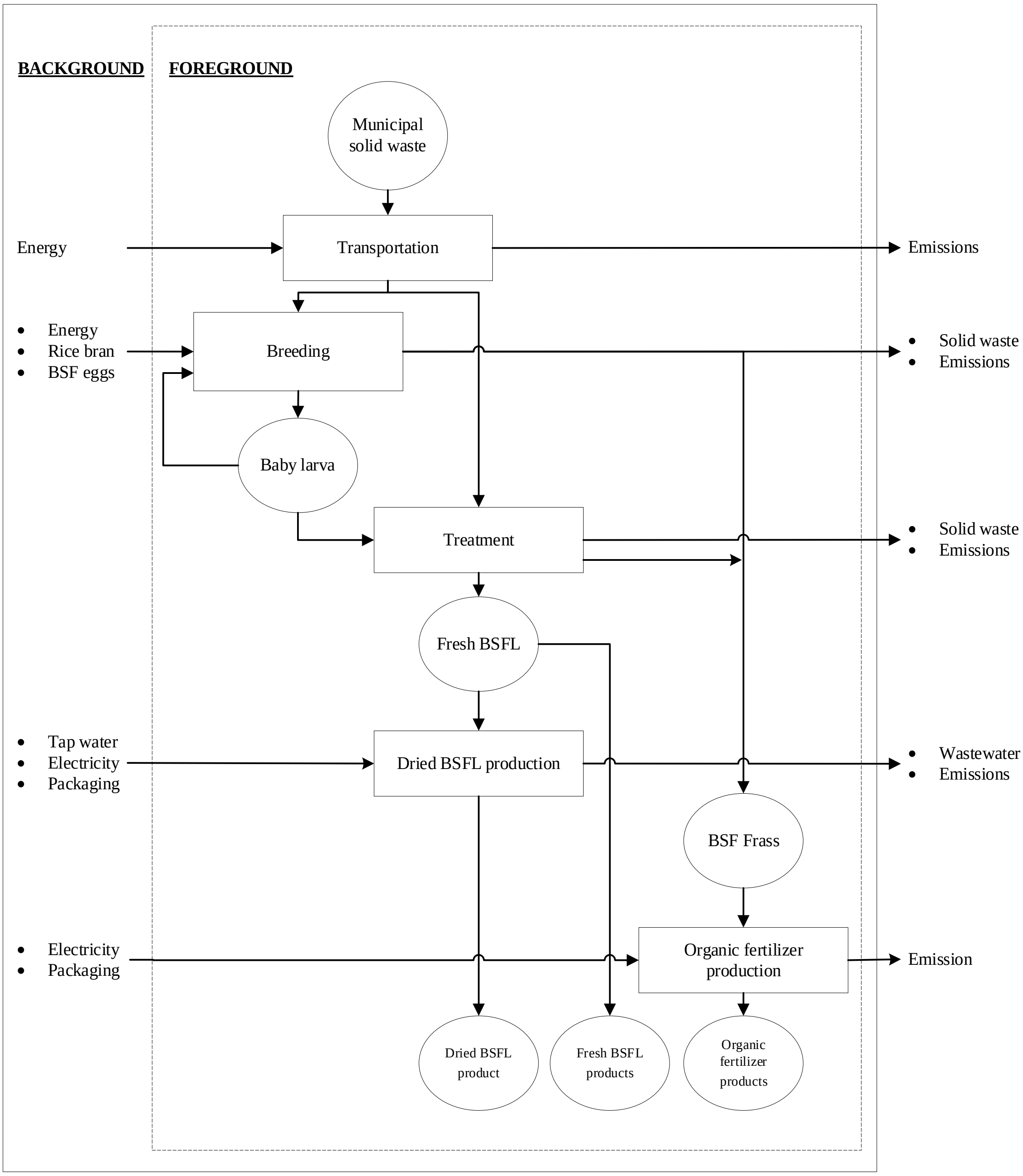


Figure 2. System boundary of the study

Given the research limitations related to data availability, time, accessibility, and other constraints, this study is scoped as follows to ensure the credibility and accuracy of the findings: 1) The research is a case study focused on analyzing the environmental and technological aspects of the MSWM system using the BSF bioconversion method at XYZ Ltd. in Depok City; 2) The study takes MSW as the object of research; 3) The impact assessment is conducted using the Environmental Footprint 3.1 (EF3.1) method, based on IPCC 2021 guidelines and the Ecoinvent v3.10 database, with OpenLCA software version 2.0; 4) Improvement scenario analysis is based on interviews with stakeholders, direct field observations, and a literature review of LCA research on MSWM using the BSF bioconversion method.

Inventory Analysis

The inventory analysis in this study aims to develop a comprehensive understanding of the MSW bioconversion process. This analysis including material flow analysis (MFA) based on the provisions of SNI ISO 14040:2017, using mass balance modelling via STAN 2.7 software. Primary data (foreground data), collected directly from interviews and field observations at XYZ Ltd. in Depok City, include input material flows such as the quantity of municipal solid waste managed (kg), vehicle type and distance travelled (tkm), operational hours of waste pulverizer diesel-fuel (hours), water usage (kg), the quantity of bran and BSF eggs (kg), type and amount of packaging (m²). Output material flows include the production of fresh and dried BSF larvae, BSF frass (kg), solid waste (kg), wastewater volume (l), quantities of attractant and dead BSF (kg). Secondary data (background data), including emission types, impact category characterization factors, and GWP100 impact assessments, were obtained from literature studies and the Ecoinvent 3.10 database. Additionally, the flow of energy use throughout the system was documented as part of the input data.

Impact Assessment

The impact assessment aims to evaluate the environmental impacts based on the inventory analysis results (Klöpffer dan Grahl, 2014). In this study, the Environmental Footprint 3.1 (EF3.1) method based on the Intergovernmental Panel on Climate Change (IPCC) 2021 with OpenLCA software version 2.0 was used to assess the impact of global warming potential within 100 years (GWP100) of the MSWM system through BSF bioconversion at XYZ Ltd. Depok City. Determination of GWP100 as a potential impact analyzed based on its direct relationship with the inventory (Guo *et al.*, 2021).

Interpretation

The interpretation aims to assess the inventory analysis and impact assessment findings, in line with the study's objectives and scope. The analysis of all emission points in the system is then interpreted into detailed information by calculating the relative contribution of each emission source to the GWP100 impact. This analysis forms the basis for evaluating and designing recommendations for alternative improvements supported by field observations and literature reviews. Several improvement scenarios are proposed. Environmental impact from the scenarios is analyzed and compared to the original impact results to determine the percentage change in environmental impact.

RESULTS AND DISCUSSION

Waste Bioconversion Process

The MSWM system using the BSF bioconversion method at XYZ Ltd. in Depok City is based on the natural life cycle of the BSF. The company's waste management process consists of 5 (five) main unit process: 1) the collecting and transportation of MSW to the facility (transportation), 2) mass breeding of BSF eggs (breeding), 3) waste bioconversion process using BSFL (treatment), 4) dried BSFL production, and 5) organic fertilizer production. Figure 3 shows a schematic flow chart of this process, which is the scope of the study observed. The system produces 3 (three) main products as outputs: fresh BSF larvae, dried BSF larvae, and organic fertilizer.

Figure 4 shows the total mass flow in the MSWM system using the BSF bioconversion method. The MSW managed by XYZ Ltd. collected from the company's clients located around Jakarta, Bogor, and Depok. When this research was conducted, XYZ Ltd. was currently in cooperation with 9 (nine) clients. A segregation process distinguishing between organic and inorganic waste has been implemented by the client, but due to limited time and facilities, the sortation process is not fully efficient, leading to some mixing of inorganic waste. The collected waste is then transported by XYZ Ltd. using Light Commercial Vehicles (LCVs), generally used to carry loads of less than 3.5 tons.

MSW delivered to XYZ Ltd.'s waste management facility is allocated to two units process: breeding (14,502 kg) and treatment (1,434 kg). The breeding unit process ensures a continuous supply of BSF insects through in-house breeding. In this unit process, MSW is utilized as egg-hatching media, attractant, and feed for BSFL rearing. Waste used for hatching and attractants is manually sorted before finally pulverized using a diesel-powered engine, 3 kg of bran also added to maintain texture and moisture content consistency.

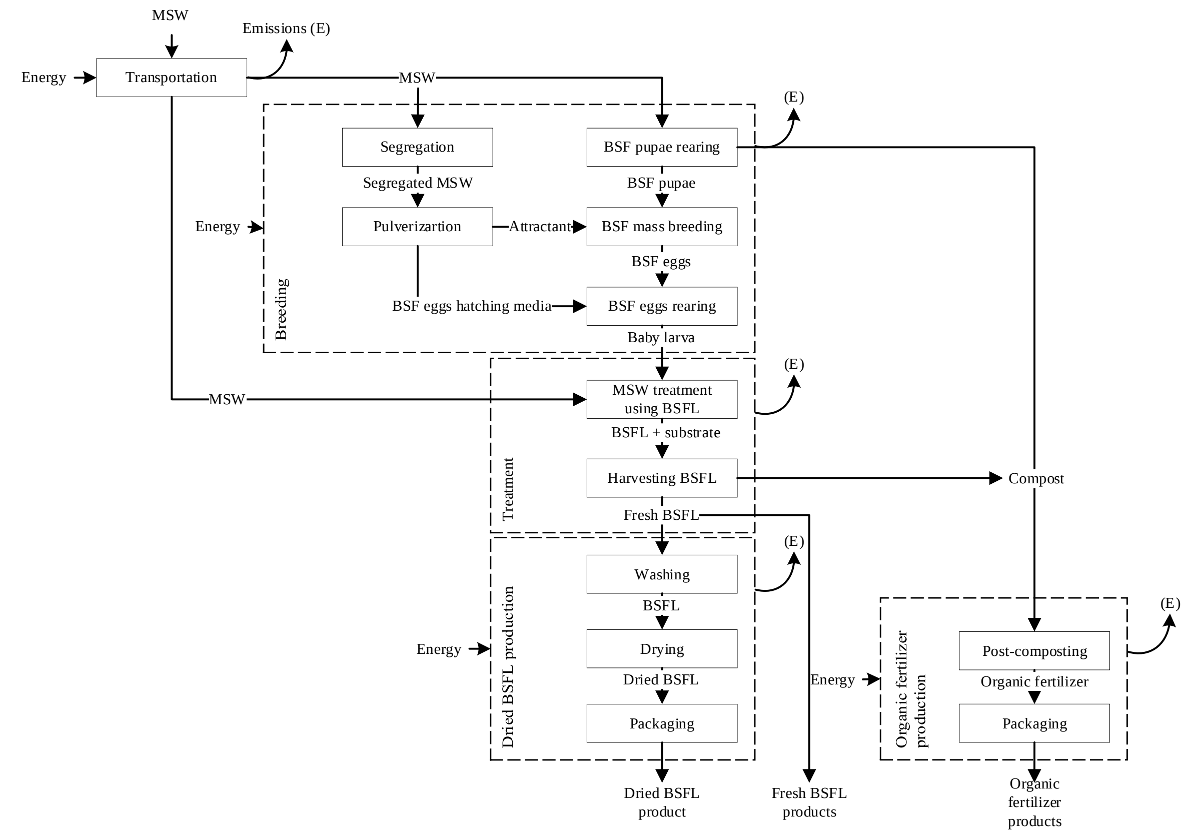


Figure 3. Scope of the study

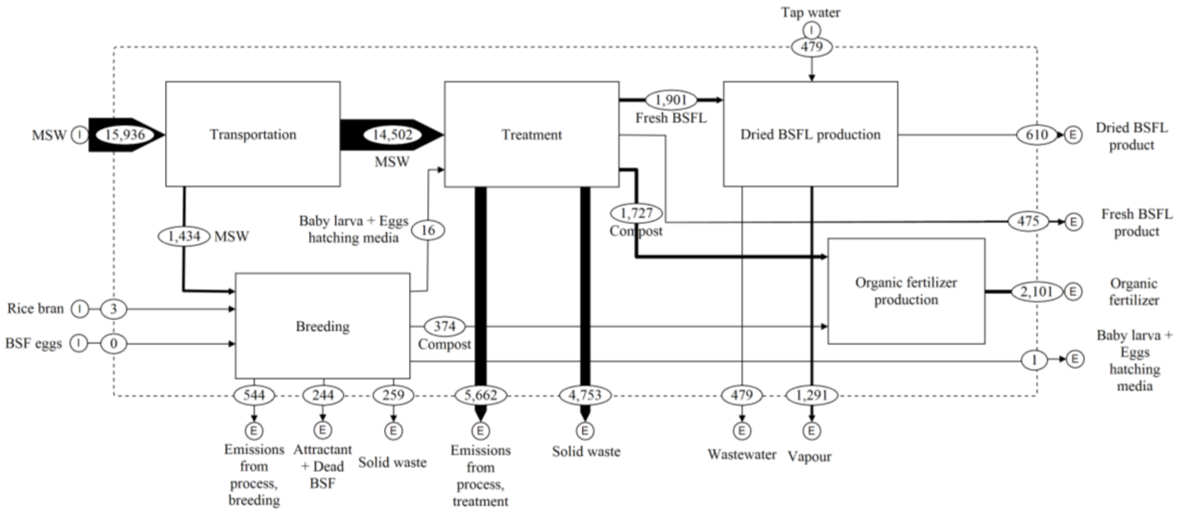


Figure 4. Total material flow analysis (MFA)

In contrast, waste used for BSFL feed is directly placed into bio-pond without sorting or pulverization. The BSFL rearing process typically lasts 1–2 months, untill the larvae metamorphose into adult flies (imago) ready for reproduction. The eggs are hatched in containers that have been filled with hatching media. Baby larva and egg hatching media as output of this unit process allocated as feedback for the breeding unit process (1 kg) and input for treatment unit process (16 kg). The breeding unit also generates 374 kg of BSF frass, 244 kg of attractants and dead BSF (reused), and 259 kg of solid waste. Additionally, the mass flow analysis indicates 544 kg mass loss attributed to emissions from the unit process of breeding.

The treatment of MSW using bioconversion represents the core business process of XYZ Ltd. In this unit process, organic materials in MSW are bio-converted into biomass and stored within the BSFL. The rearing process lasts 14 days until the BSFL are harvested. Harvesting is performed manually by sorting the BSFL, BSF frass, and solid waste. BSFL outputs allocated as fresh BSFL product (475 kg) and input for dried BSFL production unit process (1,901 kg). The treatment unit process produces 1,727 kg of BSF frass, 4,753 kg of solid waste, and 5,662 kg of emissions. The solid waste—consisting of non-degraded organic matter and inorganic waste from breeding and treatment units—disposed through open dumping.

The activities in the unit process of dried larvae production include fresh larvae drying using an electric oven and packaging. In this unit process BSFL are washed using tap water (479 kg) to remove any residues. The output from this unit process is dried BSF larvae (610 kg), water vapor (1,291 kg), and wastewater (479 kg). In the unit process of organic fertilizer production, post-composting and packaging processes are conducted. BSF frass from the unit process of breeding (374 kg) and treatment (1,727 kg) undergoes post-composting to achieve characteristics that meet the standards. Organic fertilizer (2,101 kg) is the output of this unit process.

Inventory Analysis

The inventory analysis of the MSWM system using BSF bioconversion in this study encompasses the inputs and outputs of all unit process, as presented in Table 1. The transportation of municipal solid waste from clients to XYZ Ltd. is carried out using two light commercial vehicles (LCVs) fueled by gasoline. The inventory data for the transportation process is measured in ton-kilometers (tkm), calculated by multiplying the vehicle load (tons) by the distance travelled (km). The distance between client locations and XYZ Ltd.'s waste management facility ranges from 10 to 45 km, with waste loads varying from 700 kg to 1.5 tons.

The material and energy consumption inputs for the unit process of breeding include MSW, a diesel-fueled waste pulverizer, and bran. The inventory analysis of the pulverizer's is measured in terms of operating time (hours). Outputs from the breeding process consist of solid waste, attractants, dead BSF, and emissions from the process. The attractants and dead BSF are reused in subsequent breeding cycles, while the solid waste identified as output are disposed through open dumping.

In the unit process of treatment, MSW is the primary input, with solid waste and emissions recorded as outputs. In the dried BSF larvae production unit process, 714 kWh of electricity is consumed to operate the oven and packaging machinery, while 183 m² of aluminium foil is used for packaging the dried larvae. In the organic fertilizer production unit process, inputs include 2,101 kg of BSF frass, 185 kg of low-density polyethylene (LDPE) for packaging, and 0.01 kWh of electricity for packaging operations.

Table 1. Life cycle inventory (LCI) of MSWM system using BSF bioconversion

Unit Process	Input	Amount	Unit	Output	Amount	Unit
Transportation[1]	LCV Clients 1	50	tkm			
	LCV Clients 2	13	tkm			
	LCV Clients 3	9	tkm			
	LCV Clients 4	41	tkm			
	LCV Clients 5	62	tkm			
	LCV Clients 6	108	tkm			
	LCV Clients 7	12	tkm			
	LCV Clients 8	21	tkm			
	LCV Clients 9	3	tkm			
Breeding	MSW	1,434	kg	Solid waste	259	kg
	Waste pulverizer machine[2]	2	hours	Attractant and dead BSF	244	kg
	Rice bran	3	kg	Emissions from process, breeding	544	kg
Treatment	MSW	14,502	kg	Solid waste	4,753	kg
				Emissions from process, treatment	5,662	kg
Dried BSFL production	Fresh BSFL	1,901	kg	Wastewater	479	kg
	Electricity	714	kWh			
	Oven	713	kWh			
	Sealer	1	kWh			
	Aluminium foil	183	m2			
Organic fertilizer production	BSF frass	2,101	kg	Organic fertilizer product	2,101	kg
	LDPE	185	kg			
	Electricity	0.01	kWh			

[1]MSW transportation using LCV, petrol-fuel
[2]Waste pulverizer machine, diesel-fuel

Impact Assessment

Climate change refers to alterations in statistical properties related to precipitation, temperature, wind patterns, and humidity over time caused by natural phenomena and anthropogenic activities (Patil *et al.*, 2018). Anthropogenic activities, such as the production of goods and services, have been scientifically shown to emit greenhouse gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O)—leading to an accumulation of these gases in the atmosphere. Over time, this accumulation forms a dense layer that prevents solar radiation from being reflected into space, contributing to global warming potential (GWP). The GWP100 impact assessment, based on the functional unit of 1 ton of MSW managed using BSF bioconversion method, categorized by process unit and emission source illustrated in Figure 5 and Figure 6,

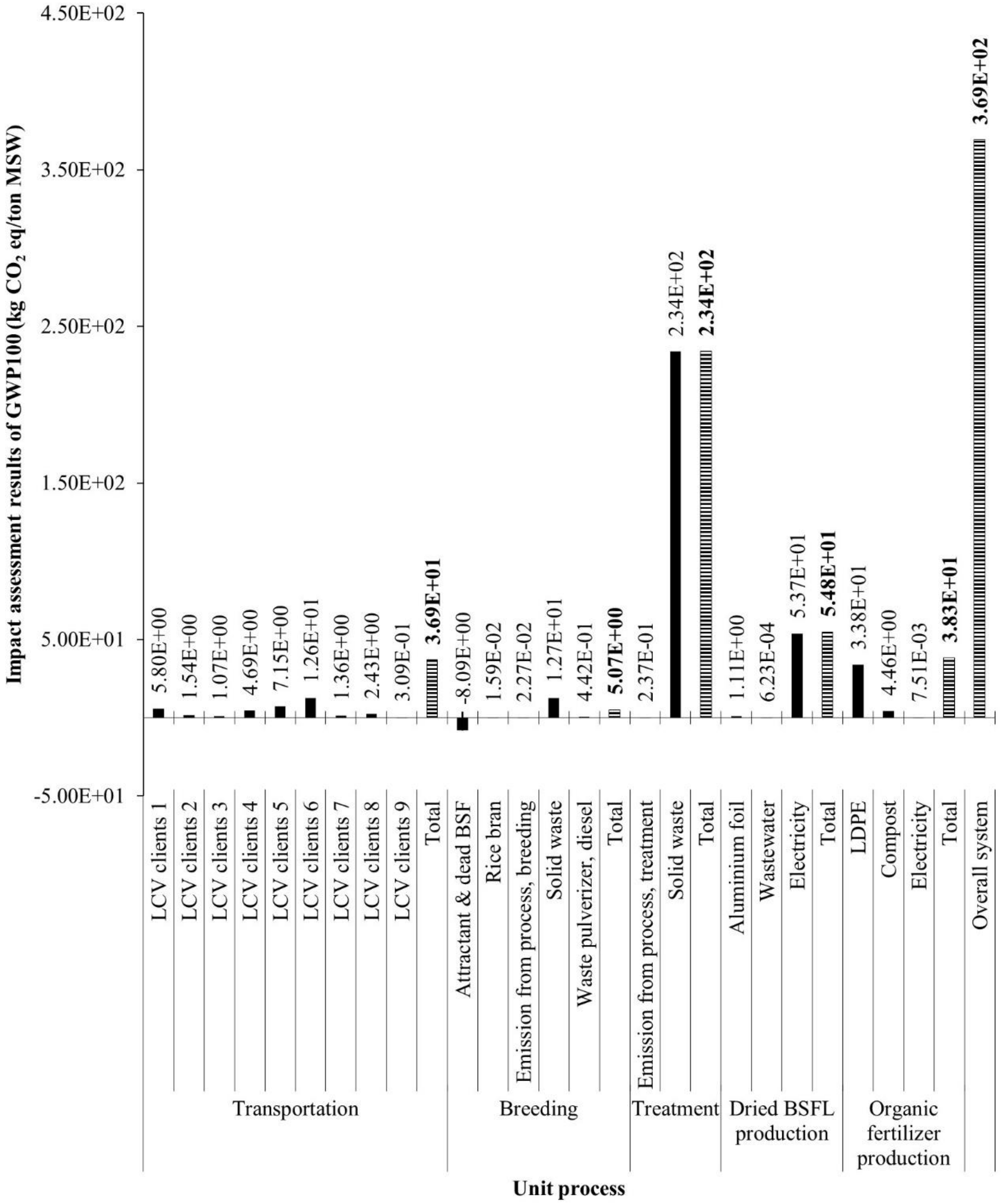
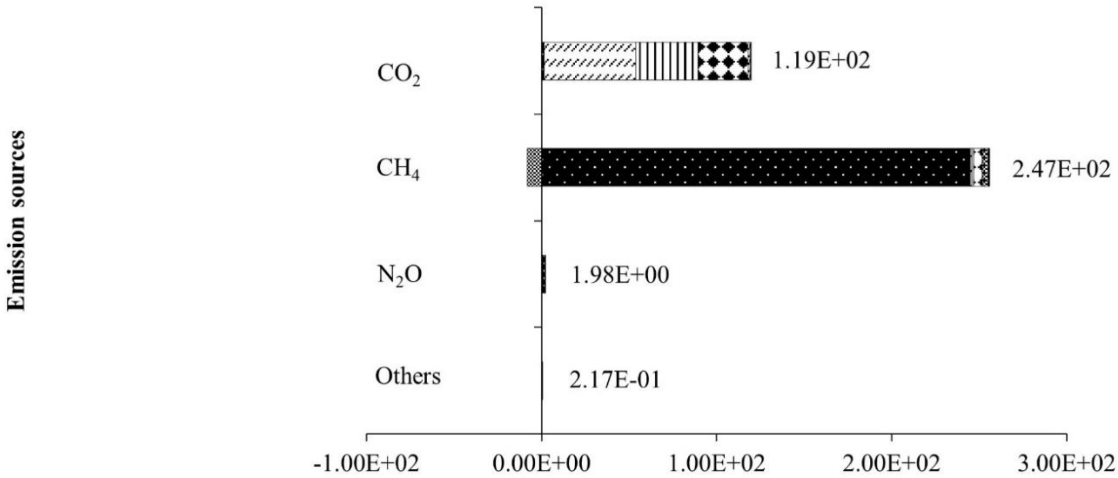


Figure 5. Life cycle impact assessment (LCIA) result of GWP100 based on process unit



	Others	N_2O	CH_4	CO_2
Solid waste	0.00E+00	0.00E+00	2.45E+02	1.66E+00
Electricity	9.18E-02	3.03E-01	1.05E+00	5.22E+01
LCV	4.83E-02	3.63E-01	1.03E+00	3.55E+01
LDPE	7.28E-02	1.54E-01	4.88E+00	2.87E+01
Compost	0.00E+00	9.00E-01	3.56E+00	0.00E+00
Aluminium foil	4.41E-03	1.08E-02	1.28E-01	9.71E-01
Waste pulverizer, diesel	1.46E-07	4.53E-03	1.60E-04	4.37E-01
Emission from process, treatment	0.00E+00	2.23E-01	1.34E-02	0.00E+00
Emission from process, breeding	0.00E+00	2.14E-02	1.29E-03	0.00E+00
Rice bran	1.11E-05	1.92E-04	4.08E-04	1.53E-02
Wastewater	0.00E+00	5.46E-04	5.04E-05	2.64E-05
Attractant & dead BSF	0.00E+00	0.00E+00	-8.09E+00	0.00E+00

Impact assessment results of GWP100a (kg CO_2 eq/ton MSW)

Figure 6. Life cycle impact assessment (LCIA) result of GWP100 based on type of emissions

The impact assessment results indicate that the GWP100 impact from MSWM systems using BSF bioconversion method is 3.69E+02 kg CO_2 eq/ton MSW. The most considerable environmental impact arises from the unit process of treatment, contributing 2.34E+02 kg CO_2 eq/ton MSW. Other process units, ranked from highest to lowest in terms of GWP100 impact, are dried BSF larvae production, organic fertilizer production, transportation, and breeding.

This study identified that most potential environmental impacts in a MSWM system utilizing BSF bioconversion stem from non-degradable solid waste produced by the unit process of treatment and breeding. The cumulative GWP100 impact from this solid waste is 2.47E+02 kg CO_2 eq/ton MSW, primarily due to high methane (CH_4) emissions from the open dumping of solid waste (Mohan dan Joseph, 2021). It is widely accepted that CO_2 emissions generated in organic waste management are biogenic and therefore considered neutral (IPCC, 2014; Wang dan Nakakubo, 2020).

Electricity consumption in the unit process of dried larvae and organic fertilizer production was identified as a significant emission source, contributing 5.37E+01 kg CO_2 eq/ton MSW, primarily due to CO_2 emissions from energy use of electricity. Furthermore, the transportation of MSW using light commercial vehicles (LCVs) results in a cumulative GWP100 impact of 3.69E+01 kg CO_2 eq/ton MSW, attributed to CO_2 emissions from fossil fuel consumption. These results are consistent with findings by Muis *et al.* (2023), which proved that greenhouse gas emissions from waste management processes, primarily driven by fossil fuel use, significantly contribute to global warming.

Low-density polyethylene (LDPE) packaging for organic fertilizer was also identified as a source of GWP100, with an impact value of 3.38E+01 kg CO_2 eq/ton MSW due to indirect CO_2 emissions from LDPE production. In contrast, reusing attractants and dead BSF produced a negative GWP100 impact (-8.09E+00 kg CO_2 eq/ton MSW). Emissions from post-composting, breeding, and treatment processes, along with aluminium foil packaging, waste pulverizers, bran, and wastewater, were minor due to the relatively small quantities involved.

Methane (CH_4) and carbon dioxide (CO_2) were the dominant contributors to GWP100 impacts, with impact values of 2.47E+02 kg CO_2 eq/ton MSW and 1.19E+02 kg CO_2 eq/ton MSW. Additionally, nitrous oxide (N_2O) emissions contributed 1.98E+00 kg CO_2 eq/ton MSW. Other minor greenhouse gas emissions identified in the study collectively resulted in an impact value of 2.17E-02 kg CO_2 eq/ton MSW.

Interpretation and Recommendations for Improvement

The relative contribution results presented in Figure 7 indicate that the process units with the highest to lowest percentages of contribution are as follows: treatment (64%), production of dried BSFL (15%), production of organic fertilizer (10%), transportation (10%), and breeding (1%). Additionally, solid waste was identified as the most significant emission source, contributing 67% to GWP100a impacts (Figure 8). The contribution by source, from highest to lowest, was electricity consumption (15%), LCV use (10%), LDPE packaging (9%), and BSF frass production (1%). Reusing attractants and dead BSF reduced the environmental impact of GWP100a by 2%.

Based on the data above, solid waste disposed of through open dumping, originating from the treatment and breeding process units and not reused by the company, is the primary contributor to GWP100a impacts. The interpretation results align with the understanding that open dumping, particularly under anaerobic conditions, generates significant greenhouse gas (GHG) emissions, with methane (CH_4) accounting for 50–60% and carbon dioxide (CO_2) for 30–40% of the waste volume (Abushammala *et al.*, 2012). Moreover, CH_4 has a global warming potential 28–34 times greater than CO_2 over a 100-year period (Mousania *et al.*, 2024). Methane is produced by microbial activity during the decomposition of organic matter, which, in this case, originates from solid waste that BSFL does not degrade

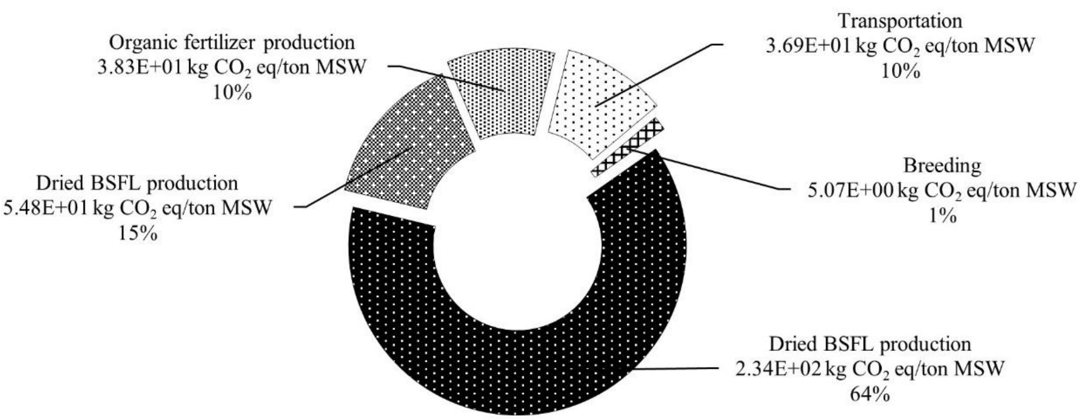


Figure 7. Relative contribution to the GWP100 impact based on unit process

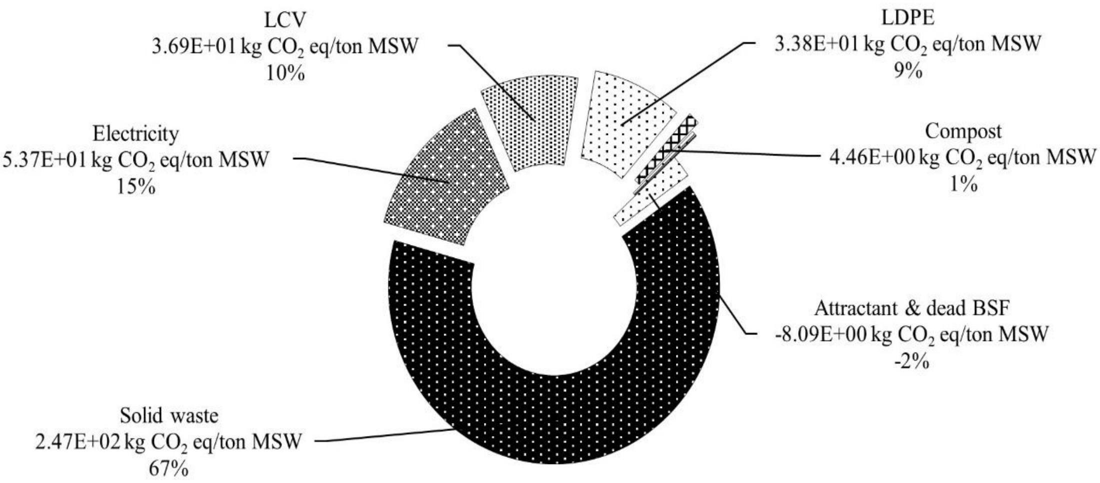


Figure 8. Relative contribution to the GWP100 impact based on emission source

Furthermore, the GWP100 impact of the MSWM system using BSF bioconversion derives from non-renewable materials and energy. The GWP100 impacts associated with electricity consumption are primarily due to Indonesia's heavy reliance on coal (Batih and Sorapipatana, 2016). According to research by Hasan *et al.* (2012), over 85% of the emissions from coal use in steam power plant turbines are GHG emissions.

Petroleum-based vehicle fuels and plastics are widely known to cause GHG emissions, which aligns with the findings of this study. Transportation of municipal solid waste using fossil-fueled LCVs contributes to GWP100a impacts. Numerous life cycle assessment (LCA) studies have shown that the distance and weight of materials transported by LCVs directly correlate with environmental impacts (Zuhria *et al.*, 2022; Brilianty *et al.*, 2023). This study also identified using LDPE for packaging organic fertilizer as a source of GHG emissions contributing to GWP100a impacts. These emissions are primarily generated from granulates which are plastic raw materials, and the electricity consumed in the extrusion process during LDPE production (Bakshi *et al.*, 2022).

Based on the interpretation of the results, improvements recommendation to reduce the potential GWP100 impact include enhancing bioconversion performance to reduce the amount of solid waste generated. Additionally, substituting and conserving energy and materials derived from non-renewable resources are advised. These measures are expected to mitigate CH_4 and CO_2 emissions, the dominant contributors to GWP100 impacts.

This study suggests five critical improvement scenarios: introducing pretreatment of municipal solid waste (S1); substituting electricity with photovoltaic (S2); prioritizing clients based on proximity (S3); substituting LDPE packaging with biocomposites (S4); and implementing a combination of all the scenarios (S5). The resulting changes in environmental impacts for each scenario are detailed in Table 2.

Scenarios 1: introducing pretreatment of municipal solid waste

Introducing pretreatment of municipal solid waste in BSF bioconversion, such as segregation and fermentation with bioactivators, has achieved a substrate consumption rate of 72% (Pathiassana *et al.*, 2020). Under these conditions, the residual output, consisting of solid waste and BSF frass, can be reduced to less than 28%, reducing emissions from the treatment process unit. This results in a 19% decrease in the GWP100 impact of the MSWM system. Based on observations, this improvement is feasible, given the availability of necessary facilities. Furthermore, almost similar pretreatment methods are already used in the BSF egg mass breeding unit.

Scenarios 2: substituting electricity with photovoltaic

Photovoltaic power systems are widely recognized as a sustainable energy source (Ansanelli *et al.*, 2021). In the MSWM system utilizing BSF bioconversion at XYZ Ltd. in Depok City, electricity powers the ovens and packaging machines in the unit process of dried BSF larvae and organic fertilizer production. Replacing conventional grid electricity with photovoltaic electricity is projected to reduce emissions from energy consumption across both production processes. Under this scenario, the electricity demands of the process units are met by photovoltaic power. The impact of this substitution on emissions was evaluated using the Ecoinvent v3.10 database, revealing a 13.88% reduction in potential GWP100 impacts from electricity consumption.

Scenarios 3: prioritizing clients based on proximity

The analysis of the findings indicates that the utilization of LCVs for the transportation of MSW from client sites to the waste management facility managed by XYZ Ltd. is a substantial source of emissions that contributes to the possible GWP100 effect. Emissions from this procedure are mostly determined by the weight of the cargo and the distance covered. Field observations suggest that XYZ Ltd.'s facility is optimally situated for governmental partnership, roughly 15 kilometers from the Cipayung Landfill in Depok City. This context allows for the consideration of prioritizing clients situated nearer to the facility, while preserving the identical load weight specified in the study's inventory data. The implementation of this scenario is anticipated to decrease the GWP100 effect by 2.50%.

Table 2. Changes in impact assessment results

Scenarios	Business as usual (kg CO_2 eq/ton MSW)	Scenario implementation (kg CO_2 eq/ton MSW)	Impact changes (kg CO_2 eq/ton MSW)	Percentage (%)
S1	3.69E+02	2.99E+02	7.01E+01	19.00%
S2	3.69E+02	3.18E+02	5.12E+01	13.88%
S3	3.69E+02	3.60E+02	9.23E+00	2.50%
S4	3.69E+02	3.36E+02	3.26E+01	8.84%
S5	3.69E+02	1.62E+02	2.07E+02	56.02%

Scenarios 4: Substituting LDPE Packaging With Biocomposites

Numerous studies have been undertaken to develop biocomposite films as a more sustainable alternative to low-density polyethylene (LDPE) (Abbate *et al.*, 2022). This study builds upon the work of Günkaya dan Banar (2016), who developed biodegradable films from pectin jelly sourced from orange peel and corn starch, which are considered to have a lower environmental impact than LDPE. Replacing LDPE packaging with these biocomposite films has been shown to reduce the GWP100 impact value by 8.84%.

Scenarios 5: Implementing A Combination Of All The Scenarios

It is essential to highlight that several assumptions have been revised in calculating the impact changes associated with this scenario. In contrast to the previous scenario, waste pretreatment in the first scenario is assumed to reduce solid waste generation while increasing the input of fresh BSF larvae and BSF frass into the BSF larvae production and solid organic fertilizer units. While the environmental impact of solid waste generation decreases, the higher inputs of fresh larvae and BSF frass lead to increased demand for electrical energy and packaging materials in the production processes. Additionally, emissions from bioconversion and post-composting processes also rise. Under these conditions, the simultaneous implementation of all proposed improvements would result in a 56.02% reduction in the GWP100 impact of the MSWM system using BSF bioconversion.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The findings of this study indicate that the management of 1 ton of municipal solid waste through the BSF bioconversion method has a potential GWP100 impact of 3.69E+02 kg CO_2 eq/ton MSW. The primary greenhouse gases contributing to this impact are CH_4, with an impact value of 2.47E+02 kg CO_2 eq/ton MSW, and CO_2, with an impact value of 1.19E+02 kg CO_2 eq/ton MSW. Solid waste output from the treatment and breeding process, disposed of in open dumping, is identified as the most significant emission source, accounting for 67% of the total potential GWP100 impact (2.57E+02 kg CO_2 eq/ton MSW). Significant contributors include electricity use in producing dry BSF larvae and organic fertilizer, using light commercial vehicles (LCVs) for transportation, and LDPE packaging for organic fertilizer products.

The proposed improvement strategies focus on enhancing bioconversion efficiency to minimize solid waste generation and reduce reliance on non-renewable materials. Recommended measures include introducing pretreatment of municipal solid waste; substituting electricity with photovoltaic; prioritizing clients based on proximity; substituting LDPE packaging with biocomposites; and implementing a combination of all the scenarios. These combined interventions could reduce the overall GWP100 impact by 56.02%.

Recommendations

Further research needs to be conducted to evaluate various categories of impacts with coverage of the entire product life cycle (cradle-to-grave). Standardization is needed to build an emissions database, especially in assessing the environmental impacts of MSWM systems using the black soldier fly (*Hermetia illucens*) bioconversion method in Indonesia, both direct and indirect. Furthermore, conducting an in-depth analysis of recommendations for improvement through economic, policy and management approaches is necessary. To minimize the overall environmental impact, research must be conducted to design a MSWM system with a closed-loop model.

Implementing the BSF bioconversion method in organic waste management has proven effective, efficient, and environmentally friendly. However, the efficiency of this method can be achieved optimally if organic waste has been separated from inorganic waste since the collection and transportation process. Therefore, cooperation between various parties is needed to implement this. Support from the government through implementing policies that encourage the implementation of collaborative MSWM systems can make a significant contribution. This can be done through incentive schemes or grants in the form of facilities or equipment, given the funding opportunities through the Carbon Pricing policy.

ACKNOWLEDGMENTS

The author extends sincere gratitude to the top manager and staff of XYZ Ltd. Depok City, for their valuable cooperation during the data collection process for this study. Additionally, this research was supported by the Patera Nusantara Lestari Foundation (Patera Foundation), for which the author is deeply appreciative.

REFERENCES

Abbate E, Rovelli D, Andreotti M, Brondi C, Ballarino A. 2022. Plastic packaging substitution in industry: Variability of LCA due to manufacturing countries. *Procedia CIRP*. Volume ke-105. Elsevier B.V. P 392–397.

Abushammala MFM, Basri NEA, Basri H, Kadhum AAH, El-Shafie AH. 2012. Methane and carbon dioxide emissions from Sungai Sedu open dumping during wet season in Malaysia. *Ecological Engineering*. 49 : 254–263.

Ansanelli G, Fiorentino G, Tammaro M, Zucaro A. 2021. A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels. *Applied Energy*. 290 : 116727.

Bakshi P, Pappu A, Bharti DK, Parmar B, Patidar R, Srivastava AK. 2022. Life cycle assessment of calcium-rich industrial waste reinforced polypropylene and low-density polyethylene composites using the cradle-to-gate approach. *ACS Sustainable Chemistry & Engineering*. 10 (41): 13710–13721.

Batih H and Sorapipatana C. 2016. Characteristics of urban households' electrical energy consumption in Indonesia and its saving potentials. *Renewable and Sustainable Energy Reviews*. 57 : 1160–1173.

Bava L, Jucker C, Gislon G, Lupi D, Savoldelli S, Zucali M, Colombini S. 2019. Rearing of Hermetia Illucens on Different Organic By-Products: Influence on Growth, Waste Reduction, and Environmental Impact. *Animals*. 9 (6): 289.

Brilianty SL, Suprihatin, and Purwoko. 2023. Penilaian daur hidup produk susu sapi segar: studi kasus di KPBS Pangalengan. *Jurnal Teknologi Industri Pertanian*. 32 (3): 220–228.

Ermolaev E, Lalander C, and Vinnerås B. 2019. Greenhouse gas emissions from small-scale fly larvae BSF frassing with Hermetia illucens. *Waste Management*. 96 : 65–74.

Fatimah YA, Govindan K, Murniningsih R, Setiawan A. 2020. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: A case study of Indonesia. *Journal of Cleaner Production*. 269 : 122263.

Günkaya Z and Banar M. 2016. An environmental comparison of biocomposite film based on orange peel-derived pectin jelly-corn starch and LDPE film: LCA and biodegradability. *International Journal of Life Cycle Assessment*. 21 (4): 465–475.

Guo H, Jiang C, Zhang Z, Lu W, Wang H. 2021. Material flow analysis and life cycle assessment of food waste bioconversion by black soldier fly larvae (Hermetia illucens L.). *Science of The Total Environment*. 750

Hasan MH, Muzammil WK, Mahlia TMI, Jannifar A, Hasanuddin I. 2012. A review on the pattern of electricity generation and emission in Indonesia from 1987 to 2009. *Renewable and Sustainable Energy Reviews*. 16 (5): 3206–3219.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Summary for Policymakers. (ed.) *Climate Change 2013 – The Physical Science Basis*. Cambridge: Cambridge University Press. P 1–30.

Ites S, Smetana S, Toepfl S, Heinz V. 2020. Modularity of insect production and processing as a path to efficient and sustainable food waste treatment. *Journal of Cleaner Production*. 248 .

Kawasaki K, Kawasaki T, Hirayasu H, Matsumoto Y, Fujitani Y. 2020. Evaluation of fertilizer value of residues obtained after processing household organic waste with Black Soldier Fly Larvae (Hermetia illucens). *Sustainability*. 12 (12): 4920.

Kaza S, Yao LC, Bhada-Tata P, Van Woerden F. 2018. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. Washington, DC: World Bank.

Klöpffer W and Grahl B. 2014. *Life Cycle Assessment (LCA): A Guide to Best Practice*. Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA.

Lohri CR, Camenzind EJ, and Zurbrügg C. 2014. Financial sustainability in MSWM – costs and revenues in Bahir Dar, Ethiopia. *Waste Management*. 34 (2): 542–552.

Mohan S and Joseph CP. 2021. Potential hazards due to municipal solid waste open dumping in India. *Journal of the Indian Institute of Science*. 101 (4): 523–536.

Mousania Z, Rafiee R, Moeinaddini M, Atkinson JD. 2024. Anaerobic digestion of the organic fraction of municipal solid waste in a simulated bioreactor to improve predictive modeling of landfill systems. *Journal of Hazardous Materials Advances*. 13.

Muis R, Rachman I, and Matsumoto T. 2023. A life cycle assessment of biological treatment scenario of municipal solid waste in developing country (case study: Makassar, Indonesia). *IOP Conference Series: Earth and Environmental Science*. Volume ke-1263. Jakarta, Indonesia.

Paes MX, de Medeiros GA, Mancini SD, Bortoleto AP, Puppim de Oliveira JA, Kulay LA. 2020. Municipal solid waste management: Integrated analysis of environmental and economic indicators based on life cycle assessment. *Journal of Cleaner Production*. 254 .

Pathiassana MT, Izzy SN, Haryandi, Nealma S. 2020. Studi laju umpan pada process biokonversi dengan variasi jenis sampah yang dikelola PT. Biomagg Sinergi Internasional menggunakan Larva Black Soldier Fly (Hermetia illucens). *Jurnal Tambora*. 4 (1): 86–95.

Patil A, Phule Krishi Vidyapeeth M, Mutum Lamnganbi I. 2018. Impact of climate change on soil health: A review Atish Patil and Mutum Lamnganbi. ~ *2399 ~ International Journal of Chemical Studies*. 6 (3).

Peña C, Civit B, Gallego-Schmid A, Druckman A, Caldeira-Pires A, Weidema B, Mieras E, Wang F, Fava J, Canals LM. 2021. Using life cycle assessment to achieve a circular economy. *International Journal of Life Cycle Assessment*. 26 (2): 215–220.

Salomone R, Saija G, Mondello G, Giannetto A, Fasulo S, Savastano D. 2017. Environmental impact of food waste bioconversion by insects: Application of Life Cycle Assessment to process using Hermetia illucens. *Journal of Cleaner Production*. 140 : 890–905.

Smetana S, Palanisamy M, Mathys A, Heinz V. 2016. Sustainability of insect use for feed and food: Life Cycle Assessment perspective. *Journal of Cleaner Production*. 137: 741–751.

Spykman R, Hossaini SM, Peguero DA, Green A, Heinz V, Smetana S. 2021. A modular environmental and economic assessment applied to the production of Hermetia illucens larvae as a protein source for food and feed. *he International Journal of Life Cycle Assessment*. 26 : 1959–1976.

Suprihatin, Indrasti NS, and Romli M. 2008. Potensi penurunan Emissions gas rumah kaca melalui pengomposan sampah. *Jurnal Teknologi Industri Pertanian*. 18 (1): 53–59.

Wang K and Nakakubo T. 2020. Comparative assessment of waste disposal systems and technologies with regard to greenhouse gas emissions: A case study of municipal solid waste treatment options in China. *Journal of Cleaner Production*. 260 : 120827.

Wiloso EI, Nazir N, Hanafi J, Siregar K, Harsono SS, Setiawan AAR, Muryanto, Romli M, Utama NA, Shantiko B, *et al.* 2019. Life cycle assessment research and application in Indonesia. *The International Journal of Life Cycle Assessment*. 24 (3): 386–396.

Xin C, Zhang T, Tsai SB, Zhai YM, Wang J. 2020. An empirical study on greenhouse gas emission calculations under different MSWM strategies. *Applied Sciences (Switzerland)*. 10 (5).

Yuwono AS and Mentari PD. 2018. *Penggunaan Larva (BSFL) Black Soldier Fly (BSF) dalam Pengelolaan Limbah Organik*. Ed ke-1. Bogor: SEAMEO BIOTROP. www.biotrop.org.

Zuhria SA, Indrasti NS, and Yani M. 2022. Kajian dampak lingkungan produk tepung agar menggunakan metode life cycle assessment (LCA). *Jurnal Teknologi Industri Pertanian*. 31 (3): 343–355.