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Regional Case Study

Evaluating the Environmental Impacts of Thermoplastic Based-Product Manufacturing Using Life Cycle Assessment (CML-IA Midpoint)

Rahmad Firnandi[1], Tanti Utami Dewi[1]*, Rizka Amalia[2,3], Mirna Apriani[1]
[1] Waste Treatment Engineering Study Program, Department of Marine Engineering, Politeknik Perkapalan Negeri Surabaya, Jalan Teknik Kimia, Keputih, Sukolilo, Surabaya, Jawa Timur, Indonesia 60111
[2] Department of Industrial Chemical Engineering, Vocational School of Diponegoro University, Jalan Prof. Soedarto, S.H., Tembalang, Semarang, Jawa Tengah, Indonesia 50275
[3] RWTH Aachen University, Templergraben 55 52062 Aachen, Germany
* Corresponding Author, email: tanti.dewi@ppns.ac.id

Abstract
The rapid growth of thermoplastic manufacturing in Indonesia, particularly in thermoplastic-based products such as children's toys, has not been accompanied by sufficient environmental assessment, especially Life Cycle Assessment (LCA). While previous studies have mainly focused on extrusion processes, this study incorporated additional processes, such as spray coating, to provide a more representative evaluation. This study evaluated the environmental impacts of vacuum cleaner manufacturing using LCA with the CML-IA midpoint method. The data were processed using OpenLCA 2.4.1 and the ELCD database. The results indicate that producing one unit of a vacuum cleaner contributes to multiple environmental impact categories, including acidification (0.001 kg SO_2-eq), eutrophication (0.0001 kg PO_4^{3-}-eq), Freshwater Aquatic Ecotoxicity (0.001 kg 1,4-DB eq), and Global Warming Potential (4.208 kg CO_2-eq). Additional impacts were identified in Human Toxicity (0.406 kg 1,4-DB eq), Marine Aquatic Ecotoxicity (2558.698 kg 1,4-DB eq), Photochemical Oxidation (0.000025 kg C_2H_4-eq), and Terrestrial Ecotoxicity (0.041 kg 1,4-DB eq). Among these, Marine Aquatic Ecotoxicity emerged as a dominant contributor because of the presence of hydrogen fluoride released into the environment during the spraying process. To address this issue, mitigation measures, such as substituting inorganic paints in the spray coating process with organic or ecolabel-certified alternatives, have been proposed.

Keywords: Emissions; life cycle assessment; marine aquatic ecotoxicity; openLCA; vacuum cleaner.

1. Introduction

Plastic items are widely used in daily life. Plastic is utilized because of its water resistance, light weight, and inexpensive production costs (Kumar et al., 2020). Since the 1950s, plastic production has continued to expand owing to the economic advantages of plastic (Abrahms, 2023). The global production of plastics is estimated to reach 902-1124 million tons by 2050 (Geyer et al., 2017). Plastic is one of the main contributors to greenhouse gas emissions, accounting for 4.5% of the total emissions produced by various sectors (Issifu et al., 2025). From 2010 to 2015, plastic production increased by 4% per year, equivalent to 1.8 gigatons (Gt) CO2 eq. The production of plastics influences the global environmental system through carbon dioxide emissions. The Intergovernmental Panel on Climate Change (IPCC, 2021) states that the relationship between cumulative carbon emissions and global warming is direct. The IPCC estimates that every 100 Gt of CO_2 equivalent emitted to the atmosphere results in an increase in global temperature by 0.8–2.4°C.

The thermoplastic manufacturing sector in Indonesia has developed rapidly, especially in the production of consumer goods, such as children's toys. However, little attention has been paid to the environmental effects of the utilization of materials and manufacturing methods, while each product can give rise to various environmental impacts throughout its life cycle. In addition, the study of Life Cycle Assessment (LCA) in the thermoplastic industry in Indonesia is still very limited, which shows that there is a substantial gap in research on the assessment of the environmental performance of these products. Prior studies on thermoplastic production have predominantly focused on its basic processes, especially extrusion, which is a major source of environmental consequences. However, this approach may not completely characterize the general impact of a product system.

In this study, the assessment also considered additional processes, particularly the spray (coating) process, to enable a more complete and representative assessment of environmental loads. This procedure was included because it contributes to additional emissions from the chemicals used in the coating materials. The environmental problems associated with plastics are not limited to emissions from their production processes. Plastic waste is a major threat to terrestrial, marine, and freshwater environments (Stegmann et al., 2022). According to the studies conducted by Belli et al. (2024), plastic with a size of 25 mm or more can trigger toxic effects on biological ecosystems. Levesque et al. (2022) also showed that thermoplastic products contribute to several environmental impact categories, such as acidification (0.0051 kg SO_2 eq), eutrophication (0.0031 kg N eq), photochemical ozone formation (2.05 $\times 10^{-8}$ kg O_3 eq), and ozone depletion (2.05 × 10–8 kg CFC-11 eq). Furthermore, thermoplastics cause ecotoxicity (0.0174 CTUe) and greenhouse gas emissions (1.5375 kg CO_2 eq). Mannheim (2021) reported the following environmental impacts per kg of mixed plastics: abiotic depletion potential (fossil) 383 MJ eq, acidification potential 35 $\times 10^{-12}$ kg SO_2 eq, eutrophication potential 4.98 × 10 –12 kg PO 4 eq, and global warming potential (GWP) 119 × 10 –12 kg CO_2 eq. Other environmental impacts reported include human toxicity (38.90 × 10 – 12 kg DCB eq)q, marine aquatic ecotoxicit (586 × 10 – 12 kg DCB eq)q, photochemical ozone creatio (63.70 × 10 – 12 kg C_2H_4 eq)eq, and abiotic depleti (0.51 × 10 – 12 kg Sb eq)eq. The manufacturing of thermoplastic-based products generates significant environmental impacts; therefore, a thorough assessment of the process is required to prevent future environmental issues. Life Cycle Assessment (LCA) is one of the most commonly used approaches to determine the environmental impacts of plastic production (Wang et al., 2024). LCA is accepted worldwide as a legitimate and valid tool for statistically assessing the environmental implications of processes. The CML-IA, developed by the Centre for Environmental Science of Leiden University, the Netherlands, was used for the characterization approach applied in this study. The CML-IA midway technique is particularly relevant because its impact categories are widely acknowledged worldwide and provide a complete overview of natural resource depletion. Using the midpoint strategy (Levesque et al., 2022), this approach allows for the identification of specific environmental consequences. The CML-IA technique, first published in English in 1993, is considered a key advance that greatly reinforced the scientific basis of Life Cycle Assessment (Gabathuler, 1997).The midpoint method simplifies complex environmental data, provides more interpretable results, and allows for the direct evaluation of the most important effect categories (Asif & Javed, 2024).

The objective of this study is to provide the thermoplastic manufacturing industry with insights on how to tackle environmental impacts through the identification and mitigation of hotspots in the production process. Thus, thermoplastic-based products will not only be of excellent quality and earn industrial profit but also encourage environmentally friendly and sustainable production techniques.

2. Methods

The data used in this study were obtained from a thermoplastic-based product manufacturing industry, where the range of products produced was highly diverse. The dataset includes machine specifications, operational time, production volume, raw and auxiliary materials, detailed specifications of individual product components, and emissions released into the environment, such as ammonia (NH_3), chlorine (Cl), hydrogen chloride (HCl), hydrogen fluoride (HF), nitrogen dioxide (NO_2), particulate matter, sulfur dioxide (SO_2), hydrogen sulfide (H_2S), mercury (Hg), arsenic (As), antimony (Sb), cadmium (Cd), and zinc (Zn). The analysis was conducted using OpenLCA software supported by the ELCD database. The methodological framework of this study follows the guidelines of the ISO 14040 and ISO 14041 standards.

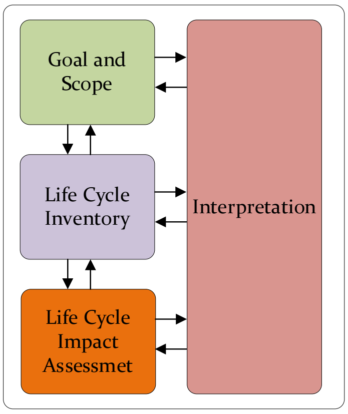

Figure 1. Stage of LCA framework

2.1 Goal and Scope Definition

The first step in a Life Cycle Assessment is to define the goal and scope, following the ISO 14040/44 standards. The goal is important because it dictates the intended use of this study. The objective of this study was to identify and quantify the potential environmental impacts related to the manufacturing of thermoplastic-based products, based on the methodological framework developed by Ly et al. (2025). In addition to identifying the impacts, this study aims to propose actionable mitigation strategies that can be applied to minimize the environmental burdens resulting from production processes. The scope of the study is illustrated in Figure 2, which provides a complete overview of the processes and flows.

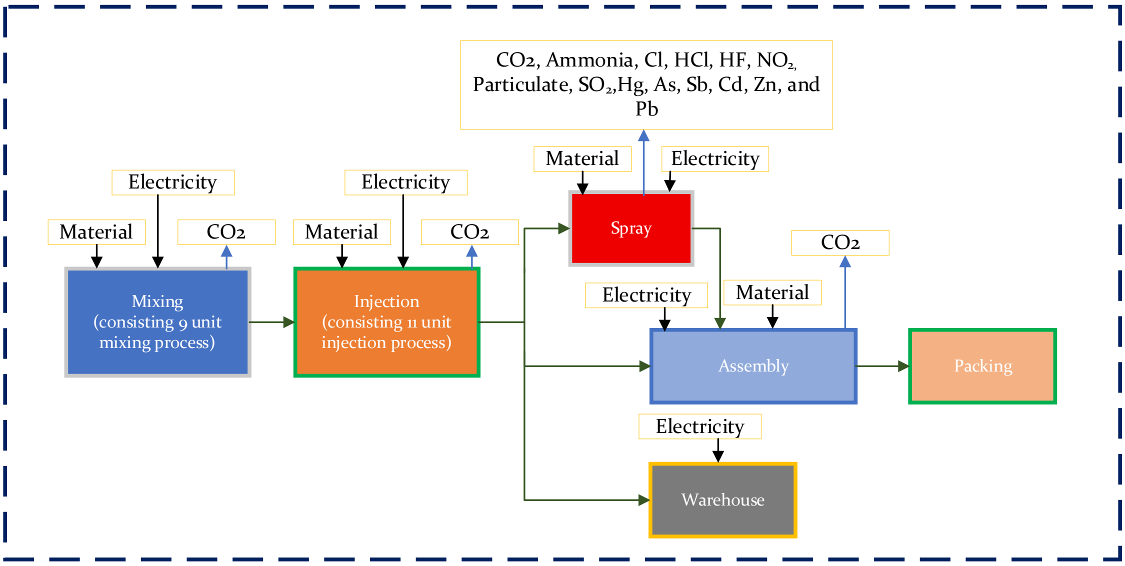

Figure 2. Scope of Research with gate-to-gate system boundary

2.2 Life Cycle Inventory

All data and information used to analyze the environmental impacts of thermoplastic-based products were subsequently entered into the OpenLCA software (The LCI) stage involved compiling detailed input and output data for each production process, including the quantity of raw materials, electricity consumption, and emissions released into environmental media such as air, water, and soil. The dataset processed in OpenLCA was derived from operational records covering a one-year period.One unit of the vacuum cleaner, including its packaging, has a total mass of 3.44 kg. Accordingly, the functional unit applied in this study was defined as one vacuum cleaner unit or piece.

2.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) stage is designed to perform a comprehensive assessment of the potential environmental impacts of a product. In this stage, researchers select the characterization method that will be employed to measure and quantify the impacts. The choice of an appropriate method is crucial because it directly affects the accuracy and reliability of the assessment outcomes. Through the LCIA process, the environmental impact values of the analyzed product can be calculated based on the inventory results obtained from the Life Cycle Inventory phase. All input data, including the amount of raw materials and energy consumed, as well as output data, such as emissions to air, water, and soil, compiled during the LCI stage, were subsequently transformed into specific impact categories. Thus, LCIA does not merely present raw data but provides a quantitative interpretation of the potential contributions of a product to various environmental issues, including global warming, eutrophication, and acidification. The impact categories that can be calculated using the CML IA characterization method are as follows:

2.3.1 Global Warming Potential

Global Warming Potential (GWP) is an indicator that refers to the increase in the average temperature at the Earth's surface as a result of greenhouse gas emissions. The largest contribution originates from the combustion of fossil fuels, such as coal, oil, and natural gas. GWP is expressed in kg CO2 equivalents (kg CO2 eq), where all emissions of greenhouse gases are converted to the equivalent impact on the global warming potential of 1 kg of CO2. Typical greenhouse gases include CO2, CH4, and N2O (Wan et al., 2024).

2.3.2 Human Toxicity

This indicator refers to the potential impact on human health caused by exposure to substances released into the air, water, and soil. While the direct effects of specific products on human health have not been measured recently, all factors with the potential to harm ecosystems are categorized into human toxicity, terrestrial ecotoxicity, and freshwater ecotoxicity. These impacts were measured in kg 1,4-dichlorobenzene equivalent (kg DCB eq) (Singh et al., 2024).

2.3.3 Photochemical Ozone Formation

Ozone in the tropospheric layer is considered harmful as it attacks organic compounds in plants and animals and increases the risk of respiratory problems during photochemical smog episodes. Photochemical ozone formation is expressed in kilograms of ozone equivalents (kg O_3 eq). Ozone is continuously formed and decomposed in the stratosphere during daytime through the Chapman mechanism.In the upper stratosphere where the air is less dense, oxygen atoms (O) may recombine to form O_2. With a higher concentration of O_2, oxygen atoms in the lower stratosphere are more likely to react with O_2 to produce O_3. Therefore, most of the ozone production occurs in the lower stratosphere at heights of 15–35 km, where there is sufficient O_2 and not all UV-C has been absorbed (Van et al., 2024).

2.3.4 Marine Eutrophication

Eutrophication occurs when nitrogen (N) and phosphorus (P) containing substances are released into the environment. Excessive amounts of these nutrients can cause the growth of algae and specific aquatic plants. Nitrogen is predominantly generated from agricultural fertilizer applications but can also be generated by combustion processes. Marine eutrophication is expressed in terms of kilograms of nitrogen equivalents (kg N eq). Excess ammonia in water bodies is a significant contributor to eutrophication (Stasiulaitiene et al., 2016).

2.3.5 Acidification

Acidification refers to the potential of emissions to cause acidification. The main emissions that contribute to acidification are sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3). These emissions were converted into a common unit of measurement expressed as kilograms of SO_2 equivalent (kg SO_2 eq) (Huang & Wang, 2024). The activities that trigger acidification include industrial processes, transportation, and agricultural practices.

2.4 Interpretation

Interpretation represents the final stage of Life Cycle Assessment. At this stage, recommendations are proposed in accordance with the defined goals and scope of the study. Mitigation strategies are directed toward hotspot processes and impact categories within the analyzed process to minimize potential environmental impacts. The results were interpreted using both the Life Cycle Inventory and Life Cycle Impact Assessment.

3. Result and Discussion

3.1 Thermoplastic based-product manufacturing

The production of thermoplastic-based products involves a sequence of stages, including mixing, injection, spray coating, assembly, and packaging. However, certain components produced during the injection molding stage are stored in warehouses as part of the inventory to meet product demand in the following year. The overall process flowchart for thermoplastic product manufacturing is shown in Figure 3.

Thermoplastic-based product process flowchart The first stage in the production process is mixing the thermoplastic material with the pigment. The pigment used was in powdered form. To achieve this, the materials were dispersed using a mechanical mixer, which applies mechanical energy to guarantee the homogeneous distribution of the pigment in the thermoplastic matrix. This step produces thermoplastic granules with a pigment-coated surface, delivering the desired color and specific visual characteristics according to the product specifications. Water or liquid is not added during the mixing step because the presence of liquid can degrade the intrinsic properties of thermoplastics (Foster Corporation, 2018). The moisture content of thermoplastic materials should not exceed 0.02%, as the material becomes brittle above this value. The water content influences the properties of the final product and energy consumption because of the additional drying step before the injection process (Ma et al., 2024). Injection molding is the most important step in the manufacturing of thermoplastic products because it allows the manufacturing of products with high dimensional accuracy and precision (Hu et al., 2025). The process starts with feeding thermoplastic granules into a hopper with a controlled heating system. The material is then transferred to the barrel, which is also equipped with a heating system, and melted at a temperature corresponding to the properties of the thermoplastic used. The melted polymer is injected under high pressure through the barrel using a screw or plunger mechanism, and the material is directed into a mold where it assumes the desired shape

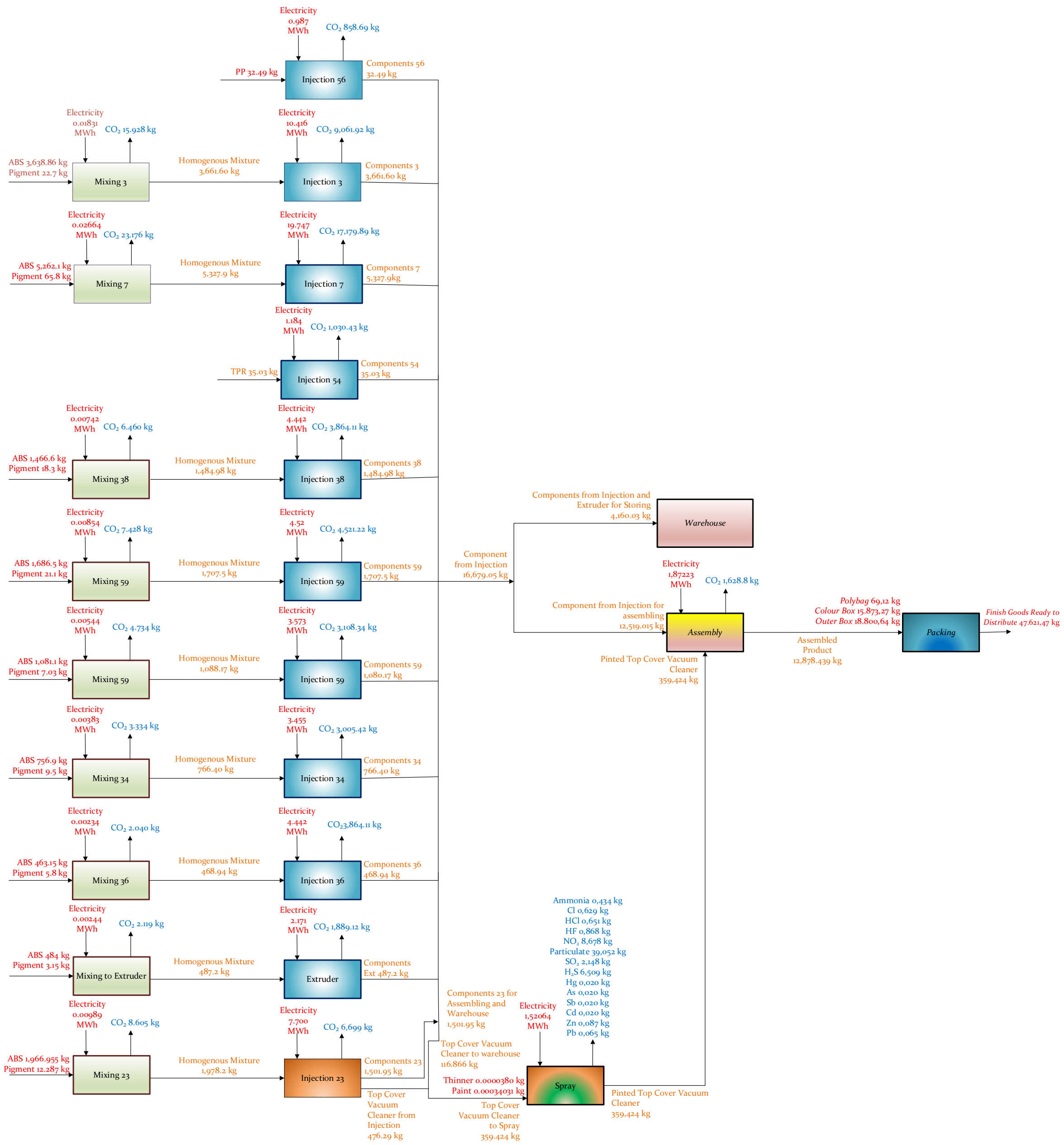

Figure 3. Thermoplastic based-product process flowchart

The spray process is used to coat specific product surfaces with paint. In this study, the component subjected to this process was the upper cover of the product. Spray coating requires additional materials, namely paint and thinner. Thinner has multiple functions, such as increasing gloss, increasing paint volume, and speeding up the drying process (Khasib, 2017). The next stage is assembly, which is the combination of components produced by injection molding and spray coating. This stage is performed manually and mechanically with the help of instruments such as screwdrivers, ultrasonic machines, and soldering tools. The result of this stage is a fully assembled component, which is then prepared for packaging. Packaging is the final step before product distribution. This stage is performed manually, where the product is first wrapped in a polybag and then placed in a packaging box to be distributed to consumers.

3.2 Characterization

The characterization stage involves identifying and classifying the input data from the life cycle inventory analysis into impact categories (Saffira et al., 2023). This stage is performed according to the chosen characterization method and database used, enabling a structured assessment of the potential environmental impacts. The characterization value is determined by multiplying the mass of each pollutant by its respective characterization factor for a specific environmental impact category. The results of the characterization stage are presented in figure 4.

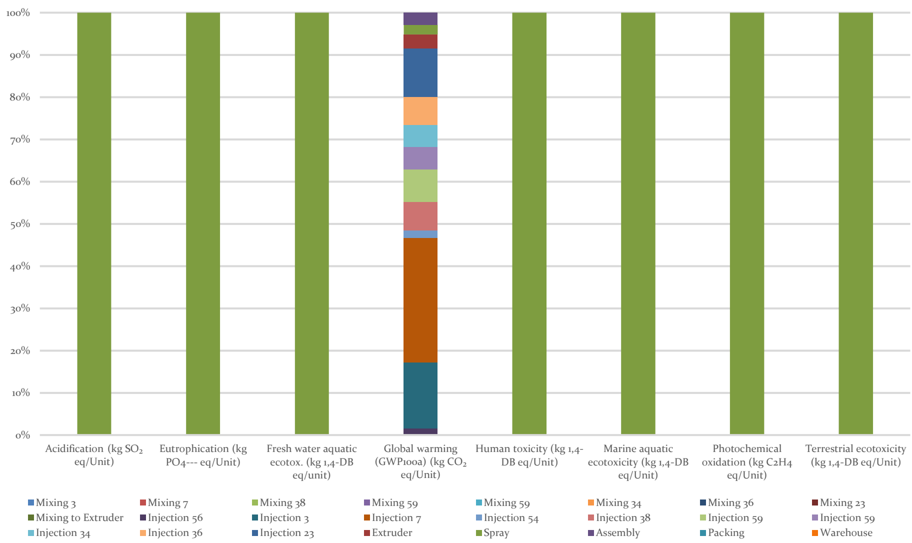

Figure 4. Result of characterization stage from thermoplastic based-product manufacturing

Global Warming Potential is identified as one of the major environmental impacts of vacuum cleaner manufacturing, contributing more significantly than other impact categories. The production of one unit of vacuum cleaner resulted in emissions equivalent to 4.208 kg CO_2-eq. Carbon dioxide is classified as a greenhouse gas that contributes to global temperature rise (Skytt et al., 2020). The high GWP value in the manufacturing of vacuum cleaners was caused by the electricity consumption during machine use, which directly led to CO_2 emissions. A study conducted by Kerr et al. (2022) also emphasized that the manufacturing sector significantly contributes to carbon dioxide emissions. High concentrations of $CO2$ or GWP can promote increasing temperatures, rising seawater levels, and heatwave risk (Al-yasiri & Geczi, 2021). The process unit that produces the highest $CO2$ is Injection 7, with a total of 17,179.89 kg $CO2$ eq produced during 1 year of the Vacuum Cleaner manufacturing process.

The environmental impact of Terrestrial Ecotoxicity refers to the negative effects of pollutants on terrestrial organisms. Following identification using OpenLCA, this impact was found to originate mainly from the spray unit. According to OpenLCA, the pollutants contributor of this effect are Hg, Cd, Zn, Pb, Sb, and HF. Following research conducted by Winter et al. (2025) explained that such pollution may disrupt the nitrification processes carried out by soil microorganisms. The presence of mercury in the coating process causes terrestrial ecotoxicity. Other pollutants, such as Polycyclic Aromatic Hydrocarbons (PAHs) (Aabbar et al., 2024), can also contribute to this effect. Ecotoxicity can be influenced by several factors, such as abiotic conditions, variations in the composition of the environmental matrix, pH, mineral conductivity, and biotic factors, particularly the structure and metabolic activity of microbial communities (Klátyik et al., 2023). The finished product, a Vacuum Cleaner ready for distribution, contributes 0.041 kg 1.4 DB eq.

Photochemical oxidation is an atmospheric impact category that refers to the formation of reactive oxidant compounds, particularly ground-level $O3$, through photochemical reactions involving precursor pollutants such as NOx and VOCs under solar radiation (Mishra et al., 2024). These reactions lead to the accumulation of secondary pollutants, which contribute to the formation of photochemical smog. Photochemical Oxidation has the potential to form summer smog resulting from reactions between sunlight and volatile organic compounds (VOCs) in the atmosphere (Baumann et al., 2004). The production of one vacuum cleaner contributed 0.000025 kg C_2H_4-eq to this impact category. Photochemical oxidation has many negative effects, including health problems in humans, such as irritation of the respiratory tract and reduced lung function, and damage to vegetation through impaired photosynthesis and reduced crop yields. High ozone levels can also damage materials such as rubber and plastics, affecting the lifespan of infrastructure if exposed for a long period. Thus, photochemical oxidation is an important environmental problem related to air pollution and urban industrial emissions (Kim et al., 2020).

The Human Toxicity category in vacuum cleaner manufacturing as a thermoplastic product is caused by the release of heavy metals such as Cd, Hg, and HF. The total impact of the Human Toxicity during one year of production was 5618.106 kg 1,4-DB eq, and the impact per unit product was 0.4009 kg 1,4-DB eq. Human Toxicity is the potential effect of toxic substances on human health. Microplastics and nanoplastics can also be considered emerging contributors to Human Toxicity (Jahedi & Fard, 2025). The human toxicity impact category in LCA is related to the potential negative effects on human health caused by exposure to toxic substances released during a product's life cycle, from production to use and final disposal. This impact category includes several exposure pathways, such as inhalation, ingestion, and dermal contact, through which hazardous chemicals, such as heavy metals, organic pollutants, and carcinogenic compounds, can enter the human body (Health, 2026). The effects of human toxicity can be acute, such as irritation and poisoning, or chronic, such as organ damage, endocrine disruption, reproductive toxicity, and increased cancer risk (Cheng, 2025). In LCA, these impacts are commonly quantified using characterization models, which convert emissions into a common unit (e.g., kg 1,4-dichlorobenzene equivalent) to allow comparison between different pollutants and processes. The human toxicity category provides an overall indication of the potential health burden associated with chemical exposure, leading to well-informed choices for safer and more sustainable product systems.

Freshwater aquatic ecotoxicity is the toxic effect of chemical pollutants on freshwater ecosystems, which can lead to loss of biodiversity and even extinction of some species (Oginah et al., 2023). This impact category could be caused by chemicals, heavy metals, microplastics and other pollutants on freshwater ecosystems. The impacts on aquatic organisms, including algae, daphnia, and fish, are estimated using acute and chronic toxicity tests with endpoints based on mortality, growth inhibition, and behavioral changes (Ghosh & Saha, 2022). Vacuum cleaner production affects this category because of the emissions of Hg, Cd, HF, and Zn, according to OpenLCA. The total impact per year of production was 17.5762 kg 1,4-DB eq, and the contribution per unit product was 0.0013 kg 1,4-DB eq.

Marine Aquatic Ecotoxicity is caused by toxic chemical pollutants that negatively affect marine ecosystems. HF is the major contributor to vacuum cleaner manufacturing. HF emissions released into the atmosphere can be transported and eventually deposited into marine environments, thereby decreasing the quality of oceanic ecosystems. Each vacuum cleaner unit contributed 2,558.6983 kg 1,4-DB eq to this impact category. Marine aquatic ecotoxicity refers to the adverse effects of hazardous substances on aquatic organisms in marine ecosystems following their release into the environment, including heavy metals, persistent organic pollutants (POPs), hydrocarbons, and other industrial chemicals (Bhuiyan et al., 2026). These contaminants enter the marine environment from several sources, including atmospheric deposition, river discharge, surface runoff, and direct industrial outfalls. These contaminants can also be present in seawater as dissolved substances, adsorbed on suspended particles, or settled as sediment, leading to their persistence and availability for organisms to uptake. Marine organisms, such as phytoplankton, zooplankton, fish, and benthic species, are exposed to such contaminants through direct absorption from water, ingestion of contaminated particles, or bioaccumulation via the food chain, causing toxic effects. Biomagnification results in an increase in the concentration of toxic substances at higher trophic levels over time (Sefali et al., 2026). Eutrophication causes growth stunting, reproductive failure, behavioral changes, oxidative stress, and increased mortality (Sefali et al., 2026).

Eutrophication can result in loss of biodiversity, destabilization of the structure and function of the ecosystem, and changes in trophic interactions (Sefali et al., 2026). Eutrophication is an environmental problem caused by excess nutrients in aquatic systems, especially nitrogen (N) and phosphorus (P), which cause rapid growth of algae and aquatic plants (Pannard et al., 2024). It can be caused by several pathways, including agricultural runoff containing fertilizers, direct discharge of untreated or partially treated domestic sewage, industrial effluents, atmospheric deposition of nitrogen compounds, and leaching from soil (Omoregie et al., 2025). It is caused by excess nutrients in the water, especially nitrogen, which causes algal blooms (Dong et al., 2023). The main pollutants causing eutrophication in the vacuum cleaner manufacturing industry are nitrogen dioxide and ammonia, according to the OpenLCA analysis. The annual eutrophication impact was 1.280 kg PO_4-eq, and each vacuum cleaner was 0.0000926 kg PO_4-eq. The addition of these nutrients to freshwater or marine systems results in the overgrowth of algae, resulting in algal blooms. Algal blooms can be so dense that they block sunlight and prevent the photosynthesis of submerged plants, upsetting the balance of primary production. When algae die and decay, microbial activity increases, using up dissolved oxygen in the water and creating hypoxic or anoxic conditions in the water. A lack of oxygen can result in mass mortality of aquatic animals, such as fish and invertebrates. Particular species of algae produce toxins (harmful algal blooms) that can affect aquatic life, livestock, and human health. Prolonged eutrophication can cause changes in species composition, decreased biodiversity, and decreased overall ecosystem function (Akinnawo, 2023). Eutrophication is an environmental problem caused by anthropogenic nutrient inputs, which affects the stability and sustainability of aquatic ecosystems.

3.3 Normalization

Normalization is the process of dividing the impact value by the normalization factor based on the selected method Laurentiis et al., (2023). This stage allows for the identification of the impact category contributing most significantly to environmental damage. Because the normalized values are dimensionless, the results enable precise comparisons across different impact categories. Figure 5 shows the normalization results for thermoplastic-based product manufacturing processes.

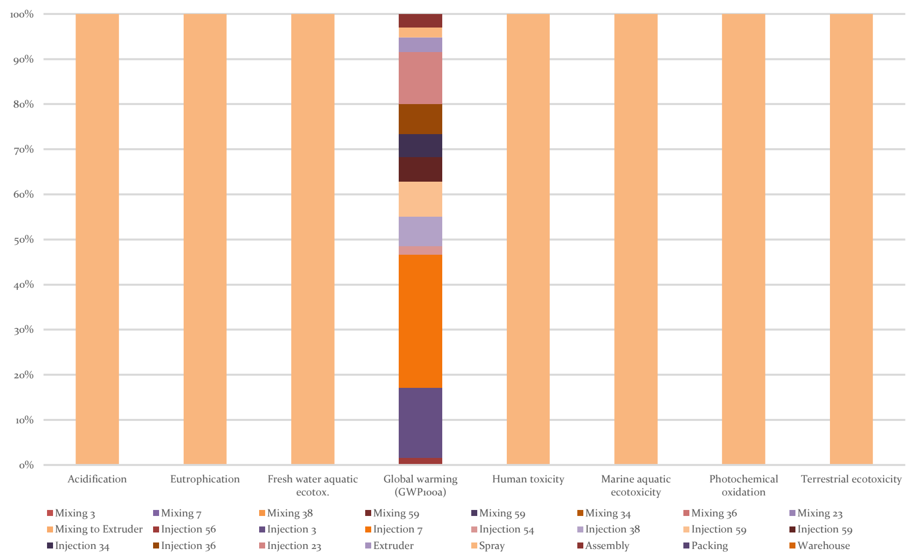

Figure 5. Impact of manufacturing thermoplastic based-product after normalization process

The process unit with the highest impact value was the spray stage. Based on the normalization results, the impact category with the highest contribution was marine aquatic ecotoxicity. Toxicity in marine ecosystems can cause neurotoxicity, oxidative stress, and behavioral alterations in fish, according to a study conducted by Silveira et al. (2024). This impact is primarily caused by emissions released during the spray process, particularly heavy metals and hydrogen fluoride.

3.4 Interpretation

This stage is carried out by identifying hotspots based on the results of the Life Cycle Inventory and Life Cycle Impact Assessment. During this phase, the normalized impact values were ranked according to their percentage contributions. The ranking procedure followed the criteria established in SNI ISO 14044:2017.

Table 2. Total contribution of each impact

Impact Category	Value	Contribution (%)	Level
3.5 ***Acidification***	2.31E-15	0.02	E
Eutrophication	5.85E-16	0.00	E
Freshwater aquatic ecotoxicology.	5.38E-16	0.00	E
Global warming (GWP100a)	1.01E-13	0.74	E
Human toxicity	1.56E-13	1.15	E
Marine aquatic ecotoxicity	1.32E-11	97.8	A
Photochemical oxidation	6.81E-16	0.01	E
Terrestrial ecotoxicity	3.68E-14	0.27	E
Total	1.35E-11	1.00E+02	

Based on the table above, it can be concluded that the primary hotspot in terms of environmental impact is Marine Aquatic Ecotoxicity. This impact is attributed to the use of paint and thinner during the spray coating or labeling of the vacuum cleaner components. The normalization result shows a value of 1.32061E-11, with a percentage contribution of 97.8%. This finding indicates that the majority of the environmental burden associated with the product system is concentrated in toxicity-related impacts on the marine ecosystem.

Marine Aquatic Ecotoxicity is mainly associated with the spray coating (labeling) process, which requires the use of paint and thinner containing hazardous chemical substances. These substances are known to emit various substances, including volatile organic compounds (VOCs), hydrogen fluoride (HF), and trace heavy metals during application. These emissions are released into the environment through atmospheric dispersion and then deposited into aquatic systems via wet and dry deposition. This pathway is consistent with the environmental fate mechanisms described in other studies, in which airborne pollutants act as indirect sources of pollution in marine environments (Mikheeva, 2024). Additionally, hydrogen fluoride (HF), one of the substances involved, is highly soluble in water and readily dissolves upon contact with atmospheric moisture, forming acidic compounds that can be deposited into the surface waters. According to the Australian Government's Department of Climate Change, Energy, the Environment, and Water (2022), HF in the atmosphere can cause both aquatic and terrestrial toxicity after deposition. In marine environments, these substances can harm aquatic organisms by disrupting physiological processes, inhibiting growth and reproduction, and increasing mortality rates of these organisms. In addition, the presence of heavy metals further worsens toxicity because of their persistence, bioaccumulation potential, and ability to undergo biomagnification across trophic levels (Oros, 2025).

Marine aquatic ecotoxicity, an impact category representing toxic effects on marine ecosystems, can be associated with the emission of pollutants into the atmosphere (Cerati et al., 2024). The main contributors to the impact of vacuum cleaner manufacturing are hydrogen fluoride (HF) and heavy metals. Hydrogen fluoride in the atmosphere can dissolve when in contact with water, as reported by the

Australian Government's Department of Climate Change, Energy, Environment, and Water (2022). Once in solution, HF can be very damaging to marine ecosystems and terrestrial organisms, such as plants, birds, and other animals. The relatively high contribution of Marine Aquatic Ecotoxicity points to the importance of considering not only direct emissions to water but also indirect pathways through air emissions, which are often underestimated in conventional assessments. This is consistent with the work of Guinée et al. (2002), who highlighted that impact categories in LCA are strongly affected by emission pathways, environmental fate, and exposure mechanisms. Furthermore, recent studies have shown that coating operations in polymer-based manufacturing can contribute to ecotoxicity owing to the use of solvent-based materials and additives (Firoozi et al., 2025). As spray coating is a hotspot, this indicates that mitigation strategies should be directed towards substituting hazardous materials, such as inorganic solvent-based paints, with more environmentally friendly ones, such as water-based or organic coatings. In addition, improving emission control technology and optimizing process efficiency can also help to reduce the release of toxic substances. Addressing these hotspots can help reduce the environmental burden of thermoplastic manufacturing products and contribute to more sustainable industrial practices.

3.6 Mitigation to Reduce Environmental Impact

3.5.1 Shifting from Inorganic Pigment to Organic Pigment

The environmental impact mainly results from the use of paint during the spray process. The paint is inorganic and contains TiO_2, which produces a pungent odor. Inorganic paint is a serious hazard to the environment and human health because of its toxicity. Alternatively, organic pigments are considered to be superior owing to a number of advantages including high photo-sensitivity, brilliant coloration, strong transparency, enhanced color strength, and cost-effectiveness (Pandian et al., 2021). Moreover, natural pigments have additional advantages, particularly in terms of environmental sustainability and human health (Ib et al., 2024). Perylene-based pigments are among the most popular organic pigments used in the plastics and automotive industries (Zhang et al., 2021). This pigment can provide a vorious range of colours like orange, red, violet, brown, and black (Rostami et al., 2020) (Rostami et al., 2020). Compared with inorganic pigments, organic pigments offer a major advantage by providing a broader range of color variations (Hatch & de Silva, 2011).

3.5.2 Application of Ecolabel Certified Pigment

Ecolabels serve as a clear justification that a product or service is committed to environmental sustainability while also acting as an essential instrument to prevent greenwashing. According to data reported by the Ecolabel Index, 456 ecolabels are registered across 199 countries worldwide. The European Union (EU) Ecolabel is one of the most well-known ecolabels and a trailblazer in the implementation of the circular economy concept, which was introduced in 1992. This framework encompasses water and energy efficiency, sustainable raw material management, product recyclability, and eco-design (Commission, 2012). An example of a certified product is LUC'O PREMIUM VELVET – Air Pur, a water-based paint that demonstrates significantly lower environmental hazards than paints formulated with synthetic chemical solvents.

4. Conclusions

Life Cycle Assessment analysis using the CML IA baseline method for the manufacturing processes of vacuum cleaners as thermoplastic-based products revealed that each product generated eight environmental impact categories. For one unit of vacuum cleaner, the environmental impact contributions include acidification of 0.0006 kg SO_2-eq, eutrophication of 0.0001 kg PO_4^{3-}-eq, Freshwater Aquatic Ecotoxicity of 0.0013 kg 1,4-DB eq, Global Warming Potential ($GWP_{100}a$) of 4.208 kg CO_2-eq, Human Toxicity of 0.406 kg 1,4-DB eq, Marine Aquatic Ecotoxicity of 2,558.698 kg 1,4-DB eq, Photochemical Oxidation of 0.000025 kg C_2H_4-eq, and Terrestrial Ecotoxicity of 0.0402 kg 1,4-DB eq. Among these categories, the most significant impact was associated with Marine Aquatic Ecotoxicity, primarily caused by the use of inorganic paints in the spray coating process. The results of this study contradict the general assumption that Global Warming Potential is the only driver of environmental impacts in thermoplastic manufacturing. This highlights the need to broaden the system boundaries in LCA studies to include all relevant processes to enable more accurate identification of environmental hotspots and support the development of more effective mitigation strategies.

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Ethics Statement

This study does not involve human participants, personal data, or animal experimentation. All data were obtained through direct field observations and investigations conducted within a thermoplastic manufacturing industry.

CRediT Author Statement

Rahmad Firnandi: Idea Development, Drafting, Research Design, Formal Analysis, Data Collection, Visualization, and Investigation. **Tanti Utami Dewi :** Idea Development, Research Design, Investigation, Supervision, Manuscript Review and Revision, and Financial Support Acquisition**. Mirna Apriani :** Idea Development, Research Design, Investigation, Supervision, Manuscript Review and Revision. **Rizka Amalia :** Formal Analysis, Project Administration, and Manuscript Review and Revision.

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