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Developing the Product Carbon Footprint for Polymer-based Chemicals via a Life Cycle Assessment Approach

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In the pursuit of mitigating the adverse environmental impacts of industrial activities, the concept of product carbon footprint (PCF) has gained significant traction in recent years, especially for polymers and plastics that are difficult to degrade naturally. To evaluate the global warming potential of polymer-based chemicals, this study assesses the PCF of Chemical A produced by a chemical plant in Malaysia. The analysis follows ISO 14067:2018 and the PCF Guideline for the Chemical Industry, considering a cradle-to-gate approach for the fiscal year 2021. The results indicate significant carbon emissions at various life cycle stages of polymer, in which the material acquisition stage was identified as the GHG hotspot contributing 77 % to Chemical A’s PCF. One kg of Chemical A produced is associated with an emission of 3.73 kg carbon dioxide equivalent (CO_2e). The study highlights areas for potential environmental improvement from the sourcing of energy and raw materials, to outline corporate sustainability strategies and serves as a model for other chemical companies.

1. Introduction

Polymer products are ubiquitous in our daily lives, appearing in items such as pens, bottles, coatings, composites, and tires (Thomas and Patil, 2023). As polymers take a very long time to degrade, carbon footprint assessment of polymer-based materials plays a crucial role in evaluating their environmental performance and guiding the development of more sustainable alternatives (Suárez et al., 2021). By quantifying the greenhouse gas (GHG) emissions associated with the entire life cycle of a product, product carbon footprint (PCF) study can help identify hotspots for improvement and inform decision-making processes (Kharissova et al., 2024). The concept of carbon footprint originates from ecological footprint and has been extended to quantify product level GHG accumulation, including emissions from its upstream and downstream value chain (Li et al., 2024). The use of PCF has been useful in evaluating the environmental impact from food industry (Karalis and Kanakoudis, 2023) to aquaculture industry (Yang et al., 2023). Life cycle assessment (LCA) studies have been applied to examine the PCF for a range of polymer products, including bio-based and fossil fuel-based polymers (Lang et al., 2024). Hu et al. (2022) studied the global warming potential of an emerging polymeric material known as polyvinylidene fluoride (PVDF) whereas Kumar et al. (2022) compared the climate change impacts between acrylonitrile butadiene styrene (ABS), polylactic acid, and polyethylene terephthalate glycol (PETG). Existing carbon footprint studies tend to focus on the sustainability implications of plastic products and packaging materials. There is lack of comprehensive studies on polymer-based chemicals served as additives or modifiers in plastic products, which is a significant research gap in the development of green plastic supply chain.
This study aims to quantify the GHG emissions associated with the production of a polymer-based chemical product, Chemical A, manufactured by a plant. Chemical A alters the properties of the original plastics to improve on the lack of certain properties. In polyvinyl chloride (PVC), this chemical is added to improve the impact resistance. In certain engineering plastics, Chemical A is added to improve appearance, impact resistance or even to provide flame-retardancy. The PCF assessment of Chemical A adheres to international standards,

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providing a basis for strategic sustainability initiatives. By focusing on these specific products, the study highlights the emission-intensive phases of their cradle-to-gate life cycle, from raw material extraction, transportation to production. Despite the increasing awareness of environmental sustainability, there is a significant lack of comprehensive carbon footprint data for specific chemical products like Chemical A and Chemical B. This gap limits the ability of companies to implement targeted sustainability initiatives effectively. The motivation behind this study is to assist this plant in planning and strategising its environmental sustainability initiatives by identifying key areas where emissions can be reduced. This research not only supports the company's internal sustainability goals but also aligns with Malaysia's national commitments to achieve net zero. The findings are expected to serve as a model for other companies in the region, demonstrating the practical application of PCF assessments in driving substantial environmental benefits.

2. Methodology

International standards have been developed to standardise the definition and boundary of product carbon footprint such as the "ISO 14067: 2018 Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification and communication" published by International Organization for Standardization (ISO) (Li et al., 2024). The PCF quantification in this study follows the ISO 14067:2018 guidelines and the "The Product Carbon Footprint Guideline for the Chemical Industry" published by Together for Sustainability (TfS). The study covers a cradle-to-gate scope, examining emissions from raw material acquisition to the factory gate. The declared unit is one tonne of product. Data for the fiscal year 2021 were provided by the company, supplemented with secondary data where necessary. The system boundary includes raw material extraction, transportation, manufacturing, and associated emissions.

2.1 Data collection

Primary data were collected from the company's production records, including energy usage, raw material consumption, and production volumes. Secondary data were sourced from reputable databases for emission factors, including Ecoinvent and DEFRA. The data quality was ensured through cross-verification with industry standards and by applying uncertainty analysis to account for any data gaps or assumptions.

2.2 Goal and scope definition

The goal of the study is to provide a comprehensive carbon footprint analysis of Chemical A to identify major emission sources and opportunities for mitigation. The scope includes defining the system boundaries, selecting appropriate emission factors, and applying allocation procedures for multi-output processes

2.3 System boundary and process map

The system boundary includes upstream processes such as raw material extraction and transportation to the manufacturing plant, as well as core processes like production and packaging. A detailed process map (Figure 1) was created to visualize all relevant stages and their associated emissions, ensuring a thorough assessment. This map includes specific stages such as polymerization, extrusion, blending, and packaging.

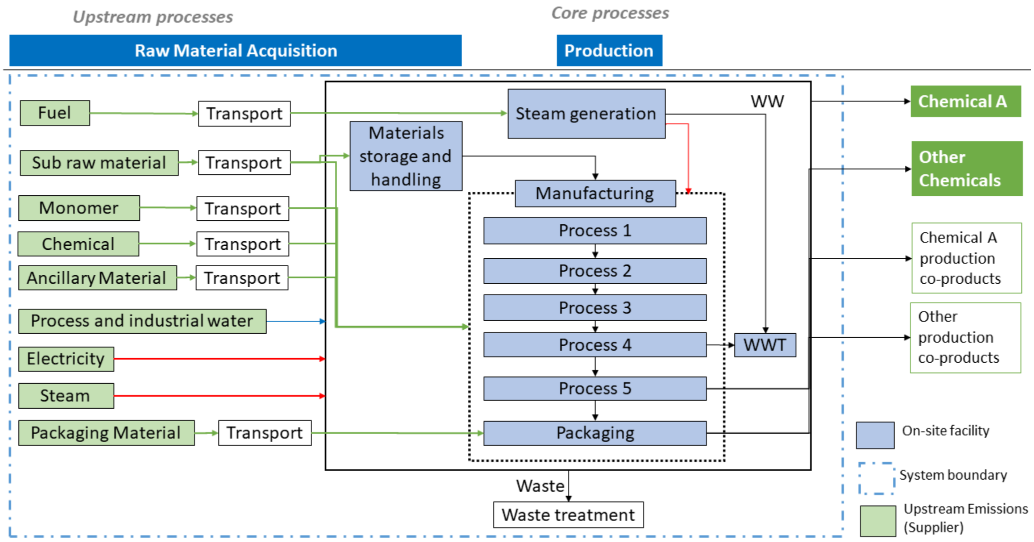

Figure 1: System boundary for PCF assessment of Chemical A

2.4 Allocation procedures

Allocation procedures were necessary for processes that produce multiple outputs. Physical allocation based on mass was applied, as it is consistent with the nature of the production processes and provides a straightforward approach to distributing emissions. This method ensures that the carbon footprint is accurately attributed to each product based on its proportion in the total output.

2.5 Life cycle inventory analysis

Life cycle inventory (LCI) analysis involved compiling and quantifying inputs and outputs for each process within the system boundary. This included materials, energy, and emissions data, which were then used to calculate the overall carbon footprint. Key inventory data are summarised in Table 1 and Table 2. Table 1 summarised the emission factors gathered for transportation activities based on mode of transportation and production waste treatment based on treatment type and waste type.

Table 1: Inventory data for transportation and waste treatment

Data Item	Material Type	Origin	Emission Factor (EF)			
			Value	Unit	Source	EF Description
Truck (3.5-70 t Gross Vehicle Weight)	Transport	Asia	0.384 - 0.066	$kgCO_2e$/ metric t*km	GLEC Framework v3	-
Truck/ Lorry	Transport	Global	0.1347	$kgCO_2e$/ metric t*km	Ecoinvent 3.8	GLO, market group for transport, freight, lorry, unspecified
Container Ship	Transport	Global	0.0094	$kgCO_2e$/ metric t*km	Ecoinvent 3.8	GLO, market for transport, freight, sea, container ship
Landfill Disposal	Waste	Malaysia	0.954	$kgCO_2e$/ kg	BUR 4	-
Incineration (hazardous waste)	Waste	Malaysia	2.417	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, treatment of hazardous waste, hazardous waste incineration
Incineration (polypropylene)	Waste	Malaysia	2.555	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, treatment of waste polypropylene, municipal incineration
Incineration (paper)	Waste	Malaysia	0.071	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, treatment of waste packaging paper, municipal incineration
Incineration (SW410)	Waste	Malaysia	2.159	$kgCO_2e$/ kg	Supplier, Ecoinvent 3.8	RoW, treatment of hazardous waste, hazardous waste incineration
Wastewater Discharge	Waste	Malaysia	0.0088	kg CH_4/ kg COD	IPCC guidelines	-
			0.0079	kg N_2O/ kg N	IPCC guidelines	-
Aerobic Wastewater Treatment	Waste	Malaysia	0.0251	kg N_2O/ kg N	IPCC guidelines	-

Table 2 documented the emission factors applied for the consumption of packaging materials, fuel, water utility, and energy utility during the production of Chemical A.

Table 2: Inventory data for utility and other materials

Data Item	Material Type	Origin	Emission Factor (EF)			
			Value	Unit	Source	EF Description
Jumbo Bag (500 kg)	Packaging material	Vietnam	2.843	$kgCO_2e$/ piece	Ecoinvent 3.8	GLO, market for polypropylene, granulate + market for extrusion, plastic film
Paper Bag	Packaging material	Asia	0.699	$kgCO_2e$/ piece	Supplier	-
Liquefied Petroleum Gas (LPG)	Fuel gas	Global	0.621	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, market for liquefied petroleum gas
Natural Gas	Fuel gas	Global	0.284	$kgCO_2e/m^3$	Ecoinvent 3.8	RoW, market for natural gas, high pressure
Waste Gas	Fuel gas	Malaysia	3.259	$kgCO_2e$/ kg	Stoichiometry	-
Nitrogen	Ancillary material	Global	0.429	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, market for nitrogen, liquid
Process Water	Water	Global	2.7E-4	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, water production, deionized (waste excluded)
Industrialised Water	Water	Global	6.4E-5	$kgCO_2e$/ kg	Ecoinvent 3.8	RoW, water production, decarbonized (waste excluded)
Steam	Utility	Cogeneration plant	0.288	$kgCO_2e$/ kWh	Supplier	Combustion EF
		Cogeneration plant	0.033	$kgCO_2e$/ kWh	PGB	Upstream EF
Electricity (market-based)	Utility	Cogeneration plant	0.288	$kgCO_2e$/ kWh	Supplier	Combustion EF
			0.033	$kgCO_2e$/ kWh	PGB	Upstream EF
Electricity (location-based)	Utility	Peninsular Malaysia	0.758	$kgCO_2e$/ kWh	Energy Commission	Combustion EF
			0.154	$kgCO_2e$/ kWh	DEFRA	Upstream EF

2.6 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) focused on quantifying GHG emissions using the Global Warming Potential (GWP) over a 100-year time horizon. The primary impact category assessed was climate change, given its relevance to the study's objectives. The impact assessment involved applying characterisation factors to convert inventory data into potential environmental impacts.

3. Results and Discussion

The PCF for Chemical A was calculated as 3.73 kg carbon dioxide equivalent (CO_2e) per kg product without packaging, revealing that the majority of emissions stem from raw material extraction and energy consumption during manufacturing. The PCF profile breakdown for Chemical A based on one-year data of fiscal year 2021 are presented in Table 3 and Figure 2.

Table 3: GHG emissions from the life cycle stages of Chemical A production

Life cycle stage	Activity	GHG emissions (t CO_2e)	CFP (kg CO_2e/ kg)	Percentage contribution
Raw Material Acquisition	Raw material manufacturing and preprocessing	28,106.31	2.871	76.9 %
	T&D of raw materials	264.42	0.027	0.72 %
	Generation of energy utilities purchased	6,126.40	0.626	16.8 %
	Material storage and handling	0.56	0.0001	0.002 %
Production	Steam generation	1,860.00	0.190	5.09 %
	Manufacturing	30.42	0.003	0.08 %
	Wastewater treatment	11.62	0.001	0.03 %
	Waste treatment	139.42	0.014	0.38 %
Total		36,435.46	36,435.46	3.73

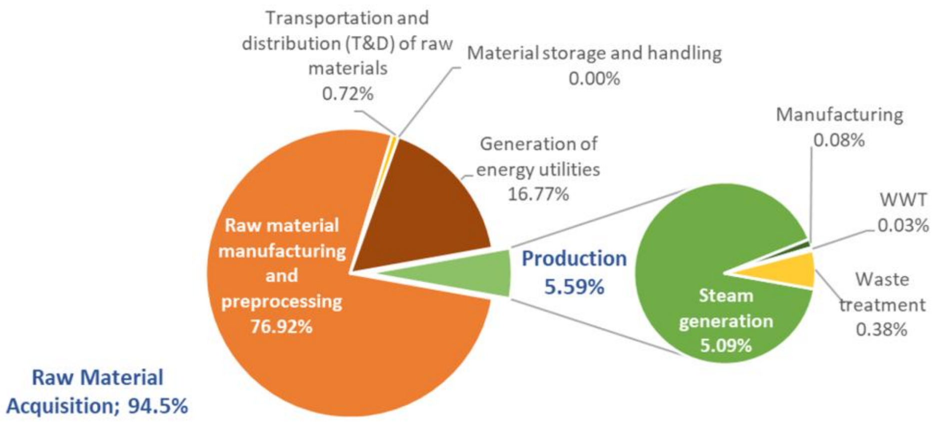

Figure 2: Product carbon footprint profile of Chemical A.

3.1 Detailed Emission Sources

Emissions from raw material extraction were significant, accounting for approximately 77 % of the total carbon footprint. This stage includes the extraction and initial processing of raw materials such as petroleum-based chemicals, fuel, catalyst, water, etc. A mixture of primary (supplier-specific) and secondary emission factors was applied for the LCIA. It is forecasted that the increase in the proportion of supplier-specific emission factors in future PCF assessment to improve data quality could greatly affect the raw material emissions due to adjustment based on technological and geographical specifications.

The manufacturing stage contributed around 24 % of the total emissions. This includes energy consumption for processes like polymerization, extrusion, and finishing, as well as emissions from process waste treatment. Generation of energy utilities purchased contributes up to 17 % of GHG emissions, followed by on-site steam production (5 %) to meet the electrical and thermal energy demand of Chemical A production.

Transportation of raw materials accounted for about 1 % of the emissions. This includes emissions from fuel combustion in trucks and ships for the delivery of raw material from the manufacturer to the plant gate. A shift from foreign suppliers to local suppliers could greatly reduce the transportation emissions.

3.2 Sensitivity Analysis on Energy Source

One of the GHG reduction initiatives that have been implemented by the chemical plant is the use of cleaner market-based electricity supplied from a nearby cogeneration plant (CP). Currently only less than 3 % of the electricity consumption for Chemical A production is supplied by the national grid. To exhibit the GHG reduction potential of shifting the energy source, a comparative analysis is performed to evaluate the GHG emission profile of Chemical A in Scenario A, B, and C: A) baseline scenario, B) 100 % grid electricity supply scenario, and C) 100 % CP electricity supply scenario. The results for the three scenarios are illustrated in Figure 3. It is proven that the substitution of 97 % electricity use with market-based electricity has helped the plant to reduce 67 % of GHG emissions in the generation of purchased utility and 25 % of Chemical A's PCF. There is a potential to further reduce the GHG emissions by 115 t CO_2e/y if all electricity consumed during Chemical A production is supplied by CP as in Scenario C.

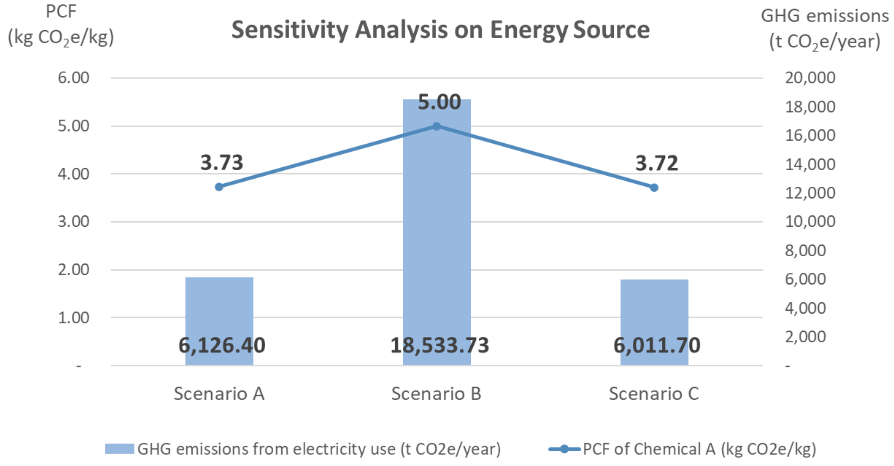

Figure 3: Sensitivity analysis on energy source for Chemical A production.

4. Conclusion

The PCF study of Chemical A provides a comprehensive understanding of the emissions associated with their production. The results serve as a benchmark for the company to enhance its environmental performance. Future work should focus on implementing the identified improvement strategies and continuously monitoring the carbon footprint to achieve long-term sustainability goals. Targeting raw materials with lower PCF or from nearer suppliers may effectively reduce the emissions at raw material acquisition stage, which is the GHG hotspot of Chemical A's life cycle. Full supply of greener electricity from CP could further reduce the GHG emissions in utility generation by 2 %. This study highlights the importance of integrating PCF assessments into corporate sustainability strategies and provides a model for other companies in the chemical industry. It is highly recommended to extend the scope of PCF study to include use stage and end-of-life stage of Chemical A for a more comprehensive environmental assessment featuring the complete plastic supply chain.

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