ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE
CENTER OF ENVIRONMENTAL SCIENCE

Comparative Environmental Life Cycle Assessment of Plastic and Glass Bottle for Soft Drink Packaging: Case of Addis Ababa, Ethiopia

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Comparative Environmental Life Cycle Assessment of Plastic and Glass Bottle for Soft Drink Packaging: the Case of Addis Ababa, Ethiopia

Genet Getachew
Addis Ababa University, 2024

Abstract

This study investigated the environmental effects of plastic and glass bottles throughout their life cycle. To evaluate the environmental impacts of plastic and glass bottles, this study utilized the ISO14040 and ISO 14044 frameworks and guidelines. Relevant data on the life cycle of plastic and glass bottles were collected, and the impact of the process was analysed using Open LCA 1.11 software, eco invent 3.9 database and CML v4.8 2016 impact assessment method by considering nine impact categories. The results revealed Plastic bottle has acidification 0.00032 Kg SO2-Eq, abiotic depletion potential 1.18 $x10^{-5}$ *Kg Sb-Eq, energy depletion 2.87 MJ, terrestrial eco toxicity 0.0032 Kg 1,4 DCB-Eq, freshwater eco toxicity 0.039 Kg 1,4 DCB-Eq, ozone depletion* $3.76x10^{-7}$ *Kg CFC-11-Eq, photochemical oxidant formation* $3.04x10^{-5}$ *ethylene-Eq, human toxicity 0.109 Kg 1,4 DCB-Eq and global warming potential 0.125 Kg* CO_2*-Eq impact amount to the environment. In addition, glass bottle that is reused three to four times has environmental impact of acidification 0.00171 Kg SO2-Eq, material/ resource depletion* $3.8x10^{-6}$ Kg Sb-Eq, *photochemical oxidant formation* $8.9x10^{-5}$ *Kg ethylene-Eq, energy depletion potential 4.1 MJ, terrestrial eco toxicity 0.0021 Kg 1,4 DCB-Eq, freshwater eco toxicity 0.22 Kg 1,4 DCB-Eq, human toxicity of 0.331 Kg 1,4 DCB, Ozone depletion potential* $0.33x10^{-8}$ *Kg CFC-11-Eq and global warming potential of 0.35 Kg CO2-Eq. Based on these nine categories, glass bottles were found to have a higher environmental impact as compared to plastic bottles. Therefore, companies that use glass bottles are advised to either improve their production process to reduce environmental impacts or consider alternative packaging materials with lower environmental impacts.*

Key words: *Life cycle assessment, plastic bottle, glass bottle, environmental burden, impact assessment,*

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Contents

List of Abbreviations and acronyms

BPA	Bisphenol A
CED	Cumulative Energy Demand
CFC-Eq	Chlorofluorocarbon Equivalent
CO_2-Eq	Carbon Dioxide Equivalent
HCFCs	Hydro Chlorofluorocarbons
DCB-Eq	Dichlorobenzene Equivalent
CHDM	Cyclohexane Di methanol
MEG	Monoethylene Glycol
IPA	Isophthalic Acid
PTA	Purified Terephthalic Acid
EOL	End of life
EU	European Union
EVOO	Extra Virgin Olive Oil
GHG	Greenhouse Gas
GJ	Gigajoule
GWP	Global Warming Potential
HDPE	High Density Polyethylene
ISO	International Organization for Standardization
KWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PBDEs	Polybrominated Diphenyl Ethers
PLA	Poly lactic acid
PET	Polyethylene Terephthalate
R-PET	Recycled PET
SO_2-Eq	Sulphur Dioxide Equivalent
Sb-Eq	Antimony Equivalent
UHT	Ultra High Temperature
POCPs	Photochemical Ozone Creation Potentials

List of Figures

List of Plates

List of Tables

List of Annex

1 Introduction

1.1 Background

Plastic and glass bottles are both packaging materials used in beverage industry (Ferrara et al., 2021). Plastics are organic polymeric materials composed of a large collection of synthetic organic materials and a compound formed by assembling many repeating units (monomers) to form a copolymer (Hammer et al., 2012; Hussein et al., 2021). In the beverage sector, most of the glass containers are made of soda-lime glass, the basic structure of which consists of tetrahedrons connected in a regular hexahedral lattice, inside which the remaining calcium and sodium oxides are located, interrupting grid continuity. Finally, other elements added to the mixture to give the glass properties (chemical resistance, density, gloss, colour, etc.) for specific applications. For example, substances (usually sodium sulphate) commonly added to improve the homogeneity of the glass by promoting the evacuation of air bubbles from the molten compound (Vellini & Savioli, 2009). Raw materials for glass production are Cullet, Silica sand, Soda ash, marble and lime stone (Vellini & Savioli, 2009).Solid waste is the problem in developing countries and the physical composition of municipal solid waste in Addis Ababa shows rubber/plastic 2.9% and glass 0.5% (Tassie et al., 2019)).

Today plastic products are growing rapidly in line with the increasing demand for plastic materials for packaging. Among various plastics, High-Density Polyethylene (HDPE) introduced to the global market and used in a variety of applications such as bottles, bags, packaging containers, barrels, toys, and household appliances in everyday life. Most of the plastic bottles made from PET and lids, which are from HDPE. PET is strong, lightweight transparent polyester used to make containers for soft drinks, juices, alcoholic beverages, water, edible oils, household detergents, and other food and non-food applications (Treenate et al., 2017). Plastic is a modern technological material, used in many ways as a replacement for traditional materials such as wood, glass, and metal. Approximately half of the world's solid plastic manufacturing, or over 150 million tons, is discarded annually(Rhodes, 2018). Enormous amounts of energy are consumed throughout the life cycle of products, amounting to approximately 4.27 million GJ, and in the EU approximately 204 million tons of greenhouse gases (GHG) was ejected annually

(Treenate et al., 2017). These valuable fossil fuel-based materials have increased 20-fold since 1950, resulting in large amounts of waste (Ayana et al., 2022). The polymeric properties of plastics make them non-biodegradable. A serious environmental problem called marine plastic pollution is becoming a serious global concern (Ferrara et al., 2021).

Accordingly, many people reject plastic packaging for their beverages in favour of other packaging materials, especially glass, which considered as the most sustainable packaging alternative. So, glass bottles have been considered as a substituent for plastic. Nevertheless, glass bottle lifecycle has its own influence to the environment. The primary environmental effects of glassmaking are the high energy consumption of batch melting, which releases combustion gases into the atmosphere, and the thermal reaction of the batch mix's constituent parts(Butler & Hooper, 2019).Glass production is composed of four main stages: batch preparation, melting, moulding and annealing (Vellini & Savioli, 2009). In glass bottle production, furnaces need high temperature to melt the raw material: silica sand (melting point of about 1700 °C) and soda is used to reduce melting temperature up to 1500 °C. This involves high consume of energies and greenhouse gases (CO2 and N2O) produced during the melting process. Due to their production cycles, glass bottle auxiliary materials and the packing stage also consume a lot of water. Glass bottle use of non-renewable resources through the bottle production phase .This result the production of glass contributes to the scarcity of fossil resources (Stefanini et al., 2021). Oxides of the sulphur and nitrogen-based batch mix components are produced by the batch's emissions of gaseous outputs from other additions. Additionally, the glass bottle process emits particulate matter into the atmosphere(Butler & Hooper, 2019).

Currently, it is difficult to find alternatives to plastic packaging from other beverage packaging types such as poly lactic acid (PLA) bottles and aluminium bottles. PET bottles are considered a low impact packaging solution and also reusable bottles could be an eco-friendly alternative to plastic bottles (Ferrara et al., 2021). For all of these environmental impacts of plastic and glass bottles, there is an urgent need to compare the environmental impact of these bottles in order to find solutions to environmental sustainability. Some believe that the best way is to ban the use of plastic packaging and create new materials or replace it with glass or paper. Other researchers oppose phasing out of plastic, believing that the public do not believes alternative materials are better than plastic, and that belief is based on hearsay (Stefanini et al., 2021).

Among the many techniques for estimating the environmental impact of products, Life cycle Assessment (LCA) has been defined by the International Organization for Standardization in ISO 14040-44, as a compilation and evaluation of inputs, outputs and potential environmental impacts across the life cycle of a product (Siracusa et al., 2014; Treenate et al., 2017). Life Cycle Assessment (LCA) is currently the most commonly used method to assess the sustainability of alternative systems (Ferrara et al., 2021). Life Cycle Assessment (LCA) is an established method for evaluating the environmental impacts of a product or process (system) over its entire life cycle (i.e. cradle to grave). LCA methods investigate how observed systems affect the environment and natural resources, thereby supporting system improvement and enhancing more sustainable strategies. Many recent studies apply LCA approach and provide guidance on how to trigger green actions in the food and beverage industry (Accorsi et al., 2015). For better understand LCA, environmental impact and sustainable development are considered two key concepts of this methodology. First, the application of the methodology involves quantifying the environmental impacts associated with each phase that characterizes the life cycle of a particular product or process. Second, once a Life Cycle Impact Assessment (LCIA) is completed, possible remedial solutions will be explored to ensure the environmental compatibility of the product throughout its life cycle (Siracusa et al., 2014).

There is no any study on the life cycle impact of the packing materials (plastic and glass bottles) in Ethiopia. Therefore, the aim of this paper was to investigate environmental impact of plastic and glass bottle starting from raw material transportation, production and utilization (disposal) using primary data and commonly used LCA software.

1.2 Statement of the problem

Waste management has emerged as a significant challenge in numerous developing countries. The combination of rapid urbanization, lifestyle changes, and improved living standards has led to an increase in the quantity and variety of waste generated in Ethiopia (Assnakew, 2018). Because waste plastics and glasses cannot decompose, they pollute the environment. Glass products are disposed of as solid waste material if they break or crack, and PET bottle materials are disposed of in the environment after the consumer uses the product. Following the product's initial uses, the plastic packaging and the glasses are haphazardly thrown out into the environment. Pollution of the environment is the outcome of improper management and control of those dumped solid waste products. As a result, it endangers people's safety and affects the environment, socioeconomic conditions, human and animal health, and numerous ecosystems (Worku & Alemneh, 2023).

The life cycle of both products, have impact to the environment. The production of plastic in Addis Ababa, Ethiopia relies on costly imported raw materials (Assnakew, 2018). The transportation of raw materials (PET and HDPE) from countries like Saudi Arabia, China, and India is the initial stage that has environmental impact. Subsequently, the melting of these materials to create the desired plastic bottle mould consumes a significant amount of energy. Plastic bottles, being non-biodegradable, persist in the environment for extended periods once discarded (Nkwachukwu et al., 2013). Moreover, PET bottles take approximately 450 years to fully biodegrade in landfills(Matar et al., 2014). Disposing of plastic bottles in landfills has severe environmental and social consequences. It is not only consumes valuable land but also disrupts ecosystems. When plastic bottles decompose in landfills, harmful chemicals like BPA can leach into groundwater, posing risks to both humans and wildlife (Crisp et al., 1998). Additionally, plastic degradation release toxic chemicals into the environment, including phthalates, heavy metals, and poly brominated diphenyl ethers (PBDEs). These chemicals can disrupt endocrine function and have negative impacts on reproduction and development in aquatic animals. Larger plastic products break down into micro plastics (MPs) under environmental conditions, which are of particular concern due to their potential for bioaccumulation as their size decreases (Sigler, 2014).

The significant amount of plastic waste currently needs urgent alternative and glass is considered as the substituent for it. However, glass bottle production has also been identified as having a significant impact on the environment. Excessive energy consumption during batch melting causes combustion gasses to be released and the batch mix's component parts to heat up. For the purpose of making glass containers, the molten glass in the furnace is maintained at a steady temperature for around twenty-four hours leads to high-energy consumption. Glass bottle production industry uses two main energy sources for melting (natural gas and fuel oil), with a small quantity of electricity also being used. The glass production process emits CO_2, NO_X, SO_X and dust into the environment(Butler & Hooper, 2019). Because glass bottles produce substances like hydro chlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs), and other chemicals with chlorine or bromine groups that damage human health due to an increase in radiation, they have a high potential to deplete the ozone layer during production, auxiliary material production, and distribution. Glass bottle production has fossil fuel consumption impact (Stefanini et al., 2021). (Assnakew, 2018)

There are researches in plastic and glass waste, but not on the life cycle of products in Ethiopia (eg.,Worku & Alemneh, 2023, Hussein et al., 2021, Halake, 2017, Assnakew, 2018). Therefore, it is important to compare the environmental impacts of plastic and glass bottle to commend the most eco-friendly packing material for beverage industries. Hence, the objective of this thesis is to examine the life cycle processes of plastic and glass bottles by employing inventory analysis and modelling techniques and assess their environmental impacts using open LCA software. It sought to compare the environmental burdens associated with plastic and glass bottles, with the ultimate goal of recommending eco-friendly packaging materials. The finding will help the government in making informed decisions and will raise awareness among the public regarding the adoption of eco-friendly disposal practices. In response, local governments and municipalities have enacted strict laws to limit plastic bottle disposal and encourage the development of more advanced plastic bottle recycling technologies and systems (Matar et al., 2014).

Plate 1: Plastic bottle on farmland near Abasamual River

Plate 2 Plastic bottle in Abasamual River

1.3 Research Questions

The research questions of this study are:

- What is the whole production process of **plastic** and glass bottles?
- Which process unit has significant environmental impacts?
- What are the main environmental impact categories emanating from plastic bottle and glass bottle?
- Which packaging type (plastic bottle or glass bottle) has more environmental impacts

1.4 Objectives

1.4.1 General objective

The main objective of the study is to evaluate the Environmental Impact of plastic and glass bottles for soft drink packaging throughout their life cycle.

1.4.2 Specific Objective

1. To identify data inputs of plastic and glass bottles' life cycle system processes
2. To measure the environment impacts of each process units (phases) in the course of plastic and glass bottles production

3. To investigate the cumulative effect of unit processes for plastic and glass bottle in order to identify environmental impact category.
4. To identify the more eco-friendly packing to pack 1000ml soft drink

1.5 Scope and limitation of the study

The scope of this study encompasses the entire life cycle of plastic and glass bottles, from the raw material extraction to their disposal. It takes into account all the activities that occur upstream, including the transportation of raw materials, the production process, and the end of life (disposal). Specifically for plastic bottles, this includes the transportation of PET and HDPE raw materials from Saudi Arabia, all the way to Addis Ababa and the disposal of the bottles, which unfortunately contributes to pollution of land and water bodies. The production of plastic bottles involves creation of intermediate products known as preforms. It is important to note that the extraction process of raw materials is not included in this study, as Ethiopia does not extract PET and HDPE for plastic bottle production. However, data for upstream activities and processes can be sourced from the Open LCA software database. The life cycle assessment (LCA) study for glass bottles is similar to that of plastic bottles. The raw materials used for glass bottle production, such as silica sand, marble, limestone, and cullet, are sourced from various parts of Ethiopia, with the exception of soda ash, which is mostly imported from Kenya. The functional unit for this study is a 1000 ml capacity PET bottle with the cup weighing 40 g, and a 300 ml glass bottle weighing 380 g. Like any other research work, this study also encountered limitations during the data collection process.

- Lack of proper recording of data in organizations
- Lack of instrument (for emission recording)
- Lack of previous research work on the topic

1.6 Significance of the study

Plastic and glass bottles life cycle is becoming serious environmental problems. Plastic throughout its lifecycle has high environmental impacts globally. This study quantified the environmental load of the production process of both plastic and glass bottles and compared the environmental impact of these two packaging materials. The findings of the study are important to know the environmental impact of plastic bottle production and environmental impact of glass bottle for decision-making and to identify weather or not glass bottle substitute plastic bottle. The study also helps users to buy eco-friendly beverage packaging materials.

2 Literature review

2.1 Solid waste

In Ethiopian context, solid waste refers to items used and discarded by individuals, households, hotels, small businesses, and institutions. This includes garbage (paper, packaging, plastic bottles, furniture), food leftovers, clothing, fertilizer, batteries, electrical appliances and paints. Economic development, urbanization and population growth are increasing the amount and complexity of waste generated, especially in developing countries (Teshome et al., 2022). One of the most important problems facing modern urban environments is the management of municipal solid waste, especially in developing nations like Ethiopia (Tassie et al., 2019).The physical composition of municipal solid waste in Addis Ababa shows vegetables 4.2%, rubber/plastic 2.9%, paper 2.5% (including paper bags, newspapers, paper office, magazines and catalogues, telephone directories and directories, paper miscellaneous other not mentioned), bone 1.1%, wood 2.3%, textile 2.4%, metal 0.9%, glass 0.5%, non-combustible material 2.5%, flammable leaves 15.7% and all fines 65% (Tassie et al., 2019)). In developing countries, solid waste is not properly collected and rather they are dumped in vacant lots and drains. The consequences of this event affect both human life and the environment (Teshome et al., 2022).

2.1.1 Packaging materials environmental impact

Packaging significantly influences the lifecycle of most liquid products, so it is important to compare different packaging options to minimize impact during manufacturing, transportation, use and disposal. Based solely on the manufacturing stage of the packaging, scientific studies show that glass bottles are less environmentally friendly compared to PET, HDPE, cartons, PP bottles, or aluminium cans, particularly with respect to global warming potential(GWP) and cumulative energy demand (CED) impact categories (Stefanini et al., 2021). According to Dhaliwal et al., (2014))the low impact of polymer bottles in packaging applications can be attributed to their low material and manufacturing impact, distribution impact, and end-of-life disposal impact. The study also suggested that the use of polymer bottles instead of glass bottles offers an opportunity to reduce the environmental impact of contrast agent packaging. It was focused on a comparison between a 100 mL glass bottle and a +PLUSPAK™ polymer bottle used to deliver a single dose (96 mL) of contrast agent in an X-ray examination. The comparative analysis shows that polymer bottles have a considerably lower environmental impact across all impact categories. They are considered to have lower greenhouse gas emissions compared to glass bottles (46% of emissions), less cumulative energy required (55%), and less impact on ecosystems (39%), less impact on resources (59%), less impact in all other categories considered expressed in the range of (24-43%). Secondary packaging contributes to a significant impact compared to plastic and glass bottles while polymer bottles have significantly less environmental impact than glass bottles for all multipack shipping configurations.

According to Ferrara et al., (2021) research results vary based on case studies, geographic location, and specific assumptions. The optimal eco-friendly packaging solution identified in these documents was vary based on three key factors: The number of reuses of glass bottles, the weight of two types of bottles, the recycling rate of glass and PET. Most literatures evaluated and compared the environmental impacts of different packaging options. Some of researches that evaluated different packaging are; Stefanini et al., (2021) research compares the environmental impact of bottles made from PET, R-PET, non-returnable glass and recycled glass which are used to package one litter of UHT milk. This research shows the most environmentally friendly packaging solution. According to researcher, R-PET bottles contribute the least to global warming, stratospheric ozone depletion, earth acidification, fossil resource scarcity, water consumption and carcinogenic toxicity for humans, followed by PET bottles, returnable glass bottles and finally R-PET bottles. Glass is the worst packaging option due to the high-energy demands during the production of bottles, their weight, and the transportation phase.

According to Huang & Ma, (2004) beverage packaging materials are selected as a case study. PET container comparison article, HDPE plastic containers, PP plastic containers, PS containers, Steel cans, aluminium cans Glass containers, Cardboard boxes and Liquid containers are packaging options that were compared in the paper. The methods used in Huang & Ma, (2004) were LCA and AHP using SimaPro 4.0 software. The results indicated that (qualitative and quantitative) do not give very similar results. In the LCA approach, due to the emission of carcinogens and heavy metals, aluminium cans and glass containers are considered less environmentally friendly. However, according to AHP's approach, cardboard boxes, liquid containers and aluminium cans are worse in terms of environmental concerns. This study assumed database usage, which is the main limitation. It recommended a local database for more realistic results.

Pasqualino et al., (2011) estimates from an environmental point of view the best packaging options (size and material) for three beverage categories: juices, beer and water using two indicators (GWP and CED). Larger packaging always has a lower environmental impact. All beverage packaging materials and sizes have a lower impact on the environment if they are recycled rather than thrown into landfills or incineration plants. Using GWP and CED, all types of packaging studied should be recycled due to the energy and raw material savings it offers. Based on the results, the above study concluded that recycling has a more beneficial impact on CED and GWP than using small packaging size. Treenate et al., (2017) determines the environmental performance of high-density polyethylene lubricant bottles and developed potential measures to reduce its impact using comprehensive LCA. The paper considered two different end-of-life scenarios; recycling and incineration: 4,444 plastic bottles screened to identify suitable environmentally efficient alternatives for plastic bottle production in Thailand. The results show that the total environmental impact over the entire life cycle of HDPE lubricant bottles in the recycling scenario is less than that of disposal by incineration.

2.1.2 Environmental impacts of plastic and glass bottles

According to (Stefanini et al., 2021), global warming (kg CO2 equivalent), stratospheric ozone depletion (kg CFC11 equivalent), terrestrial acidification (kg SO2 equivalent), scarcity of fossil fuels (kg oil equivalent), water consumption (m3) and human carcinogenic toxicity (kg 1.4-DCB) are impact categories for PET, R-PET, and returnable and non-returnable glass bottles. And the most impactful packaging option is a non-returnable glass bottle because of its manufacturing, packaging, and distribution phases.

Plastic products are now growing rapidly with high demand for more uses (Treenate et al., 2017). The combination of widespread use of plastics and marginal rates of reuse and recycling creates a large amount of plastic waste (Kedzierski et al., 2020). Plastic recycling is the process of recycling plastic waste and recycling materials into useful products. Recycling is part of the global effort to reduce plastic, as most plastic is not biodegradable. Several researchers recommended that recycling is best option to reduce environmental impact of plastic disposal. However, recycling uses energy to sort and process plastics, increasing resource consumption and costs (Horowitz et al., 2018). These organizations generally have a great influence on the city's waste management. Reduce recyclable waste that does not need to be sent to landfill.

In 2010, 389 billion PET bottles were produced worldwide and 46% of them for water packaging (Orset et al., 2017). In 2010, 2,983 tons of plastic waste were collected and recycled in Addis Ababa (Assnakew , 2018). The study mainly concerned about assessing the generation and collection of plastics and paper waste. According to the study, the production of plastic is 42,705 ton annually and 16,888.55 ton of plastic was collected and recycled. All of the collected plastics are recycled according to the Addis Ababa City Solid Waste Cleansing Agency. This study aimed to clarify the process of plastic bottle production and its environmental impact. One of the most important negative effects of this 'plastic revolution' is the often highlighted issue of plastic waste disposal.

Disposal of used PET bottles is a critical step in the PET lifecycle and has been the subject of several studies (Foolmaun & Ramjeawon, 2008). Discarded plastics, specifically about 8 million tonnes of plastic waste, enter the Earth's oceans each year. The rate of plastic and paper waste generation and collection has changed significantly, and much of the solid waste generated is not collected, but simply disposed of in vacant landfills and other vacant land. Rapid growth in beverage industry, trade and services accelerates plastic bottle production.

Most plastics are not biodegradable (Assnakew, 2018). Biodegradation of plastic bottles left in nature can take about 500 years to be degraded. The accumulation in the world's oceans is particularly alarming, with approximately 10% of the world's plastic production ultimately being ends each year in the ocean. Plastic waste is a direct threat to wildlife, with many diverse species adversely affected by these small plastic products. The main threat to most marine life is ingestion of the plastics (Orset et al., 2017). Decades ago, the majority of our waste consisted of organic and compostable materials. Currently, synthetic elements, such as plastics, constitute an abundant material in solid waste. Beverage bottles, packaging straps, tarpaulins and synthetic fishing lines are durable, slow to decompose and float on the surface, becoming waste over time.

Based on Orset et al., (2017),microscopic fragments to plastic fibbers, accumulation and dispersion of toxic substances found in or on plastic are the impacts of plastic debris that are less understood (Sheavly & Register, 2007). Debris accumulation and the potential threats and emerging risks to organisms from marine debris, including plastics, are a global concern and plastic waste has a general impact at ecological and economic aspects (Thushari & Senevirathna, 2020).

Plastics are resistant to chemicals, meaning they only slowly decompose, and this is why billions of tons of plastic have been accumulated in the environment. Land, water ways and oceans can be contaminated by plastic and living organisms, especially those in ocean environments, can be harmed, for example if they become entangled in plastic from packaging or fishing lines throw away fishing gear, or even swallow plastic waste. These can cause various health problems, either through the direct physical impact of the objects or plastic particles, or possibly through the release of chemicals from the plastic. Micro plastic production is also one of plastic impact. The smallest micro particles apparently detected in the ocean are 1.6 µm (1,600 nm) in diameter; it was thought that further fragmentation might occur to form Nano plastics. Due to their small size, micro plastics can also be absorbed through filtration. Micro plastics detected in the digestive tracts of various marine organisms, from where they are capable of releasing both intrinsic plastic additives (such as phthalates, used as plasticizers) and pollutants. Hydrophobic contamination that they absorb into the body of seawater (Rhodes, 2018).

According to Lehmann et al., (2005) PET appears to have a higher environmental impact than HDPE when it comes to carcinogens, radiation, Eco toxicity, land use and minerals, but the overall environmental impact is much higher with HDPE. The impact on climate change is also lower for PET, which is one of the main factors for both plastic materials. HDPE has a greater impact on the overall process than PET. Polyethylene terephthalate (PET) containers are part of our daily lives. PET is a strong, lightweight form of transparent polyester. It is used to manufacture containers for soft drinks, juices, alcoholic beverages, water, edible oils, household detergents and other food and non-food applications. Polyethylene is perhaps the most common polymer in everyday life.

HDPE plastics offer a wide range of properties and characteristics desirable for packaging applications, including toughness, low cost, and good barrier properties. Grocer bags drink bottles, children's toys and even bulletproof vests are made from this polymer. Despite being such a versatile material, it has a very simple structure, the simplest of the commercially available polymers. According to (Arena et al., 2003.) Production of 1 kg flaks total energy intakes from recycled PET requires a total energy in the rage of 42-55 MJ, depending on whether process waste (mainly from sorting and reprocessing activities). However, in this study the energy consumption of plastic bottle production from virgin PET material will be evaluated. According to Treenate et al., (2017) non-renewable energy has become a central topic, with raw material acquisition and pre-treatment stages becoming hotspots, as natural gas is used as feedstock for ethylene production, which is consistently used in HDPE manufacturing. In the proposed work it is mainly concerned about the current situation of plastic bottle production in Addis Ababa that transports raw materials (PET and HDPE) from different countries, so the assessment starts from raw material transportation to end of use. In this, different key factors will be identified in entire process. In Lehmann et al., (2005) the life cycle environmental impacts of two different plastic materials was compared. The results of this LCA clearly demonstrate that PET has a lower environmental impact and should be the preferred material of choice for bottle applications. Although slightly more expensive than HDPE, the overall environmental benefits of using PET bottles facilitate commercialization and legal compliance.

Because of high impacts of plastic pollution to water bodies and land, it needs to find substitution for plastic bottle packaging. In response to the "plastic problem", many people are rejecting plastic beverage packaging in favour of other packaging materials, including glass, which are often seen as a more sustainable alternative (Ferrara et al., 2021). However, glass bottle production has a process that affects the environment. According to Yani et al., (2014), the greatest environmental impact of glass manufacturing is the large amount of energy consumption associated with batch melting. Radiant transfer from the kiln top that heated up to 1650°C by the flame mainly provides heat, but some come from the flame itself. In the manufacture of containers, molten glass is held at a constant temperature in a furnace for approximately 24 hours. To make the glass chemically resistant, calcium oxide (CaO), which is derived from limestone ($CaCO_3$), is added to the mixture. To improve the chemical durability, magnesium oxide (MgO) and aluminum oxide (Al_2O_3) can also be applied. These additions to the batch create emissions of gaseous outputs produce oxides of sulphur and nitrogen. The breakdown of the limestone and soda ash as they heat up is what causes the majority of the emissions to the air during the batch melting process (Butler & Hooper, 2019). High consume of energies and greenhouse gases (CO_2 and N_2O) produced during the melting process. Due to their production cycles, glass bottle auxiliary materials and the packing stage also consume a lot of water. Glass bottle use of non-renewable resources through the bottle production phase .This result the production of glass contributes to the scarcity of fossil resources (Stefanini et al., 2021).

The production of glass bottles and the recycling of debris have caused an environmental impact. An environmental impact assessment for bottle glass production revealed that the quality of ambient air exceeded standards, with the exception of total particulate matter and sulphur dioxide. Because glass bottle production causes air pollution. The cullet recycling process has caused surface water pollution. Recycling and production of glass bottles require a lot of energy to melt silica and cullet. Glass bottles can be both recycled (cullet) and reused (refill) in order to decrease disposal effect (solid waste) to the environment. The most impactful stages of reuse are the sterilization and drying of returnable bottles, but recycling consumes a lot of heat and electricity during the glass melting and bottle shaping stages. From an environmental point of view, it turns out that reusing bottle glass is better than recycling (Stefanini et al., 2021).

2.2 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is the most widely used method of assessing the environmental impacts associated with the life cycle stages of a production process, from raw material extraction to product manufacture, distribution, use, and final disposal. LCA is a decision support tool (Li et al., 2015).

2.2.1 Importance of LCA

LCA provides decision-makers with information about all product impacts to find the best solutions to improve the product. According to ISO 14040; LCA is “the synthesis and assessment of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle. Knowledge of the environmental impact of production and consumption patterns is essential to improve the performance of industries and consumers in this sector. An integrated assessment of all environmental impacts, from start to finish, provides the basis for achieving more sustainable products and services. One of the widely used assessment approach for this purpose is environmental life cycle analysis (LCA) (Azapagic & Solberg-Johansen, 1998). LCA is an analytical approach that helps to capture the overall environmental impacts of a product, process, or human activity, from raw material procurement, through production and use, to waste management. This comprehensive perspective makes LCA unique in the environmental management toolkit (Curran, 2013).

It is currently the most commonly used method to assess the sustainability of alternative systems. A life cycle assessment allows us to compare the potential environmental impacts that occur at all stages of the life cycle (Ferrara et al., 2021). LCA provides a comprehensive view of the environmental aspects of modifying or selecting a product or process and presents an accurate picture of the potential environmental trade-offs. It is useful for solving cross-media problems and avoiding transferring problems from one medium to another or from one location to another. Without life cycle thinking, we risk focusing on environmental problems that need immediate attention and ignoring or underestimating problems that may arise in another location or elsewhere (impact). Such focused assessments can lead to decisions based on incomplete information (Curran, 2013). One of the main goals of LCA is to support the selection of different (technological) options to fulfil a given function by synthesizing and evaluating the environmental consequences of these options (Azapagic & Solberg-Johansen, 1998). To ensure a sustainable future, declarations and research must be followed by meaningful actions that effectively reduce environmental impacts and perhaps even improve the situation. For an action to be effective, three conditions must be met:

- There must be a technological solution.
- Different solutions must be prioritized and best practices selected, taking into account environmental performance, costs, and resulting economic constraints.
- Actions need to be optimized to further minimize impacts.

Therefore, Life cycle analysis (LCA) is a technique that specifically helps to addresses the need to select and optimize available technology solutions. LCA is particularly relevant from a sustainability perspective because it covers the entire lifecycle of a product or service, preventing local improvements from displacing environmental impacts elsewhere. LCA differs from other environmental methods by linking environmental performance to functionality, quantifying pollutant emissions and raw material usage based on product or system functionality. It helps identify areas where environmental improvements can be made during the product life cycle and facilitates the design of new products. This tool is mainly used to compare different products, processes or systems as well as different stages in the life cycle of a particular product (Jason Pierce & Seeley, 2014).

2.2.2 Stages/Phases of LCA

LCA is a young discipline with 50 years of history and less than 30 years of strong development and application. Over the years, the methodology and applications have evolved to the point of achieving scientific consensus and standards on how to perform LCA (Hauschild et al., 2017). The first standard (ISO 14040) establishes guidelines for performing LCA. ISO 14044 replaced ISO 14041, 14042 and 14043 in 2006 to describe the stages of inventory, impact assessment and interpretation (Jason Pierce & Seeley, 2014). The LCA study conducted according to the four LCA phases recommended by ISO standards (ISO 14040, 2006, ISO 14044, 2006): Defining goal and Scope, life Cycle Inventory, life cycle impact assessment and Interpretation of results. The analysis conducted according to a 'cradle-to-grave' approach. Therefore, all lifecycle stages of the packaging system were considered within the system limits of the study (Ferrara et al., 2021). Current LCA practice, according to ISO standards, follows four interrelated stages:

Defining goal and scope of the study

Clearly define the objectives and scope of the study (including the selection of functional units) (Curran, 2013). The goal and scope definition phase is the first phase of LCA. It establishes the objectives of the intended research, functional units, reference lines, product systems and product systems being researched, as well as the breadth and depth of research related to this goal. This step assists in defining the study boundaries and guides the data collection effort. Identify the function performed by the system associated with the target. Ultimately, all environmental impacts are related to this function, providing the basis for comparison (Hauschild et al., 2017).

A requirement of the goal and scope definition phase, as well as a unique feature of LCA, is the definition of a functional unit that describes the main function performed by the system (product) and the quantification of the functional part. This feature must be taken into account in the planned project LCA research. It is uses as a basis for selecting one or more alternative systems (products) that can provide these functions. The functional unit can consider different systems as functionally equivalent and calculate reference flows throughout the system. No calculations were performed and no data was collected in the goal and scope definition. This is the time for initial consideration of data modelling and calculations (Hauschild et al., 2017).

Life cycle inventory analysis

In life cycle inventory (LCI) analysis, inputs to raw materials and natural resources as well as outputs to the environment are determined, first qualitatively and then quantitatively (Azapagic & Solberg-Johansen, 1998). It compile an inventory of energy, input materials, and related environmental discharges (Curran, 2013). The basis of inventory analysis is the unit process (Hauschild et al., 2017). Before defining a unit process system, system boundaries must be defined between product systems. The next step consists of drawing a schematic diagram of the system under study. It forms the basis of the entire analysis and identifies all relevant processes of the product system with their interconnections (Azapagic & Solberg-Johansen, 1998).The result of inventory analysis is a life cycle inventory, a quantified list of basic physical flows to the product system involved in providing the service or function described by the functional unit (Hauschild et al., 2017).

Life cycle impact assessment (LCIA)

The inventory results are converted into potential environmental impacts (Miettinen & Hämäläinen, 1997). Assessment of potential environmental impacts associated with identified inputs and wastes (Curran, 2013) . The life cycle impact assessment (LCA) phase of LCA is intended to help users understand and assess the scale and significance of the potential environmental impacts of a product system throughout its life cycle. Individual impact methods convert LCI results into common units, and results are converted in groups into the same impact type by modelling possible impact pathways, LCIA addresses environmental and human health impacts, as well as resource depletion, to link the product or process under study with its potential environmental impacts. According to ISO, impact assessment is “the LCA phase aimed at understanding and assessing the scale and significance of the potential environmental impacts of a product system”. In the impact assessment phase, several stages can be distinguished: (i) Selection of impact types (ii) Selection of characterization methods: indicators, modelling Characterization and factors (iii) Classification (assigning inventory results to class effects) (iv) Characterization (v) Standardization (vi) Grouping (vii) Weighting. The first four steps are mandatory and the last three steps are optional (Azapagic & Solberg-Johansen, 1998).

Interpretation of results

Interpretation is the stage where the results are analysed and related to the objectives and scope of the study, conclusions be drawn, limitations identified and recommendations made based on the results of the stages (Hanun et al., 2019). There needs to be a final venue for analysis and interpretation of results, where goal and scope definition lay the focus and where inventory analysis and impact assessment include data collection and calculations. Essentially, these are three different types of activities: (i) Evaluation of the results achieved to date (ii) Analysis of these results (iii) Conclusion and formulation of recommendations (Azapagic & Solberg-Johansen, 1998).Interpretation of results helps decision makers make more informed decisions(Curran, 2013).

3 Materials and Methods

3.1 Study area description

Addis Ababa, the capital of Ethiopia, was founded in 1887 by Emperor Menelik II and his wife Etege Taytu (Tassie et al., 2019). The city is located in the center of the country and on the western escarpment of the main Ethiopian rift. It is bounded by longitudes 38°43' and 38°50' East and by latitudes 8°56'10" and 9°05' South (AASWMA, 2020). Addis Ababa city is home to about 30% of Ethiopia's total urban population with an annual growth rate of 3.79%. (Tassie et al., 2019). Currently the total population was over 4 million.

Addis Ababa was selected for this study due to the widespread packaging bottle fabricators. In addition, a large population with a modern lifestyle leads to increased use of packed drinks.

3.1.1 ROHA PACK PLC

Roha Pack, formerly known as 'Agere-Roha Industry PLC', is a privately owned company that was established in April 2003 with an initial capital of approximately Birr 5.0 Million. After two years, the company legally changed its name to Roha Pack Plc. As of March 30, 2022, the company's capital has grown to Birr 360.6 Million. Located in the Hana-Mariam industrial zone area of Nifas Silk Lafto sub-city in Addis Ababa, Ethiopia, Roha Pack is one of the largest plastic manufacturers in the region. The company utilizes PET and HDPE as its raw materials and employs state-of-the-art machinery such as Husky Injection Moulding and Sacmi Injection Moulding Technology. Its primary products include various plastic preforms, HDPE closures, and the distribution of preforms to water and soft drink manufacturers. Roha Pack serves a diverse clientele, including multinational companies, Young Generation water bottling industries, and Ready to Pack factories involved in the production of detergent, cosmetics, pharmaceuticals, agro-processing, edible oil, and alcoholic beverages.

3.1.2 Moha Soft drinks industry

The Moha Soft drinks industry is one of the selected clients of Roha Pack PLC. It was established on May 1996 G.C with the initial capital of 108, 654,000 birr with 950 employees. Currently, its capital is above 1.1 billion birr and with 5,000 employees. It is located in the Lemi Kura sub-city, Summit Pepsi area. This company takes the preforms from Roha Pack PLC. It converts these preforms into desired shapes and fills them to sell a variety of soft drinks and water. The products include Pepsi, Coca-Cola, Mirinda Orange, Mirinda Apple, Mirinda Tonic, Seven Up, Cool water, cool carbonated water, and carbon dioxide gas. The company uses PET bottles and returnable glass bottles for product packaging.

3.1.3 Addis Ababa Bottle & Glass Share Company “Addis Glass”

This manufacturer produces container glass products for the Ethiopian market. It was founded in 1972, located around 8.5km from Addis Ababa city centre on the Addis-Ambo road, in Addis ketama sub-city. The company's primary products include glass containers for beer, soft drinks, liquor, wine, cosmetics, mineral water, and food markets. The raw materials used in making these glass containers consist of cullet, marble, limestone, soda ash, and silica. With the exception of soda ash, which is mainly imported from Kenya, all other raw materials are locally sourced from various regions in Ethiopia.

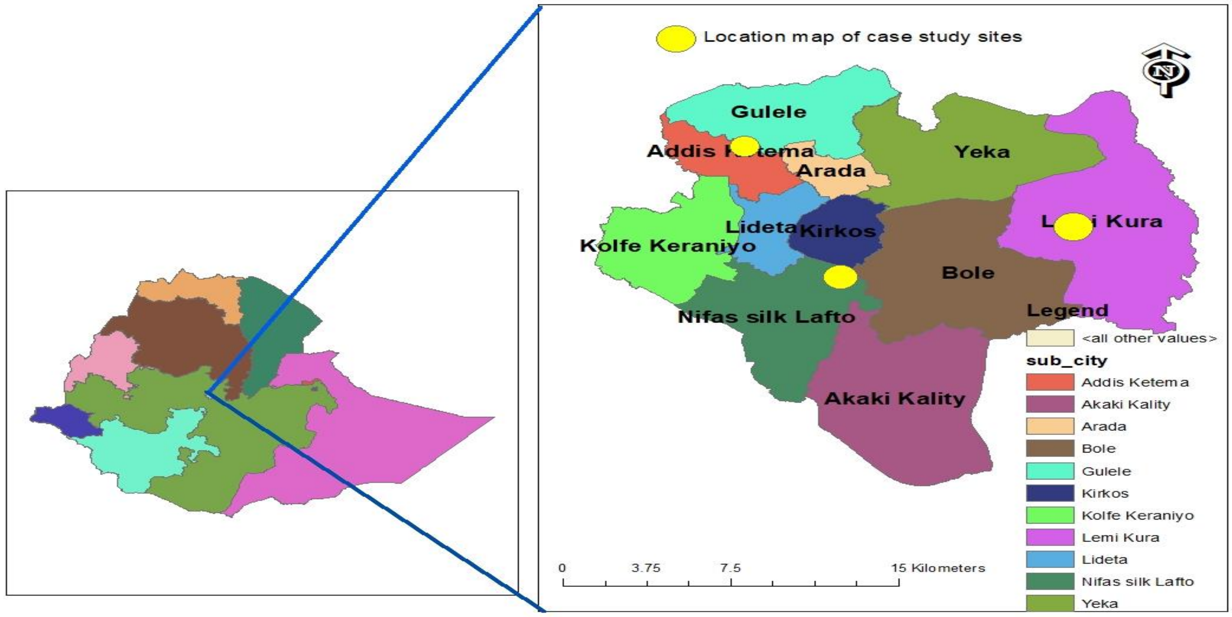

Figure1: Geographical locations of study areas

3.2 Site selection

The present study carefully selected case study sites based on strategic factors such as location, market potential, product type and quantity, data availability, and accessibility to information. The selection process also took into account the capacity of the companies in line with the study's objectives. These chosen study sites are valuable for defining the production process of plastic and glass bottles, identifying significant environmental impacts, and determining the main environmental impact categories associated with both types of packaging. The selection criteria led to the conduction of a Life Cycle Assessment (LCA) for plastic bottles at ROHA PACK PLC and Moha soft drinks industry. All data related to plastic bottles were collected from the Roha Pack industry. The assessment included the amount of raw materials used for PET bottles and HDPE cups, as well as the overall environmental impact throughout the production and disposal stages. Similarly, the LCA for glass bottles was conducted at the Addis Ababa bottle and glass manufacturing Share Company. The relevant data for the production and disposal of glass bottles were collected from the Addis Ababa Glass and Bottle Manufacturing Industry. Both plastic and glass bottles were used for soft drink packaging (Mirinda) in different volumes. In order to compare the two packaging options, they were standardized to have the same capacity. Therefore, the study results were converted to this common capacity of one Litre.

3.3 Data collection and analysis

In order to achieve the objectives of this research, combination of techniques were used. This embraces using of general methodological framework and guidelines for LCA through ISO 14040 and ISO 14044 (using four phases of LCA). Literature review was done followed by relevant data collection throughout the production process of plastic and glass bottles. The data were collected from different sources. The plastic bottle data were collected from the plastic bottle manufacturing companies while the glass bottle data were collected from the glass bottle manufacturing company. Other data related to waste were collected from the Addis Ababa City Solid Waste cleansing agency. The remaining information particularly constants/factors were gathered from specialized databases and the literature. Two functional unites were selected before starting, the actual work. The functional unites are a 1000 ml capacity plastic bottle and a 300 ml capacity glass bottle. Data collection was performed using a ‘’cradle to grave’ ’approach. For this study, both primary and secondary data were collected. Primary data were obtained through site visits to companies and questionnaires survey of the employees. On the other side, a review of literatures, eco invent 3.9 databases, and company process records are sources of secondary data. Impact assessments results and interpretation were done using Open LCA 1.11 software with eco Invent - CML v4.8 2016 impact assessment method and used mid-point impact indicators.

3.4 Steps of LCA

The LCA method follows the principles and guidelines of ISO 14040: 2006, ISO 14044: 2006 and includes four main steps/phases: Scope and goal definition, Inventory analysis, impact assessment and interpretation respectively (Stefanini et al., 2021).

3.4.1 Goal and scope definition

The primary aim of this research was to assess the environmental performance of plastic and glass bottles utilized for soft drink packaging across their life cycle. The study seeks to pinpoint and assess the environmental impacts associated with the production, usage, and eventual disposal of glass and plastic bottles. By taking the beverage companies which specialized in the bottling and distribution of soft drinks in Ethiopia, the study analysed the effects from the manufacturing phase to end-of-life, and identified a beverage packaging system with optimal environmental performance taking into account the life cycle. The evaluation focused directly on the two packaging options (glass/plastic bottle) for soft drink packaging. Each packaging type was separately evaluated due to variations in manufacturing processes, weight, and raw materials used. The analysis was conducted using a "cradle-to-grave" approach. Thus, all stages of the packaging life cycle were considered within the study's system boundaries. The functional unit (FU) was defined as the reference unit with standardized inventory data (Stefanini et al., 2021). A product's characteristics in relation to its intended use determine its function. A functional unit should encompass both the qualitative and quantitative attributes of the function that a product is designed to fulfil, as per the ISO (2006a, b) standard (Silva et al., 2015). The functional unit is established to serve as a benchmark against which inventoried input and output data are normalized, and quantified. The functional units in the study were a one-litre volume capacity CSD plastic bottle (37.2 g) with its cup (2.55 g) and a 300 ml capacity (380 g) glass bottle.

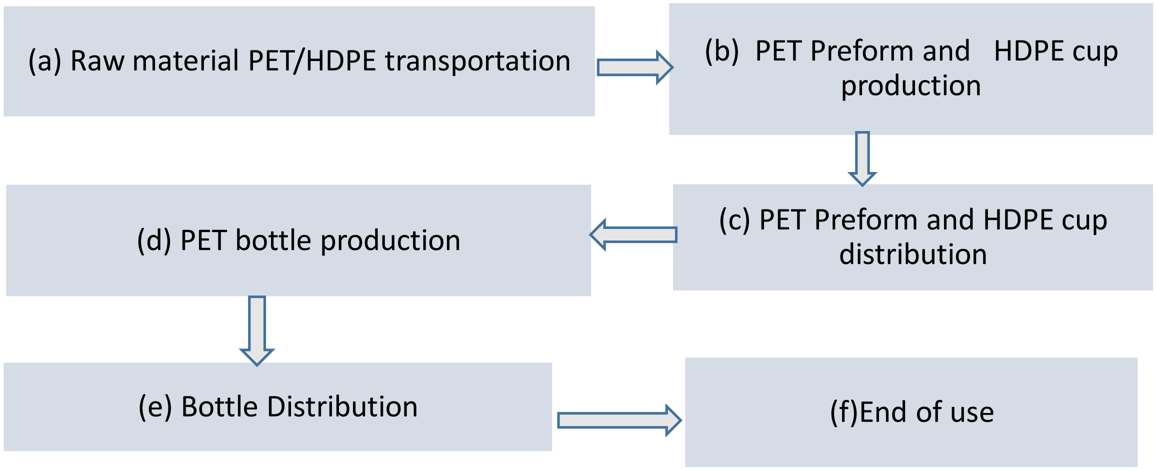

Figure 2: Plastic bottle system boundary

As illustrated in figure 2, life cycle of plastic bottle comprises the process units of transportation of raw materials (a), PET Preform and HDPE cup production (b), PET Preform and HDPE cup distribution (c), PET bottle production (d), Bottle distribution (e) and end of life (f) of a product (recycling and disposal). The system of process starts from raw material transportation (a) but all upstream activities were considered using Open LCA software database.in this unit process fuel used, distance travelled, and type of transportation determines the emission amount to the environment. In order to transport raw materials of PET and HDPE, two types of transportation (Ship and land) were considered for the study; (b) Involves injection moulding using electric energy. After moulding, there is cooling of preform and cup using air and water. Process (c) begins with loading of preform and cup. In this unit process mass of cup and preform loaded, distance travelled and type of truck used considered during data collection. In (d), Preform blow moulding is subsequent cooling to form bottle. After distribution of product in to different parts of Addis Ababa (e), process (f) involves recycling, water pollution and land pollution due to improper disposal of a product. Therefore, the study identified the amount of plastic waste recycled and disposed in order to determine the amount of solid waste produced.

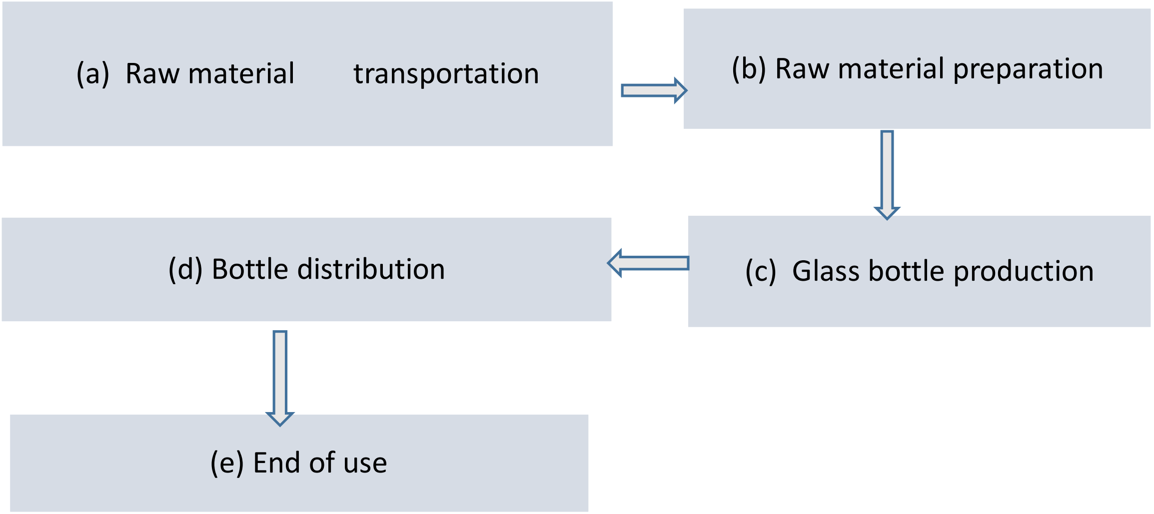

Figure 3: Glass bottle system boundary

The system boundary of glass bottle illustrated in Figure 3 comprises the process units of transportation of raw materials (a), raw material preparation (b), glass bottle production (c), bottle distribution (d) and end of life of a product (e). The system of production starts from raw material transportation but all upstream activities were considered using Open LCA software database. In this unit process fuel used, distance travelled, and type of transportation used determines the emission amount to the environment (b). Glass bottle production involves raw materials crashing, washing and drying. The process treats all the required raw materials for the next step. In this unit process, there is electric energy, fuel and water consumption. In (c) mixing of raw materials (batch mixture phase), melting the batch mixture (furnace phase), shaping bottles, reheating and cooling (annealing phase) for bottle production. Process (d), begins with loading of the product and distribute it to different parts of Addis Ababa. In this unit process, mass of bottle loaded, distance travelled and type of truck used were considered during data collection. (e) is the last unit process of a system involves reusing and recycling of product.

3.4.2 Inventory analysis

Inventory analysis includes a flow model of the activities being assessed. In order to characterize the indicated subsystems for the paper production life cycle, inventory data were gathered (Lopes et al., 2002). Life cycle inventory data of resources, material and energy consumption for both plastic and glass bottles packaging classified by phases of life cycle as raw material transportation, plastic/glass bottle production and end of use/bottle disposal, which is called system of a process was analysed. A system is a collection of operations that together perform a defined function. The system starts with all raw materials transportation from the source and ends with outputs that return to the environment. In the study, all the inputs and outputs data of system process were collected from various relevant sources. This sources are plastic and glass bottle industry, Open LCA software database (Eco invent 3.9 database) and literatures. In order for the inventory of plastic bottle, raw material transportation and preforms production data was collected from Roha Pack industry, PET bottle manufacturing data from Moha soft drinks industry and waste disposal data from literatures. Whereas for life cycle information of glass bottle all the data of raw material transportation, production, distribution and end of use were collected from Addis Ababa glass and bottle manufacturing Share Company. Additionally, emissions from the process of glass bottle production were directly measured in cooperation with the Ethiopian Environmental Protection Authority. The Eco Invent 3.9 database also serves as a proxy data source for all upstream activities of both glass and plastic bottle system processes. The functional unit plastic bottle with weight of 40.0 g was produced from 37.2 g PET and 2.55 g HDPE by blow moulding process and functional unit of glass bottle 380 g was produced from 83.17 g of Silica, 21.48 g Marble, 25.81 g Soda ash and 249.5 g Cullet. The system process of both plastic and glass bottle life cycle in a system defined below.

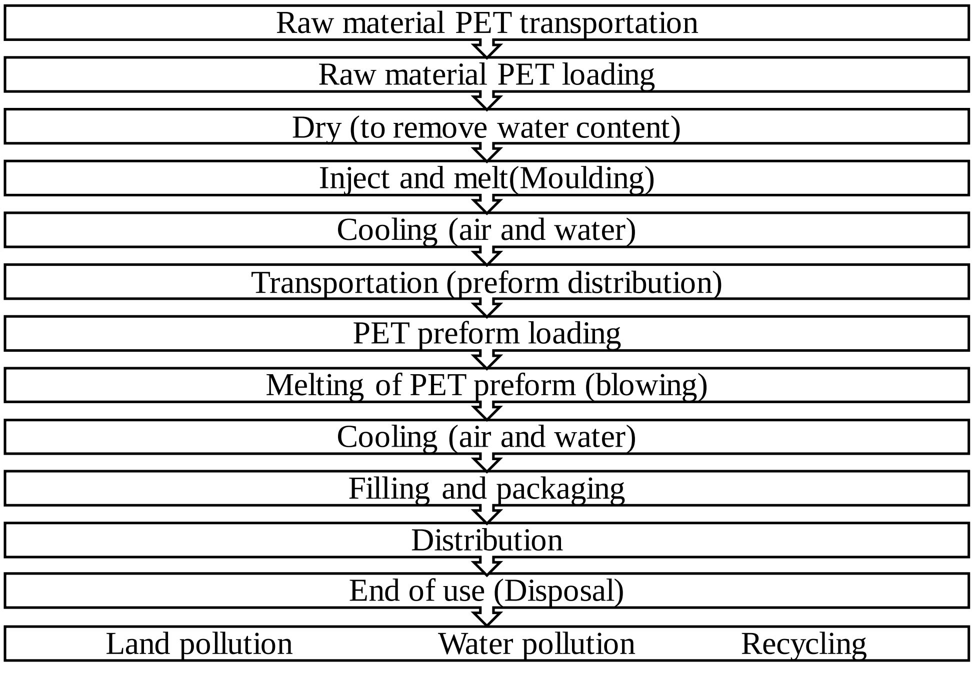

Figure 4 PET bottle production processes

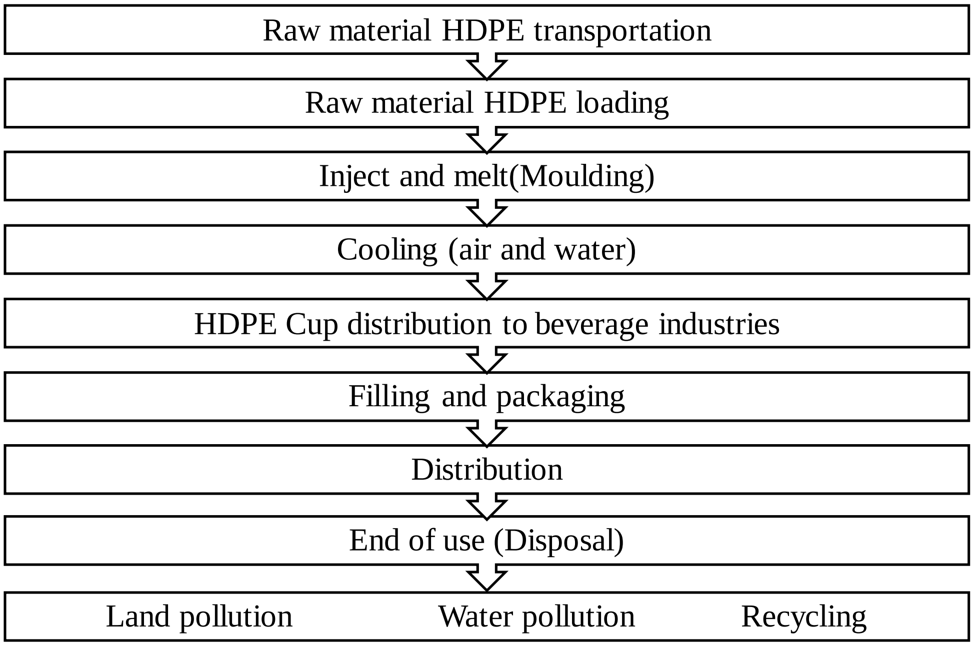

Figure 5 HDPE Cup production process

Figure 4 and 5 shows the entire manufacturing process of plastic bottles in a system boundary and each parts of a process called unit processes. As the figure shows the system processes starts from raw material transportation (data collection starts from transportation of raw material) however, open LCA software database considers all upstream activities i.e. raw material extraction. Each unit process has its own input and output. However, the environmental impacts of some of the unit processes are insignificant and not considered in the study. The main processes of plastic bottle life cycle are:

Transportation

Transportation process for the production of plastic bottle is a circulation of materials between beverage industries, source of raw materials, Roha pack and Moha soft drinks industry. The process includes raw material transportation from Saudi Arabia to Roha pack industry and distribution of preform and HDPE cup to Moha soft drink industry. After preform and HDPE cup distributed to Moha soft drinks industry, transportation of product from Moha soft drinks industry to different beverage industries (Mekele, Gondar, Dessie, Bure, and Hawassa). Both ship and land transportations used to transfer raw materials and only land transportation used for distribution. Distance travelled, type of transportation used and load capacity information normalized to 1000 ml capacity one piece (40 g) of plastic bottle in order to know transportation impact of plastic bottle to the environment. Environmental impact of transportation emanates mainly from fuel consumption which eventually causes emission to air.

Moulding

Injection moulding used for high production-volume manufacturing technologies that form plastic into many different shapes and sizes (Preform). Injection moulding is used for complex solid components. It forces plastic into a mould under high pressure. In addition, injection moulding requires heavy-duty hydraulic rams to inject the plastic raw material and to keep the mould from leaking plastic during the injection phase. Injection moulding machines work by injecting molten thermoplastic in to a mould. Therefore, injection moulding requires electrical energy (359.15 Kwh) for melting 1244.03 kg of PET and HDPE.

Blow molding

Blow moulding is used for thin-walled hollow parts. Blow moulding, expands a hollow tube of plastic into a mould using compressed air. After injection, moulding PET preform formed and the preform moulded to bottle by blow moulding. Therefore, blow moulding requires electrical energy (416 Kwh) for melting 1244.03 kg of PET preform.

Disposal

Disposal is the final stage of a system. Currently, final disposal alternatives in Addis Ababa for plastics (PET and HDPE) are recycling and landfilling. Plastic waste are recycled (39.5%) and the rest of plastics that are not recycled were considered as plastic waste in this study. Plastic wastes that are not recycled were disposed of randomly, have major contribution to water, and land pollution.

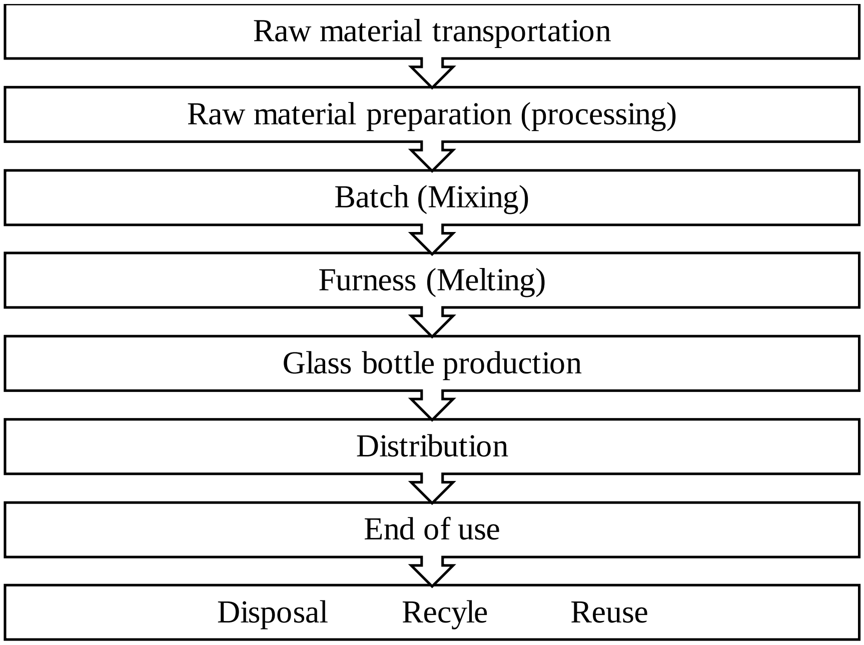

Figure 6 Glass bottle production process

Figure 6 shows the whole process of glass bottle life cycle. The main unit processes includes transportation of both raw material and product, preparation of raw materials, mixing and melting of raw materials and glass bottle production. As shown in the figure 6, the system starts from raw material transportation but, Open LCA software database considers all the upstream activities of raw materials (raw material extraction process).

Transportation

Transportation process includes the circulation of materials from different parts of Ethiopia to Addis Ababa glass and bottle industry and distribution of product to other beverage industries. Only land transportation used for transportation of raw materials (Silica sand and lime stone from mugger sheleko, Marble from Harar, Soda ash mostly from Kenya and Cullet from different parts of Addis Ababa) and for distribution of products. Distances travelled, type of truck used and load capacity information normalized to 300 ml capacity one piece (380 g) of glass bottle in order to know transportation impact of one piece of glass bottle to the environment. The average distance travelled was considered. The environmental impact of transportation is mostly because of fuel consumption and emission to air.

Raw material preparation

Raw material preparation process is all the preparation of raw materials for the next (mixing) step. This process involves crashing, washing and drying respectively. The first step of raw material preparation is crashing that directly impact the environment by releasing dust. Crashing activity uses both electrical and fuel energy which leads energy consumption. The second step is washing of raw materials after crashing. This activity consumes water. Drying is the last activity of raw material preparation process used to remove water from the materials. This activity uses fuel and electrical energy. Generally raw material preparation step has high energy consumption, fuel consumption, water consumption and emission impact to the environment.

Batch mixing and melting of raw materials

It is the process after raw material preparation. All raw materials weighted with a required amount and mixed. Mixed raw materials heated together in a Furnace to a specific melting point (1500-1600 o C), where the properties react to form liquid glass. This process consumes electrical energy of 86.4 Kwh for mixing and 940 Kwh for melting. Furnace also consumes fuel of 17.5 litter/ton for melting. This process consumes electrical energy and fuel energy. The impact of this process is mainly energy consumption and emission to the environment.

Glass bottle production

Cutting, forming of bottleneck and blowing. It is the process of forming the final output of a process called product (glass bottle).

3.4.3 Impact assessment

Significance of potential environmental impacts of a product system based on life cycle inventory results was evaluated. This includes, significance of potential environmental impacts of processes for both plastic and glass bottle were evaluated. The influence of glass and plastic bottle products on the environment was examined using Open LCA 1.11 software, an LCA program, to carry out the impact assessment phase. This program can analyse how each process affects the environment by taking into account all upstream activities. Open LCA1.11 software including of inventory, classification and characterization techniques. The assessment conducted using midpoint impact indicators. All results of inventory analysis for both products assigned to impact categories based on impact of processes to the environment. Accordingly, the most significant indicators for this study were considered: Open LCA 1.11 is LCA software used for modelling systems using the eco Invent 3.9 database as data sources and adopted the midpoint impact indicators to evaluate the impact.

3.4.4 Interpretation

Impact assessment results were analysed (interpreted) as indicating critical points in environmental performance both in terms of significant impacts and in terms of key drivers. Processes, materials, activities, and components or even a life cycle stage that contribute significantly to the environmental impact of the product system were identified. The phase of interpretation involves analysing the data in relation to the objectives and scope of the study, drawing conclusions, identifying any limitations, and formulating recommendations based on the results. Both impact assessment and interpretation stage of LCA are core for LCA study. The functional unit of glass bottle was 300 ml capacity but, in this stage all the impact results were converted to 1000 ml capacity in order to identify type of packaging material (plastic or glass) used to pack 1000ml capacity soft drink. The parameters used to evaluate impact of processes for both plastic and glass bottle life cycle are:

Acidification

The amount of hydrogen ions that can be created per mole of sulphur dioxide (SO2) is used to calculate acidification. By weighing various airborne emissions according to their Acidification Potentials, which represent their capacity to release protons relative to sulphur dioxide (SO2) (Mata & Costa, 2001). It is the result of release of sulphur dioxide and nitrogen oxide, which dissolves with condensed water in the atmosphere and falls as rain. It is measured in mass of sulphur dioxide equivalents (kg SO2-Eq). Supplementary materials, generates a great deal of NOx, NH3, and SO^2, which may alter the environments pH value.

Climate change (Global warming)

A measurement of the potential contribution of various gases to the greenhouse effect is called the global warming potential, or GWP. When comparing one mass unit of a pollutant to one mass unit of carbon dioxide (CO_2), which is employed as a reference gas (Mata & Costa, 2001). It is the result of emissions of carbon dioxide, methane and ethane measured in Kg CO2-Eq.

Terrestrial Eco toxicity

It is caused by the release of toxic substances onto the land and measured in Kg 1, 4-DCB-Eq.

Freshwater Eco toxicity

It is the result of release of heavy metals (Cr, Hg, and Zn) and polycyclic aromatic hydrocarbons (PAH) in to water bodies. It is measured in mass of 1,4 dichlorobenzene equivalents(kg 1, 4-DCB-Eq).

Abiotic/mineral depletion potential

It is the result of minerals consumption by processes. It is a measure of diminishing mineral availability. This impact indicator is caused by excessive natural resource consumption and exploitation measured in amount of antimony equivalent (Kg Sb-Eq).

Energy depletion: is the result of energy consumption (electricity and fuel used) by processes measured in mega joules (MJ).

Human toxicity: It is caused by release of toxic substances to the environment (air, water and soil) measured in 1,4 dichlorobenzene equivalents (kg 1, 4-DCB-Eq)

Ozone layer depletion: is the result of emissions of ozone depleting substances (ODSs) into the atmosphere measured in chlorofluorocarbons equivalent (kg CFC-11-Eq).

Photochemical oxidation: caused by emissions from the process reacts with sunlight (Yuguda et al., 2020). Measured in amount of ethylene equivalent (kg ethylene-Eq).

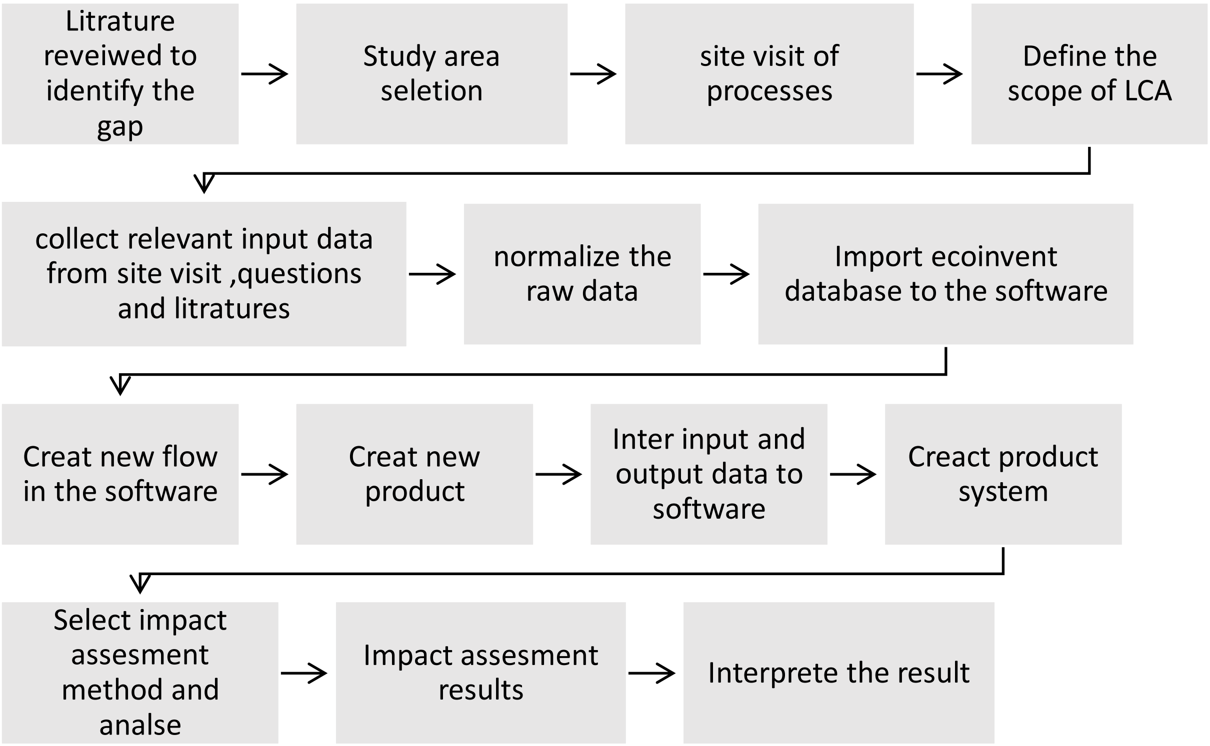

Figure 7: Methodological flow summary

4 Result and Discussion

4.1 Input of plastic and glass bottle system process

Inputs are unit processes (raw materials, energy and natural resource) consumed for product formation and outputs (products, by-products and emissions of a process). Hence, the table 1 shows all the inputs and outputs of functional unit plastic bottle. The inputs for plastic bottle lifecycle are electricity used for running a machine, polyethylene terephthalate (raw material to produce a bottle), high density polyethylene (raw material to produce a bottle cup) and both land and sea transportation (used to circulate raw material from source to the company and distribute the product). The outputs are product plastic bottle and plastic bottle waste. These are unit processes involved to produce 0.04 kg of one piece plastic bottle with a 1000 ml capacity (functional unit of plastic bottle). Plastic that was not recycled considered as plastic waste (the amount of raw material packaging plastic bag plus disposed plastic bottle).

Table 1: Input and outputs of plastic bottle life cycle for one-piece 1000 ml capacity

Input		
Unit process	**Value**	**Unit**
Electricity	0.025	KWh
Polyethylene terephthalate (PET)	0.038	Kg
high density polyethylene (HDPE)	0.0026	Kg
Raw material road transport	34.773	Kg. Km
Raw material sea transport	52.18	Kg. Km
Material distribution road transport	23.0748	Kg. Km
Output		
Plastic bottle	0.04	Kg
Plastic solid waste	0.0249	Kg

Table 2 shows all the inputs and outputs of functional unit glass bottle. The inputs for glass bottle lifecycle are electricity used for running machines, cullet, marble, silica sand and soda ash (raw materials to produce a product), natural gas consumed by processes(raw material drying and melting), water used for washing of raw materials and land transportation used to circulate raw materials from source to the company and distribute the product. The outputs are product glass bottle and emissions of processes. These are unit processes involved to produce 0.38 kg of one piece glass bottle with a 300 ml capacity (functional unit of glass bottle).

Table 2: Inputs and outputs of glass bottle life cycle for one-piece 300 ml capacity

Input		
Unit process	**Value**	**Unit**
Electricity	0.101	KWh
Cullet	0.25	Kg
Marble	0.0215	Kg
Silica sand	0.0832	Kg
Soda ash	0.026	Kg
Water	2	Kg
Raw material road transport	57.3	Kg. Km
Raw material road transport	357.2	Kg. Km
Output		
Glass bottle	0.38	Kg
Carbon dioxide(CO_2)	1.286	Mg
Particulate matter(<2.5μm)	0.00154	Mg
Particulate matter(>10μm)	0.00234	Mg
Volatile organic compounds(VOCs)	5.83	Mg

The activities involved in glass bottle production process has energy, fuel and water consumption. Raw material preparation (crashing, washing and drying) is the first step for the production then mixing of the prepared raw materials and finally melting to produce bottle. Crashing is the first process for raw material preparation. Washing is a process after crashing that consumes 67,536 m^3 water per day to wash crashed raw materials. Drying is the process after washing of raw materials which has 374 Kwh per day energy and 15 litter/ton fuel consumption. As shown in table 3, melting of raw materials has high energy (940 Kwh per day) and fuel (17.5 litter/ton) consumption because, it requires high temperature (1500-1600 °C) to melt the raw materials.

Table 3: Glass bottle life cycle processes energy, fuel and water consumption records

Activity	**Energy consumption per day**	**Fuel consumption**	**water consumption per day**	**Number of bottles produced per day**	**Weight of one glass bottle (gram)**
Crashing	144 KWh	_	_	19,298	380
Washing	_	_	67,536 m3		
Drying	374 Kwh.	15 litter/ton	_		
Mixing	86.4 Kwh				
Melting	940 Kwh	17.5 litter/ton	-		

Glass bottle production does not only involved for energy, fuel and water consumption. The process also has emission impact to the environment. Table 4 shows the process emissions of glass bottle functional unit.

Table 4: ambient air emission records for one-piece 300ml capacity glass bottle

Sampling point	**PM**$_{2.5 \mu g/m^3}$	**PM**$_{10\ \mu g/m^3}$	**CO**$_{2\ mg/m^3}$	**VOC** $_{mg/m^3}$
Furnace area	0.12	0.144	0.221	3.194
Mixing area	0.506	0.717	0.62	0.933
Crusher area	0.47	0.755	0.205	0.545
Dreier area	0.443	0.75	0.24	1.16

As the result shows, a single piece glass bottle production process involves to carbon dioxide emission of 1.286 mg/m^3. The long-documented evidence of rising surface temperatures continues to be a crucial sign of climate change. This is because of GHGs emission and CO$_2$ is one of the GHG that have impact to global warming. As Earth's surface temperature rises due to increased carbon dioxide concentrations, the ozone layer is being destroyed (Kabir et al., 2023).

Glass bottle production also involved to particulate matter ($PM_{2.5}$), particulate matter (PM_{10}) and volatile organic compounds (VOCs) emission of 1.539 µg/m^3, 2.366 µg/m^3 and 5.832 mg/m^3 respectively. According to Kim et al., (2015), particles with a diameter of less than 10µm are known to have the greatest influence on human health. Because of their extreme penetrability, these particles can enter the respiratory system and travel all the way from the nasal passages to the alveoli, which are located deep within the lungs. As the most common type of indoor air pollution, volatile organic compounds (VOCs) are those with boiling points between 50°C and 260°C. The main way that people are exposed to VOCs is by breathing. Our sense of health and wellbeing can be greatly impacted by the quality of the air we breathe (Rumchev et al., 2007). Generally, all the results obtained from inventory analysis of the functional units of glass and plastic bottle, used as inputs to the subsequent impact assessment phase.

4.2 Cumulative impact of processes for glass and plastic bottle

The impact caused from 1000ml single-piece plastic container is shown in Table 5. As it is shown, it causes nine major types of impacts throughout the plastic bottle life cycle based on eco invent CML v 4.8 2016 method. These impacts are acidification, energy depletion, fresh water eco-toxicity, global warming, mineral resource depletion, terrestrial eco-toxicity, ozone depletion potential, human toxicity and photochemical oxidant formation. Each impact category has its own contributors with different contribution amount.

Table 5: The cumulative impact of processes with contributors of a single piece 1000 ml capacity plastic bottle though-out its life cycle

Name	**Contributors**	**Impact result**	**Unit**
Acidification		**0.00032**	Kg SO2-Eq
	PET	2.6x10-5	
	Transportation	4.6x10-5	
	HDPE	1.476x10-5	
Mineral/Abiotic resource depletion		**1.1853 x10^{-5}**	Kg Sb-Eq
	PET	1.179x10^{-5}	
	HDPE	4.82x10^{-8}	
	Transportation	1.53x10^{-8}	
Energy depletion		**2.875**	MJ
	PET	2.569	
	HDPE	0.18	
	Transportation	0.1246	
	Electricity	0.00146	
Terrestrial Eco toxicity		**0.00152**	Kg 1,4 DCB-Eq
	PET	3.163x10-3	
	HDPE	2.127x10-5	
	Transportation	2.857x10-5	
	Electricity	6.83x10-6	
Freshwater Eco toxicity		**0.039**	Kg 1,4 DCB-Eq
	PET	0.035	
	Transportation	2.43x10-3	
	HDPE	1.079x10-3	
	Electricity	1.984x10-4	
Ozone depletion		**3.76x10-7**	Kg CFC-11-Eq
	PET	3.756x10-7	
	HDPE	2.56x10-10	
	Transportation	1.25x10-10	
Global warming		**0.125**	Kg CO2-Eq
	PET	0.11	
	Transportation	8.12x10-3	
	HDPE	5.28x10-3	
	Electricity	1.29x10-3	
Photochemical oxidant formation		**3.04 x10-5**	Kg Ethylene
	PET	2.507x10-5	
	Transportation	3.44x10-6	
	HDPE	1.803x10-6	
Human toxicity		**0.109**	Kg 1,4 DCB
	PET	0.099	
	Transportation	6.728x10-3	
	HDPE	2.931x10-3	

Besides, glass bottle life cycle has its own impact to the environment. A single-piece glass container with a 300 ml volume capacity contributes for nine major impact categories of eco invent CML v 4.8 2016 method. The impact analysis results of a single-piece glass bottle on the environment displayed in Table 6.

Table 6: Impact analysis results of 300ml capacity one-piece glass bottle

Name	**Impact result**	**Unit**
Acidification	0.00181	Kg SO_2
Photochemical oxidant formation	9.774×10^{-5}	Kg Ethylene
Energy depletion	4.44	MJ
Material depletion	3.79×10^{-6}	Kg Sb-Eq
Terrestrial Eco toxicity	0.00222	Kg 1,4 DCB
Freshwater Eco toxicity	0.233	Kg 1,4 DCB
Human toxicity	0.356	Kg 1,4 DCB
Ozone depletion	3.62×10^{-9}	Kg CFC
Global warming	0.37	Kg CO_2

The primary impact categories for the life cycle study of glass bottles include global warming, acidification, energy depletion, material depletion, freshwater eco toxicity, terrestrial eco toxicity, human toxicity, photochemical oxidant formation and ozone depletion potential(Table 6).

4.3 Impacts of each unit processes (phase) in the environment of plastic bottles

The contribution of different processes to abiotic mineral depletion potential, measured in Sb-Eq. PET accounts for 99.66% of the depletion potential, followed by HDPE at 0.17% and land and sea transportation at 0.16%. More or less all abiotic depletion of plastic bottle is due to polyethylene terephthalate. The high contribution of PET to this depletion potential is primarily due to its extensive use of mineral resources during the production process (Figure 8). The result shows that, PET is produced through the esterification of ethylene glycol and purified terephthalic acid (PTA). The monomers used in PET production, namely purified terephthalic acid (PTA) and Monoethylene glycol (MEG), are polymerized in the liquid phase to create amorphous PET. This particular form of the polymer is suitable for producing fibers and films. In most cases, bottle-grade PET is polyester that has been slightly modified through the addition of 1-2% benzene, 1, 3-dicarboxylic acid (isophthalic acid, IPA) or 4(hydroxyl methyl) cyclohexyl-methanol (cyclohexane di methanol, CHDM) during the polymerization process.

The second contributor is HDPE (0.17%). HDPE is primarily produced using low-pressure technologies such as the slurry suspension, solution, or gas phase processes. The catalysts used are typically Ziegler-Natta or Phillips-type catalysts, although metallocene-type catalysts can also be utilized. Polymer formation occurs in a hydrocarbon diluent, with the monomer being soluble in the solution. This process, along with the use of minerals, does have an impact on resource depletion. However, the contribution of HDPE to resource depletion is relatively small compared to PET, as only a small amount of HDPE (2.55g) is used in the production of a one-piece bottle, with the majority being PET (37.2g). Transportation accounts for 0.16% of resource depletion due to the fuel consumed during journeys, as fuel is a natural resource.

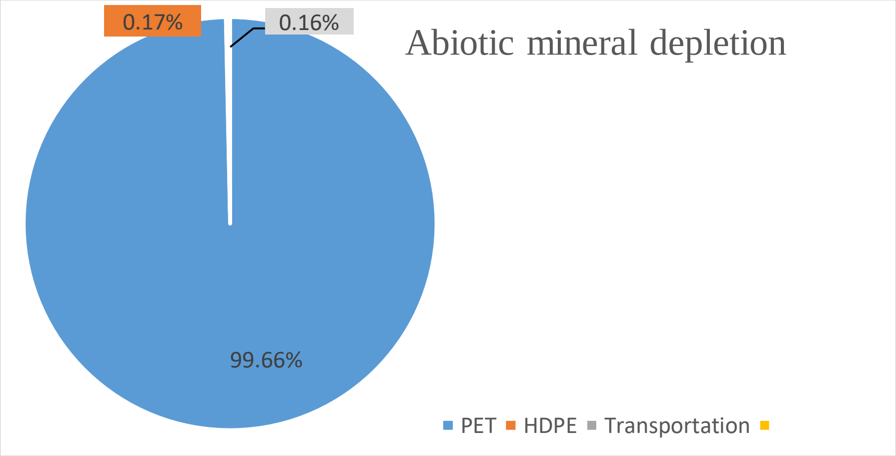

Figure 8: Percent contribution of processes to mineral depletion potential of plastic bottle

Figure 9 presents the breakdown of contributor processes to acidification in terms of SO_2 Eq. PET (85.77%), land and sea transportation (9.46%), HDPE (4.65%), and electricity (0.12%). The result shows that, PET is the primary contributor to acidification due to its high emissions of sulphur dioxide and nitrogen oxides during its extraction process. These emissions lead to the formation of sulphuric and nitric acid. The second contributor is the transportation process (9.46%), with land transportation accounting for 6.61% and sea transportation for 2.85%. Transportation processes contribute to acidification through the emission of sulphur dioxide and carbon monoxide into the environment. HDPE contributes 4.65% to acidification. Although the production process for HDPE is similar to PET, its contribution factor is lower due to the smaller amount used in bottle production. Electricity production is the least significant contributor to acidification.

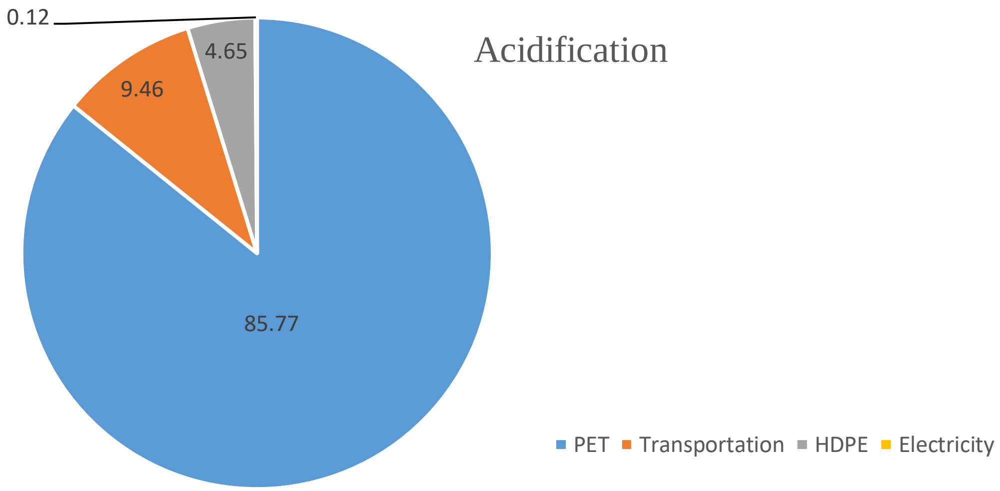

Figure 9: Contribution of processes of plastic bottle for Acidification

The figure illustrates the various contributor processes to climate change, specifically in terms of CO_2 Eq (Figure 10). The life cycle of plastic bottles is attributed to the release of carbon dioxide and methane into the atmosphere. According to the result, level of contribution from each process is mainly dependent on the quantity of carbon dioxide, methane, and ethane emissions. PET accounts for the largest share at 87.4%, followed by land and sea transportation at 6.8%, HDPE at 4.78%, and electricity at 1.03%. PET stands out as the primary driver of climate change due to its significant emissions of carbon dioxide (CO_2) and methane (CH_4). Conversely, electricity production has the smallest impact on climate change as it produces the lowest emissions of CO_2 and CH4.

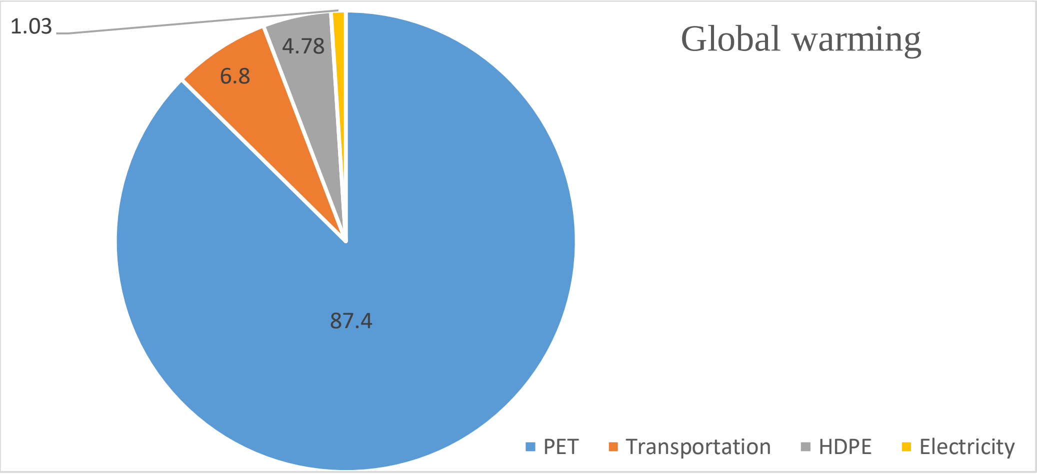

Figure 10: Contribution of processes of plastic bottle for global warming

Figure 11 illustrates the contribution of different processes to freshwater eco toxicity, specifically in relation to 1,4-DCB Eq . Eco toxicity in freshwater is caused by the release of toxic substances into water bodies during life cycle of plastic bottles. Among the various processes, the PET has the highest contribution to freshwater eco toxicity (92.58%). Land and sea transportation account for 3.84%, HDPE contributes 3.35%, and electricity is the lowest contributor (0.16%). The extent of contribution from each process depends on the type and quantity of toxic substances released. The improper disposal of plastic bottle ends in water bodies leads to the gradual release of toxic chemicals over time.

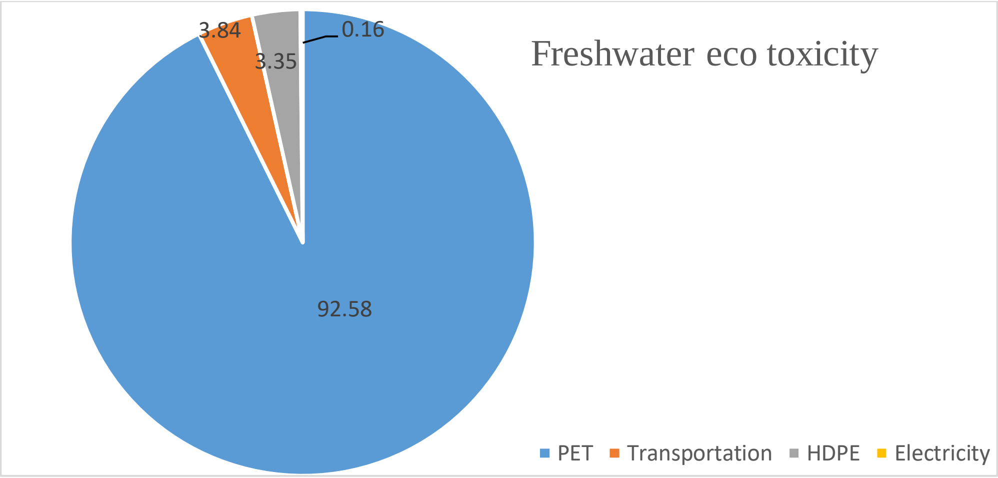

Figure 11: Contribution of processes of plastic bottle for freshwater eco toxicity

The figure illustrates the contribution of different processes to terrestrial eco-toxicity, measured in terms of 1,4-DCB Eq (Figure 12). Eco-toxicity on land, resulting from the life cycle processes of plastic bottle and each has their own contribution, is caused by the release of toxic substances onto the land. The contribution of each process is determined by the type and quantity of toxic substances released onto the surface. Based on the toxicity observed on the surface, PET is the largest contributor to the impact category, accounting for 95.19%. Land and sea transportation contribute 2.84%, HDPE contributes 1.51%, and electricity production is the smallest contributor at 0.47%.

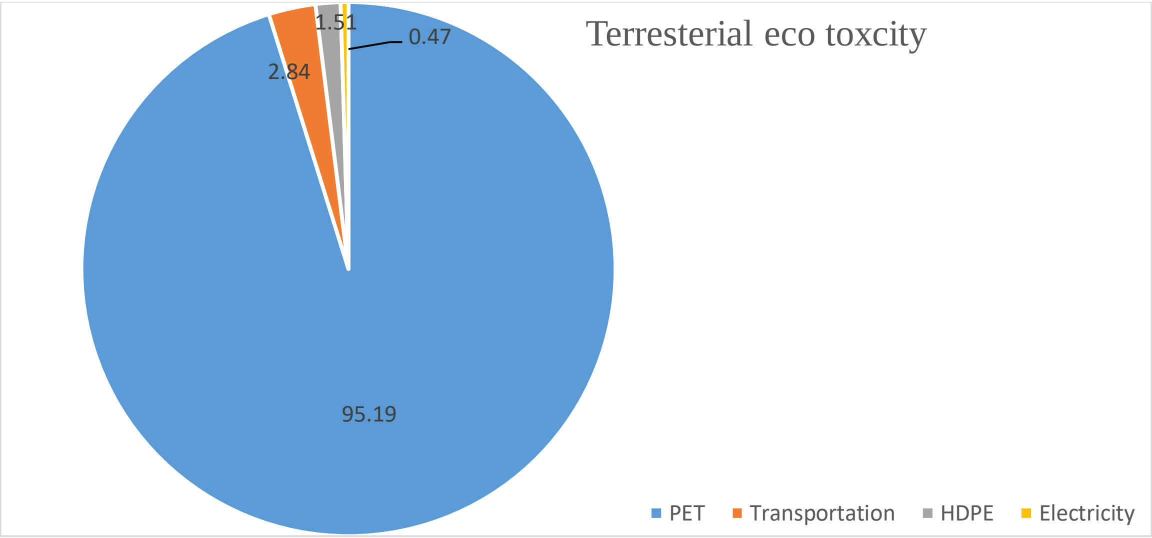

Figure 12: Contribution of processes of plastic bottle for terrestrial eco toxicity

Figure 13 illustrates the different processes that contribute to abiotic (energy) depletion in terms of mega joules (MJ). The life cycle of plastic bottles has a significant impact on energy depletion because it relies on natural energy sources such as crude oil, natural gas, and hydropower. The extent of contribution from each process is determined by the amount of crude oil, natural gas, and hydropower used. As a result, PET is the largest contributor to this impact category, accounting for 89.04% of the total. HDPE 6.62%, while land and sea transportation account for 4.29%. Electricity is the least significant contributor at just 0.05%.

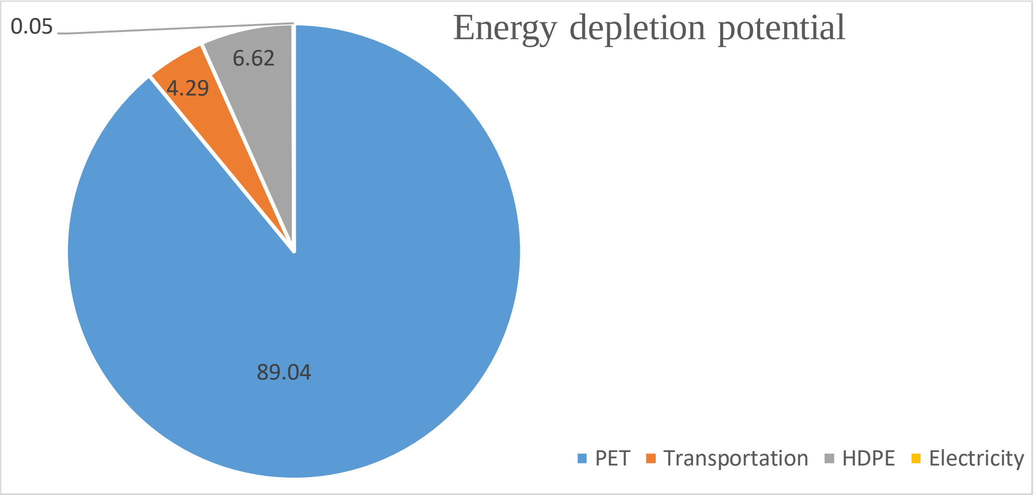

Figure 13: Contribution of processes of plastic bottle for energy depletion

The contribution of various processes to ozone depletion, was measured in terms of CFC-11-Eq. Hence, PET is the largest contributor to this impact category, accounting for 99.93%. Land and sea transportation contribute 0.06% and HDPE contributes 0.01 (Figure 14). It is worth noting that electricity in the production of plastic bottles does not contribute to ozone depletion. The production of plastic bottles leads to ozone depletion due to the emission of ozone-depleting substances (ODSs) into the environment. These ODSs include chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs), methyl bromide, carbon tetrachloride, and methyl chloroform. The extent to which each process contributes to ozone depletion depends on the type and quantity of ODSs released into the atmosphere.

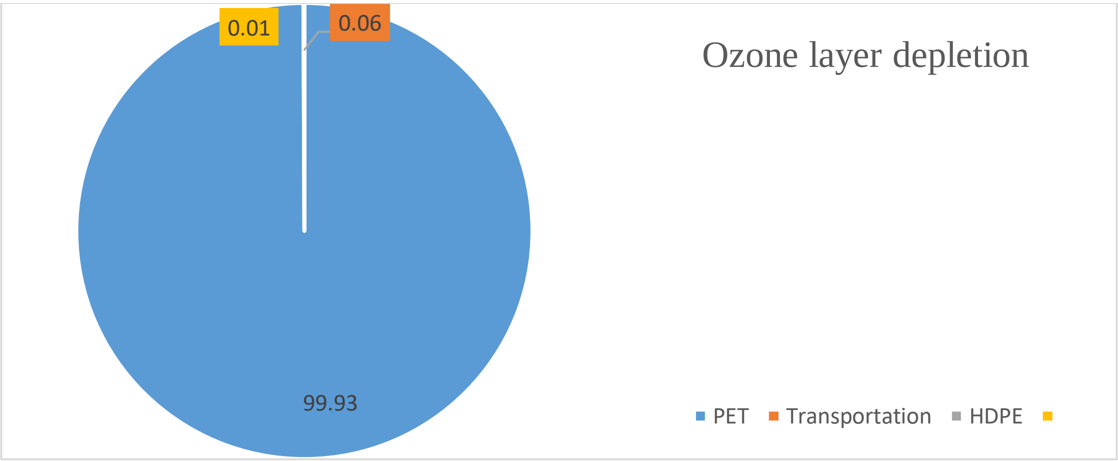

Figure 14: Contribution of processes of plastic bottle for ozone layer depletion

The contribution of various processes to photochemical oxidant formation, was measured in terms of Kg ethylene-Eq. Hence, PET is the largest contributor to this impact category, accounting for 82.48%. Land and sea transportation contribute 11.33%, HDPE contributes 5.93% and electricity contributes 0.26% (Figure 15). Photochemical oxidation impact is formed by the reaction of primary emissions of plastic bottle with the atmosphere. Because of high emissions of raw material extraction processes and degradation of disposal stage of plastics, PET makes the largest contribution.

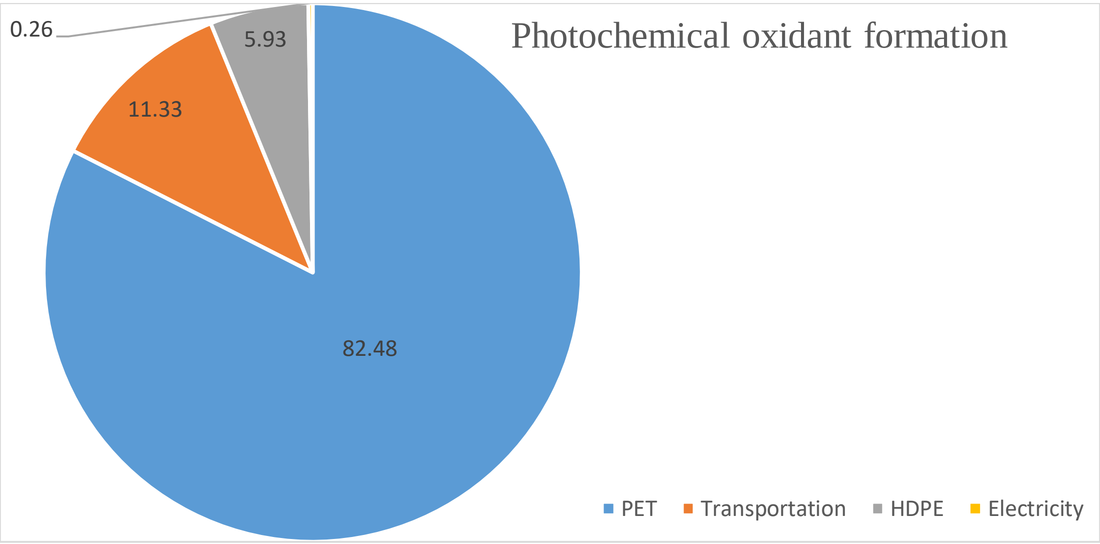

Figure 15: Contribution of processes of plastic bottle to photochemical oxidant formation

The contribution of various processes of plastic bottle to human toxicity, was measured in terms of Kg 1,4-DCB Eq. Hence, PET is the largest contributor to this impact category, accounting for 90.76. Land and sea transportation contribute 6.18%, HDPE contributes 2.69% and electricity contributes 0.38% (Figure 16). When plastic bottles decompose in landfills, harmful chemicals like BPA can leach into groundwater, posing risks to both humans and wildlife (Crisp et al., 1998) .Because of biodegradation plastics release different chemicals that have human toxicity impact, PET is the largest contributor.

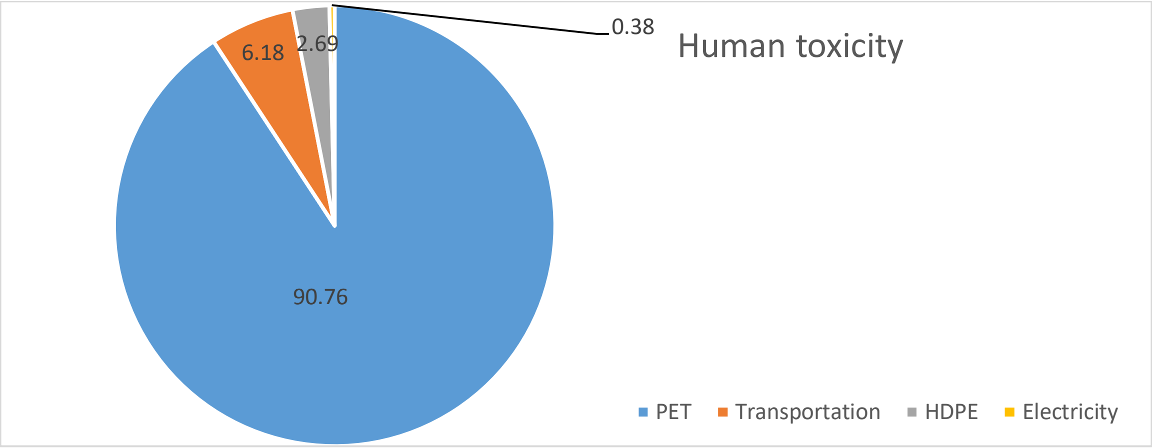

Figure 16: Contribution of processes of plastic bottle to human toxicity

4.4 Impacts of each unit processes (phase) in the environment of glass bottles for each impact category

4.4.1 Acidification

A glass bottle has acidification environmental impact of 0.00181Kg SO_2-Eq. The figure illustrates the proportion of contributor processes to acidification in terms of SO_2 Eq (Figure 17). Accordingly the contributors for this impact are-cullet (0.00083 Kg SO_2-Eq), electricity (0.00047Kg SO_2-Eq), soda ash (0.00027Kg SO_2-Eq), transportation ($2.05x10^{-4}$ Kg SO_2-Eq), silica sand ($2.275x10^{-5}$ Kg SO_2-Eq), natural gas ($1.58x10^{-5}$ Kg SO_2-Eq) and water ($3.548x10^{-6}$ Kg SO_2-Eq). Based on the contribution impact of each, percent of contribution of processes are cullet (45.63 %), electricity (26.15%), soda ash (14.72%), transportation (11.12 %), silica sand (1.26%), natural gas usage for production (0.87%) and water (0.2%). As the result shows, it is the consequence of release of sulphur dioxide and nitrogen oxide into the environment. Based on the emission amount, glass cullet is the highest contributors to acidification. Glass cullet is the highest contributor because of highest amount usage (65.65%) to produce glass bottle and activities (collecting and crashing) contribute to emission. Electricity is the second contributor to acidification. Activities that consume electricity are; raw materials preparation and production process (Melting of raw materials with high temperature). High electricity consumption leads acidification impact. In case of Ethiopia, The reservoir hydropower plants are modelled with non-alpine region plants. This dataset starts from the power plant ready to produce electricity, i.e. the reservoir filled with water by considering all upstream activities ends with 1kWh of high voltage electricity produced at the power plant and arrived at the bus bar. Using water to spin turbines to generate electricity does not directly use fossil fuels or release any emissions into the atmosphere; reservoirs built by damming rivers do contribute significantly to acidification by releasing carbon dioxide and methane due to decomposition of organic materials such as plant leaves that trapped in to the reservoir.

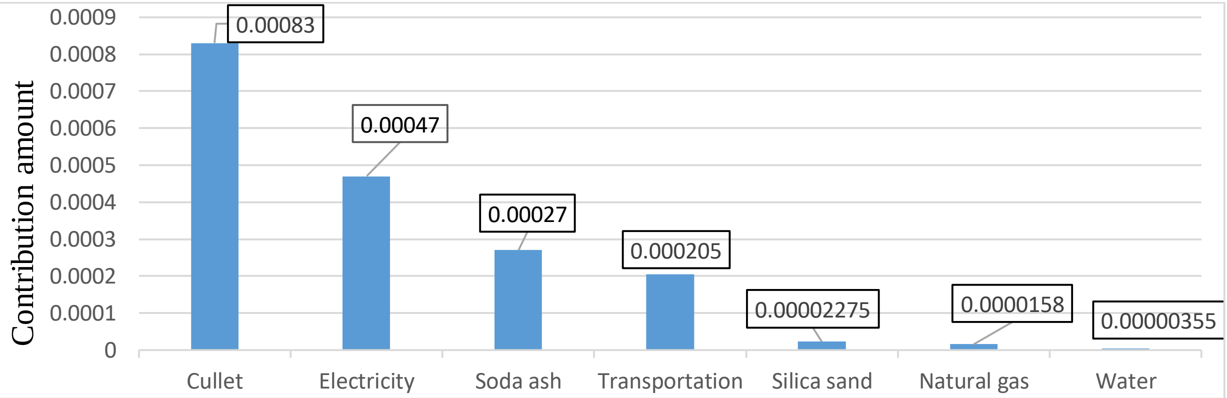

Figure 17: Contribution of processes of glass bottle (300ml capacity) for Acidification

4.4.2 Climate change (Global warming)

Figure 18 illustrates the various contributors to climate change (global warming) in terms of CO_2 Eq. Glass bottle has climate change impact amount of 0.37 Kg CO_2-Eq and the contributors are- cullet (0.167 Kg CO_2-Eq), electricity (0.125 Kg CO_2-Eq), transportation (0.049 Kg CO_2-Eq), soda ash (0.023 Kg CO_2-Eq), natural gas (0.008 Kg CO_2-Eq), silica sand (0.003 Kg CO_2-Eq) and water (0.001 Kg CO_2-Eq). The percentage contribution of cullet accounts for the largest share (44.32 %), followed by electricity (33.23%), transportation (12.93 %), soda ash (6.3%), natural gas usage for production (2.11%), silica sand (0.81%), and water (0.27%). Global warming is the result of emissions of carbon dioxide, methane and ethane. Cullet is the highest contributor because of emission contribution to the environment of cullet collection (transporting) and cullet processing. Electricity production is the second highest contributor to global warming because of electricity does not directly use fossil fuels or release greenhouse gases into the atmosphere, numerous recent studies have demonstrated that reservoirs built by damming rivers do contribute significantly to atmospheric greenhouse gas concentrations. This is because decomposing organic material such as dead plants trapped in the reservoirs releases gases into the reservoir water, including carbon dioxide and methane. Of all the possible effects on the environment, manufacturing contributed the most. It was discovered that the melting sub process during the manufacturing stage was more accountable for the consequences on the environment. Most emissions are also caused by the forming, cutting, and polishing processes. Actually, all of those stages of the crystal processing process called for the application of industrial technology. Furnaces used in industrial plants to melt raw material mixes must be maintained at a high temperature of 1,200°C or 1,300°C constantly (24 hours a day). Nonetheless, advances in technology would contribute to energy conservation (Pulselli et al., 2009).

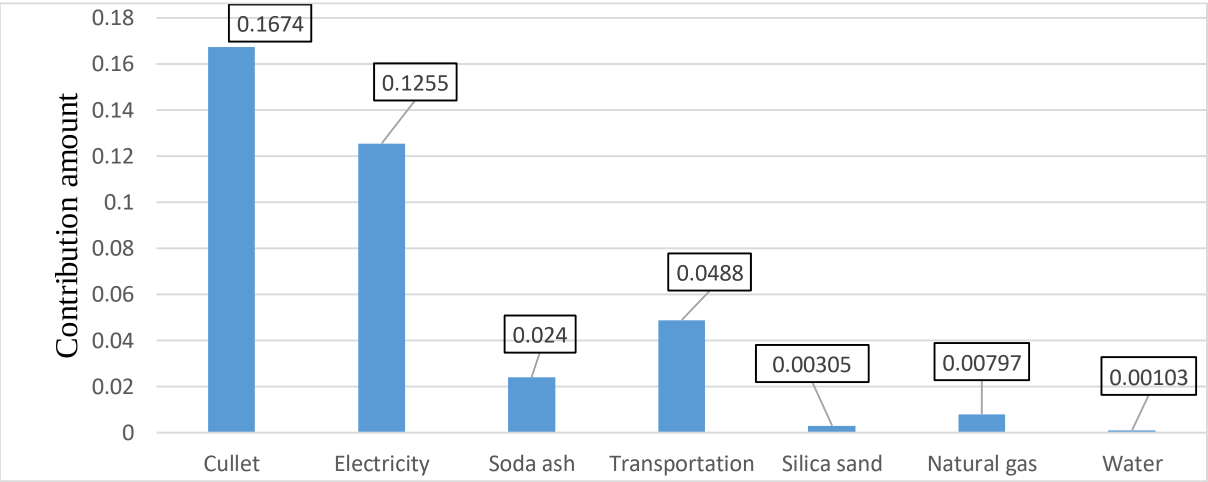

Figure 18 Contribution of processes of glass bottle (300ml capacity) for Global warming potential

4.4.3 Freshwater Eco toxicity

The figure 19 depicts the contribution of various processes to freshwater eco toxicity, measured in terms of 1,4-DCB equivalents.The impact contributors are-cullet (0.109Kg 1, 4-DCB-Eq), electricity (0.066Kg 1, 4-DCB-Eq), transportation (0.014Kg 1, 4-DCB-Eq), soda ash (0.038Kg 1, 4-DCB-Eq), natural gas (0.0031Kg 1, 4-DCB-Eq), silica sand (0.003Kg 1, 4-DCB-Eq)and water (0.00036Kg 1, 4-DCB-Eq). cullet accounts for the highest contribution (46.86%), followed by electricity (28.24%), soda ash (16.28%), transportation (5.95 %), natural gas usage for production (1.32%), silica sand (1.19%) and water (0.15%). The percentage contribution to freshwater eco toxicity for the production of glass bottle depends on the release of heavy metals (Cr, Hg, and Zn) and polycyclic aromatic hydrocarbons (PAH) into water bodies. The main cause of possible this issue was aquatic marine eco toxicity. This was mostly caused by hydrogen fluoride emissions that occurred during the production phases of acid polishing procedure (Pulselli et al., 2009).

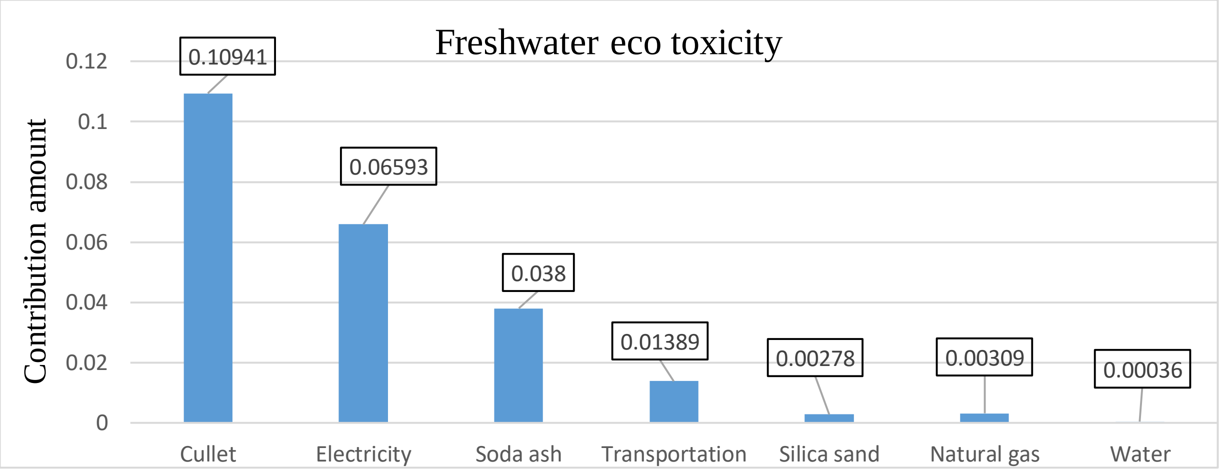

Figure 19 Contribution of processes of glass bottle (300ml capacity) for freshwater eco toxicity

4.4.4 Terrestrial Eco toxicity

The terrestrial eco toxicity contribution of various processes from glass bottle illustrates in Figure 20 in terms of 1,4-DCB Eq.It is measured in mass of 1,4 dichlorobenzene equivalents. Life cycle of glass bottle has terrestrial eco toxicity environmental impact of 0.0022 Kg 1, 4-DCB-Eq. The contributors for the impact are cullet (0.00127 Kg 1, 4-DCB-Eq), electricity (0.00024 Kg 1, 4-DCB-Eq), transportation (0.00017 Kg 1, 4-DCB-Eq), soda ash(0.00048Kg 1, 4-DCB-Eq), natural gas (3.31 x10^{-5} Kg 1, 4-DCB-Eq), silica sand (1.551 x10^{-5} Kg 1, 4-DCB-Eq) and water (6.14 x10^{-6} Kg 1, 4-DCB-Eq). The percentage of contribution for cullet accounts for the highest contribution (57.15%), followed by electricity (10.83%), soda ash (21.76%), transportation (7.79 %), natural gas usage for production (1.49%), silica sand (0.70%), and water (0.28%).Terrestrial eco toxicity impact is the result of release of heavy metals (Cr, Hg, and Zn) and polycyclic aromatic hydrocarbons (PAH) on to land.

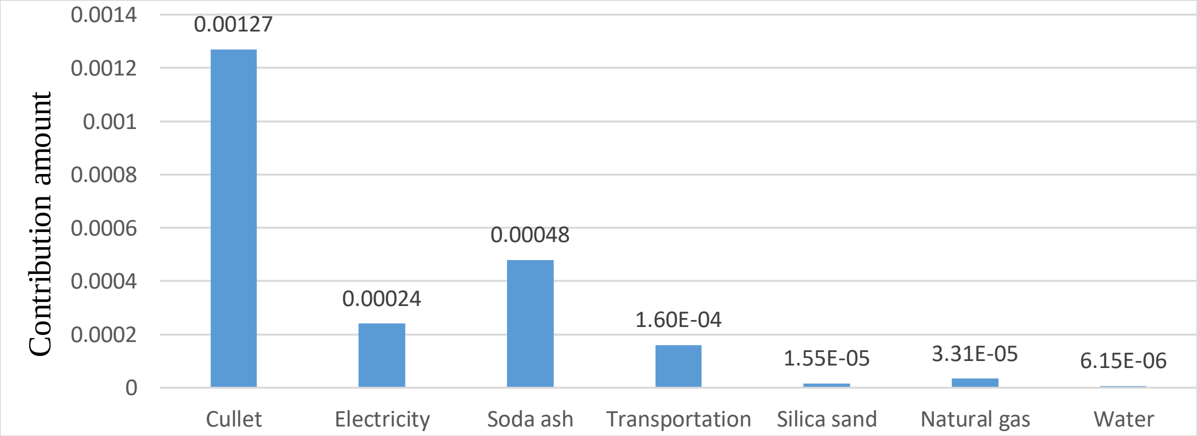

Figure 20 Contribution of processes of glass bottle (300ml capacity) for terrestrial eco toxicity

4.4.5 Energy resource depletion

Figure 21 illustrates the contribution of various processes to the depletion of energy from non-renewable resources in terms of MJ (megajoules). It is the result of energy consumption (electricity and fuel used) by processes. It is measured in mega joules. A glass bottle has energy depletion environmental impact amount of 4.44 MJ. The contributors for this impact are- electricity (1.456 MJ), cullet (1.424 MJ), natural gas (0.591 MJ), transportation (0.72 MJ), soda ash (0.201 MJ), silica (0.031 MJ) and water (0.013 MJ). Electricity accounts for 32.83% of the total, followed by cullet (32.1%), transportation (16.18%), soda ash (4.53%), natural gas usage for production (13.34%), silica sand (0.70%) and water (0.3%). The percentage of contribution to energy depletion for the production of glass bottle depends on the usage of natural gas, crude oil, and coal in these processes. Pulselli et al., (2009) indicates that, the majority of material use (93%) and energy use (89%) occur during the production process. The main cause of this is the consumption of non-renewable energy sources such natural gas, lignite, hard coal, and crude oil. Specifically, the latter accounted for the largest portion of the life cycle energy consumption, particularly in the two sub-processes of forming and melting in furnaces (about 16% and 39%, respectively). According to Krivtsov et al., (2004) study, the glass furnace step was the one that required the most energy out of all the processes that were taken into consideration. The manufacturing process uses the majority of the energy used overall. Highest temperature required for melting of raw materials and energy required for raw material preparation leads electricity the highest energy depleting process in glass bottle life cycle.

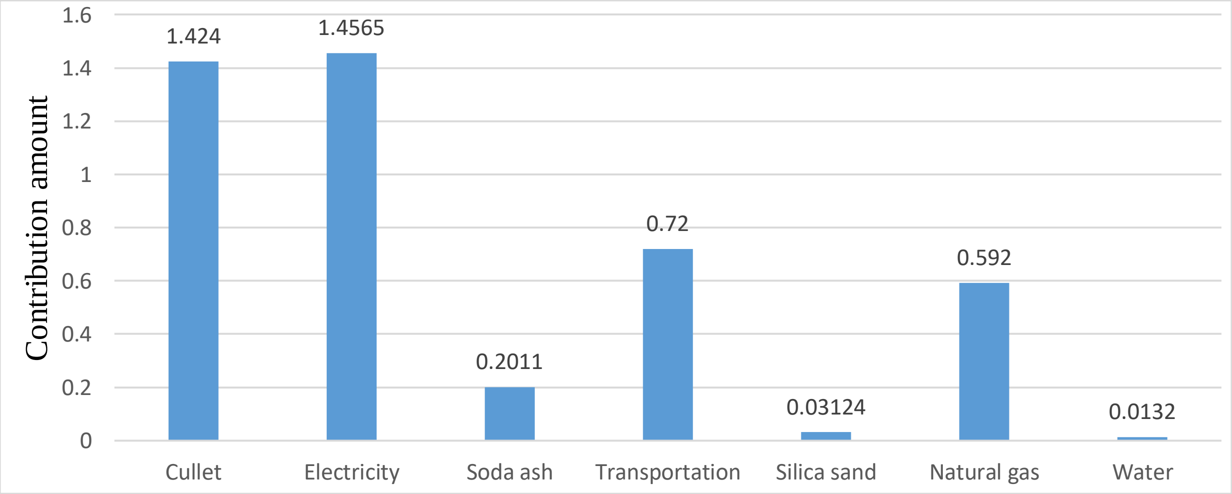

Figure 21 Contribution of processes of glass bottle (300ml capacity) for energy depletion

4.4.6 Human Toxicity

Human toxicity is a release of toxic substances i.e. Antimony, Benzene and polycyclic aromatic hydrocarbons (PAH) to the environment (air, water and soil). Figure 22 illustrates the contribution of various processes to human toxicity, measured in terms of 1,4-DCB Eq. A glass bottle has human toxicity environmental impact amount of 0.3565Kg 1, 4-DCB-Eq. The contributors of the impact are- cullet (0.18Kg 1, 4-DCB-Eq), electricity (0.066Kg 1, 4-DCB-Eq), soda ash(0.0642Kg 1, 4-DCB-Eq), transportation (0.038Kg 1, 4-DCB-Eq), natural gas (0.004Kg 1, 4-DCB-Eq), silica sand (0.003Kg 1, 4-DCB-Eq) and water (0.002Kg 1, 4-DCB-Eq). The percentage of contribution to human toxicity in the production of glass bottle depends on the emission of substances (have effect to human health) in to air and water. Specifically, cullet accounts for 50.45% of the total, electricity for 18.5%, soda ash for 18%, transportation 10.72%, natural gas usage for production for 1.13%, silica sand for 0.75% and water for 0.44%. Human toxicity is the result of exposure to polluted environment. For the purpose of assessing exposure, it is assumed that one will inhale air emissions, drink water for water emissions, and use a more sophisticated mechanism for emissions to soil. Human toxicity in the air caused by emissions of CO, SO_2, NOx, HF, Pb, Cd, and Zn(Mata & Costa, 2001). Potential for human toxicity, mostly as a result of heavy metal emissions during melting (Pulselli et al., 2009). Glass cullet has high impact because of its process. The study of Stefanini et al.,(2021) indicates returnable glass bottle, its reuse scenario emits many ozone-depleting substances (ODSs), which are lead to damage the human health because of the radiation in- crease on the earth.

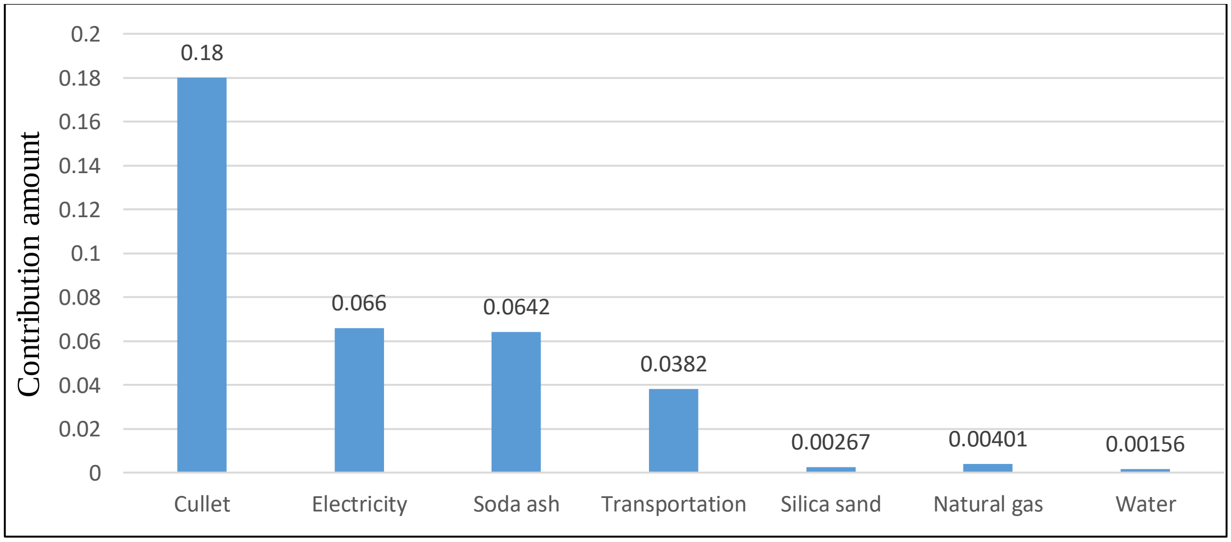

Figure 22 Contribution of processes of glass bottle (300ml capacity) for human toxicity

4.4.7 Ozone layer depletion

It is the result of release of Ozone-depleting substances (ODS$_S$) in to the environment (methane, ethane and hydro chlorofluorocarbons (HCFC-22)) into the atmosphere. Figure 23 shows the contribution of various processes to Ozone layer depletion (ODP) in terms of CFC-11-Eq. A glass bottle has ozone layer depletion impact of 3.62 x10^{-9} Kg CFC-11-Eq. The contributors of this impact category are cullet (1.503x10^{-9} Kg CFC-11-Eq), natural gas (7.54x10^{-10} Kg CFC-11-Eq), transportation (7.19x10^{-10} Kg CFC-11-Eq), electricity (4.75x10^{-10} Kg CFC-11-Eq), soda ash (1.232x10^{-10} Kg CFC-11-Eq) water (2.572x10^{-11} Kg CFC-11-Eq) and silica sand (2.0 x10^{-11} Kg CFC-11-Eq). Based on impact results, cullet accounts for 41.5% of the total, natural gas used for production 20.84%, transportation for 19.86%, electricity for 13.11%, soda ash for 3.4%, water for 0.71% and silica sand for 0.55%. Cullet is the highest contributor because its processes (production, collection and crashing) release emissions to the environment that have ozone layer depletion impact. Natural gas used in the production process and transportation contributes to this impact by releasing ODSs into the environment. Compounds with chlorine or bromine groups, such as hydro chlorofluorocarbons (HCFC) and chlorofluorocarbons (CFCs) are generated during production. Even while glass bottles that can be returned can provide some improvement, their reuse scenario releases a lot of ODSs, which can harm human health due to an increase in radiation(Stefanini et al., 2021). In terms of the impact to ozone depletion, cullet has the highest contribution, while water for washing and silica sand have the lowest contributions.

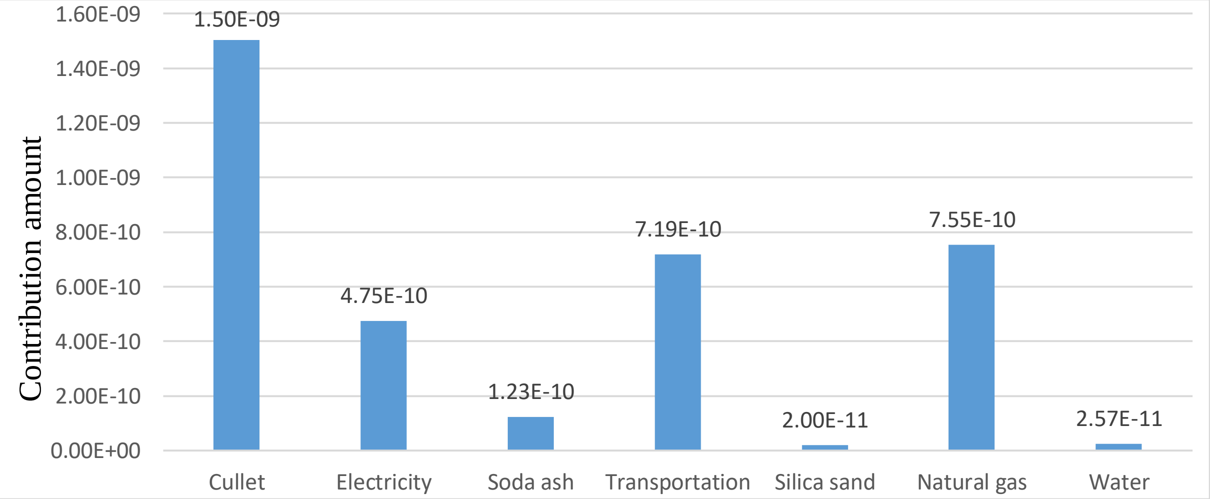

Figure 23 Contribution of processes of glass bottle (300ml capacity) for Ozone layer depletion

4.4.8 Photochemical oxidant formation

It is also known as summer smog or secondary air pollution caused by emissions from the process reacts with sunlight (Yuguda et al., 2020). Contribution of various processes from glass bottle illustrates in Figure 24 in terms of ethylene-Eq. A glass bottle has photochemical oxidant formation equivalent to environmental impact amount of 9.775 $x10^{-5}$ Kg Ethylene. The contributors for this impact are cullet (4.14 $x10^{-5}$ Kg Ethylene), electricity (2.6 $x10^{-5}$ Kg Ethylene), transportation (1.7 $x10^{-5}$ Kg Ethylene), soda ash (9.6 $x10^{-6}$ Kg Ethylene), natural gas (2.3 $x10^{-6}$ Kg Ethylene), silica sand (1.3 $x10^{-6}$ Kg Ethylene) and water (2.14 $x10^{-7}$ Kg Ethylene). According to the result, cullet accounts for the highest contribution (42.37%), followed by electricity (26.51%), transportation (17.33%), soda ash (9.83%), natural gas usage for production (2.35%), silica sand (1.33%) and water (0.22%). The result of the study shows that, the impact is a result of release of carbon monoxide, nitrogen oxide, sulphur dioxide and methane into the atmosphere measured in ethylene equivalents. Photochemical ozone creation potential (POCP) is influenced by regional factors, such as the baseline VOC and NOx concentrations in the area. VOC, hydrocarbons and CH_4 emission leads to this impact category (Mata & Costa, 2001).

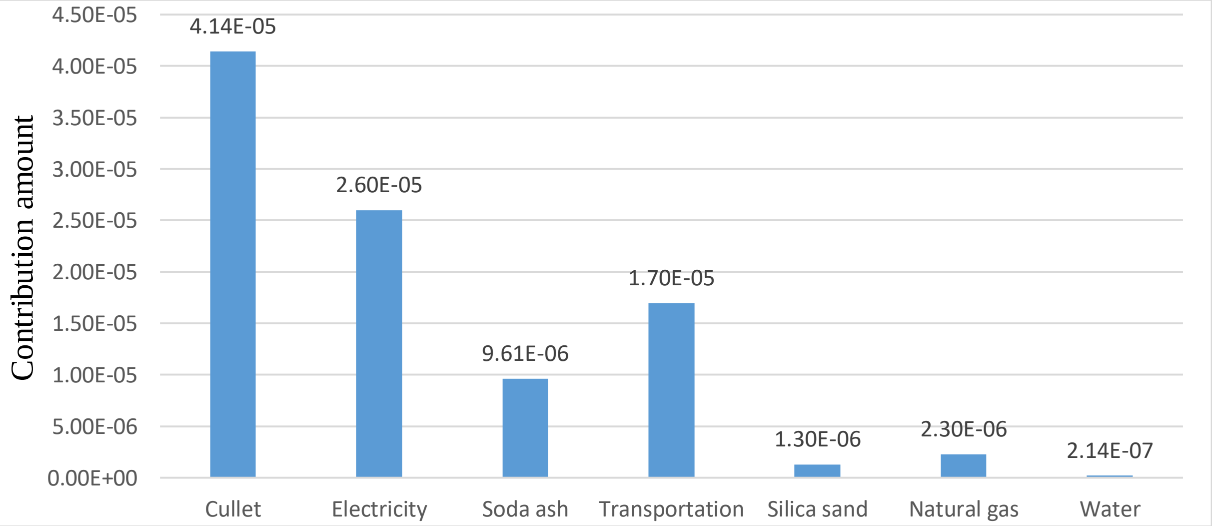

Figure 24 Contribution of processes of glass bottle (300ml capacity) for photochemical oxidant formation

4.4.9 Material depletion potential

It is the result of minerals consumption by processes. It is diminishing mineral availability because of excessive natural resource consumption and exploitation. Figure 25 illustrates the contribution of various processes to material depletion, measured in terms of Sb-Eq. A one piece of glass bottle has 3.79 x10^{-6} Kg Sb-Eq amount impact of resource depletion to the environment. The major contributor is cullet (2.51x10^{-6} Kg Sb-Eq). Other contributors are soda ash (1.08 x10^{-6} Kg Sb-Eq), land transportation of raw material and product distribution (9.02x10^{-8} Kg Sb-Eq), electricity (8.92 x10^{-8} Kg Sb-Eq), water (3.076x10^{-8} Kg Sb-Eq) and silica sand (3.12x10^{-9} Kg Sb-Eq). Cullet accounts for 66.35% of the total, raw material soda ash for 28.46%, transportation for 2.37%, electricity for 2.35%, water for 0.81% and raw material silica sand for 0.08%. In terms of the impact to material depletion, cullet has the highest contribution.To produce one glass bottle 65.65% of cullet is used as raw material and only 34.35% of virgin raw materials used.

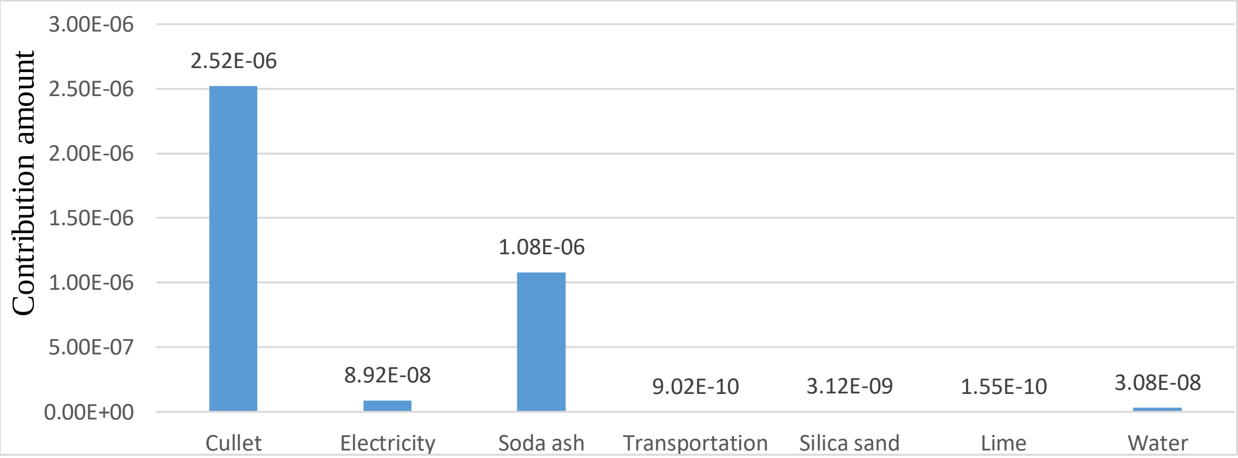

Figure 25 Contribution of processes of glass bottle (300ml capacity) for material depletion

4.5 Comparative impact result of plastic and glass bottle

The Life Cycle Assessment (LCA) method facilitates the evaluation of a product's environmental impact. It's crucial to guaranteeing the overall sustainability of a packaging product because it assesses all aspects of the product's life cycle, from the extraction of raw materials to disposal. It is important to identify the best environmental sustainable soft drink packaging by comparing the environmental impacts of plastic and glass bottle used to pack 1000 ml soft drink. For glass bottle considered three to four times reused ability and Table 7 shows comparative impact results of both plastic and glass bottle in terms of each impact category. The impact result is the life cycle of bottles for 1000ml capacity.

The result shows, plastic bottle has acidification of 0.00032Kg SO_2-Eq, abiotic depletion potential of 1.18 $x10^{-5}$ Kg Sb-Eq, energy depletion potential of 2.87 MJ, terrestrial eco toxicity of 0.0032 Kg 1,4 DCB-Eq, freshwater eco toxicity of 0.039 Kg 1,4 DCB-Eq, ozone depletion of $3.76x10^{-7}$ Kg CFC-11-Eq, global warming potential of 0.125 Kg CO_2-Eq, human toxicity impact of 0.109 Kg 1,4 DCB and photochemical oxidant formation impact of $3.04x10^{-5}$ ethylene-Eq amount to the environment.

In addition, the 1000 ml soft drink bottle made of glass that is reused three to four times has environmental impact of acidification 0.00171 Kg SO2-Eq, material/ resource depletion 0.36x10-5 Kg Sb-Eq, photochemical oxidant formation 8.9x10-5 Kg ethylene, energy depletion potential 4.1 MJ, terrestrial eco toxicity 0.0021 Kg 1,4 DCB-Eq, freshwater eco toxicity 0.22 Kg 1,4 DCB-Eq, human toxicity of 0.331 Kg 1,4 DCB, Ozone depletion potential 0.33x10-8 Kg CFC-11-Eq and global warming potential of 0.35 Kg CO2-Eq. By considering all the values of each impact category for plastic and glass bottle life cycle, glass bottle life cycle has higher impact than plastic bottle in acidification, energy depletion, freshwater eco toxicity, human toxicity, photochemical oxidant formation and global warming impact categories. However, plastic bottle has higher environmental impact of material depletion, terrestrial eco toxicity and ozone depletion potential. The study of Stefanini et al., (2021) also argue that, the environmental impact of glass bottle (1000ml capacity for milk packaging) is high due to its manufacture and transportation. But, PET bottles have the least impact because glass bottles are so heavy, trucks consume more and produce more pollution as a result. Because of these factors, including water consumption, fossil fuel shortages, acidification of the land, global warming, and ozone depletion in the stratosphere, glass bottles seem to be the most harmful materials out of all the chosen LCA categories.

In addition Odabasi & Buyukgungor, (2016) compared PET and glass bottles for water packaging demonstrate that, because glass bottles require a lot of energy to produce, they are not appropriate. When the weight of the life cycle assessments of the two types of bottles are plotted against ecosystem, human health, and resources, it becomes clear that PET bottles have a far smaller impact on the aforementioned parameters due to their simpler production process, lower fuel consumption, and shorter travel distance. This includes the cost of transportation for glass bottles and the costs incurred by consumers in getting goods to the destination or target community. In comparison to a glass bottle, the polymer bottle has a significantly lower environmental impact across all impact categories. It emits fewer greenhouse gases (46% of emissions compared to glass), uses less cumulative energy (55%), has less of an impact on ecosystems (39%), and has less of an impact on resources (59%) (Stefanini et al., 2021).

The results highlighted in Ferrara et al., (2021) presented that the the most environmentally friendly option for natural water packaging was a PET bottle. When considering returnable and non-returnable glass bottles, the PET and R-PET impacts are smaller (Stefanini et al., 2021).

Table 7: Impact assessment result of plastic and glass bottle for one litter packaging of soft drink

Name	Impact result of glass bottle	Impact result of plastic bottle
Acidification	0.00171 Kg SO_2-Eq	0.00032Kg SO_2-Eq
Material/ resource depletion	3.8×10^{-6} Kg Sb-Eq	1.18×10^{-5} Kg Sb-Eq
Photochemical oxidant formation	8.9×10^{-5} ethylene-Eq	3.04×10^{-5} ethylene-Eq
Energy depletion	4.1 MJ	2.87 MJ
Terrestrial Eco toxicity	0.0021 Kg 1,4 DCB-Eq	0.0032 Kg 1,4 DCB-Eq
Freshwater Eco toxicity	0. 22 Kg 1,4 DCB-Eq	0.039 Kg 1,4 DCB-Eq
Human toxicity	0.331 Kg 1,4 DCB	0.109 Kg 1,4 DCB
Ozone depletion	0.33×10^{-8} Kg CFC-11-Eq	3.76×10^{-7} Kg CFC-11-Eq
Global warming	0.35 Kg CO_2-Eq	0.125 Kg CO_2-Eq

The research demonstrated that the number of glass bottle reusing periods is crucial in determining the analysis's outcome. Comparing the contribution processes of each impact categories result as follows:

Acidification

The cumulative acidification impact of processes for glass bottle life cycle is 0.00171 Kg SO_2-Eq. The acidification impact is because of nitrogen oxide and sulphur dioxide emission to the atmosphere. On the contrary, the cumulative acidification impact of plastic bottle life cycle processes is 0.00032 Kg SO_2-Eq. Electricity is the lowest contributor in plastic bottle and the highest contributor in glass bottle. This is because of lower energy consumption in the processes of plastic bottle. The result of the study shows that, glass bottle contributes higher impact to acidification. Also the results of Stefanini et al., (2021) shows, acidification impact of glass bottle is 0.0000563 Kg SO_2-Eq and 0.0000427 Kg SO_2-Eq for plastic bottle. This result reveals that glass bottle has higher acidification impact than plastics.

Global warming/climate change potential

The cumulative global warming impact of glass bottle life cycle processes is 0.35 Kg CO_2-Eq. The contribution of processes for 1000 ml glass bottle that is returnable and used 3-4 times depends on, the releasing amount of carbon dioxide, methane and ethane to the atmosphere. Conversely, the cumulative global warming impact of plastic bottle life cycle processes is 0.125 Kg CO_2-Eq. Constructed on total contribution of processes for glass and plastic bottle, glass bottle has higher global warming impact. Based on Stefanini et al., (2021), global warming impact of R-PET is 0.15 Kg CO_2-Eq and returnable glass 0.222 Kg CO_2-Eq. Even if glass bottle contributes higher impact in global warming than plastic bottles, the impact for both bottles is higher for current study. Because life cycle assessment methodology, distribution distance, product process and others affect the LCIA result.

Freshwater Eco toxicity

The cumulative freshwater eco toxicity impact of glass bottle life cycle processes is 0.22 Kg 1,4 DCB-Eq. In contrast, eco toxicity to fresh water impact of plastic bottle is 0.039 Kg 1, 4 DCB-Eq. The glass bottle life cycle has higher freshwater eco toxicity impact than plastic. Emissions of glass bottle production processes ends in water bodies have great freshwater eco toxicity impact. Whereas improper disposal of plastic bottle ends in water bodies and through time, it releases toxic chemicals to the water and the release of toxic substances during the production of raw material PET leads plastic bottle contribute to freshwater eco toxicity.

Terrestrial Eco toxicity

The cumulative terrestrial eco toxicity impact of glass bottle life cycle processes is 0.0021 Kg 1,4 DCB-Eq. In contrast, the cumulative terrestrial eco toxicity impact of plastic bottle life cycle processes is 0.00316 Kg 1, 4 DCB-Eq. Based on total contribution of processes for glass and plastic bottle, plastic bottle presented higher terrestrial eco toxicity impact than glass bottle. Glass bottle reusing in addition to recycling leads glass bottle contributes lesser solid waste impact than plastics. Less solid waste impact reduces terrestrial eco toxicity impact.

Energy depletion potential

The cumulative energy depletion impact of glass bottle life cycle processes is 4.1 MJ. Highest temperature required for melting of raw materials and energy required for raw material preparation leads electricity the highest energy depleting process in glass bottle life cycle. On the other hand, the cumulative energy depletion impact of plastic bottle life cycle processes is 2.87 MJ. Compared to plastic bottle, glass bottle is the higher contributor to energy depletion impact because of high amount of energy consumed during raw material preparation and melting process.

Material depletion potential

Glass bottle life cycle have cumulative mineral depletion impact of $3.8\text{x}10^{-6}$Kg Sb-Eq. On the other hand, plastic bottle life cycle has $1.18\text{x}10^{-5}$ Kg Sb-Eq impact to mineral depletion. To produce one glass bottle 65.65% of cullet is used as raw material and only 34.35% of virgin raw materials used. Because of this reason glass bottle contributes lower material/resource depletion than plastic bottle.

Impact to human toxicity

The cumulative human toxicity impact of glass bottle life cycle processes is 0.331 Kg 1,4 DCB. Although the cumulative impact of processes for plastic bottle is 0.108 Kg 1,4 DCB. Based on the results, glass bottle is the higher contributor to human toxicity compared to plastic bottle. Because, glass bottle production process emits toxicants that have human health impact. The study of Stefanini et al., (2021) revealed that, human toxicity impact of plastic and glass bottle is 0.00523 Kg 1,4 DCB and 0.00555 Kg 1,4 DCB respectively. This means glass bottle contributes slightly higher human toxicity impact than plastic bottle. Compared to Stefanini et al., (2021), the result of this study discovered higher human toxicity impact in both plastic and glass bottle.

Ozone layer depletion potential

The cumulative impact of processes for glass bottle to ozone layer depletion is 0.33x10^{-8} Kg CFC-11-Eq. Although, plastic bottle life cycle has cumulative impact of 3.76x10^{-7} Kg CFC-11-Eq. Based on the result, plastic bottle contributes higher impact than glass bottle. Because of emissions of ODS_S during raw material extraction process of PET and HDPE leads plastic bottle the higher impact to ozone depletion. But the study of Stefanini et al., (2021) presented, the ozone depleting impact of R-PET is lower than returnable glass. According to the study, the impact result of R-PET was 5.72 x10^{-8} Kg CFC-11-Eq and returnable glass was 9.67 x10^{-8} Kg CFC-11-Eq.

Photochemical oxidant formation

The cumulative impact of processes for glass bottle to photochemical oxidant formation is 8.9x10^{-5} ethylene-Eq. Although, for plastic bottle life cycle is 3.04 x10^{-5} ethylene-Eq. The result presented, glass bottle is higher contributor to photochemical oxidant formation compared to plastic bottle. This is because of emissions from glass bottle production reacts with the atmosphere forming oxidants that harm the environment.

Mostly, cullet is the highest contributor process for all impact categories of glass bottle life cycle except energy depletion impact category (electricity production is highest contributor) and PET production is the highest contributor process for the life cycle of plastic bottle. Based on the results obtained, glass bottle has higher environmental impact than plastic bottle in acidification, energy depletion, human toxicity, photochemical oxidant formation, freshwater eco toxicity and global warming. In addition, lower impact in material depletion, terrestrial eco toxicity and ozone layer depletion potential impact categories. When compared to PET bottles, glass bottles have a greater detrimental influence on the environment. Regarding the overall environmental implications, the research findings supported the use of PET bottles. Conversely, glass bottles are inappropriate due to their excessive energy use throughout the manufacturing process (Odabasi & Buyukgungor, 2016). Consequently, plastic bottle is recommended for soft drink packaging because of lower environmental impact than glass bottle.

5 Conclusion and recommendation

5.1 Conclusion

This initial research work was devoted to assess the environmental impacts of plastic and glass bottle by adopting the life-cycle assessment (LCA) method. This result indicated that glass bottle has a greater influence to environment in all impact categories except material depletion, terrestrial eco toxicity and ozone depletion potential than plastic bottle. Based on impact assessment results of Open LCA analysis, the following conclusions can be drawn concerning the contribution of different processes to glass and plastic bottle life cycle environmental impact:

- Cullet and electricity production processes have great impact to all impact categories of glass bottle life cycle because of great electricity consumption and has lower impact to plastic bottle because of lower consumption of electricity by processes of plastic bottle life cycle.
- PET has high impact to all impact categories of plastic bottle life cycle because of its dominant amount usage and impact (Raw material extraction and end of use stage).
- The impact of plastic bottle is mostly from disposal stage and also extraction of raw materials PET and HDPE stage.
- The raw material preparation and glass production stage of glass bottle life cycle are foremost contributors to all impact categories.
- Both plastic and glass bottle have significant environmental impact. Plastic bottle has lower environmental impact than glass bottle in all impact categories except material depletion, terrestrial eco toxicity and ozone depletion. So, plastic bottle is recommended packaging for environmental sustainability compared to glass bottle.

5.2 Recommendation

- Even if plastic bottle is sustainable than glass bottle, it is recommended that companies explore alternative packaging materials or strategies to reduce their reliance on plastic bottles.

- Promote initiatives to minimize water and land pollution: Efforts should be made to address water pollution by implementing measures such as improved waste management systems, proper disposal practices, and investing in technologies that mitigate these environmental impacts.

- Enhance glass bottle production process efficiency: Companies using glass bottles should focus on improving their production processes to reduce dust generation during raw material processing, minimize energy and water consumption, as well as minimize emissions of pollutants during production.

- Consider alternative packaging materials with lower environmental impacts: Companies using glass bottles should explore other packaging options that have lower environmental impacts, such as biodegradable alternatives in order to enhance sustainability.

- Implement life cycle assessment frameworks: Companies involved in bottle production should consider adopting standardized life cycle assessment frameworks like ISO 14040 and ISO 14044 framework and guidelines to evaluate potential environmental impacts comprehensively throughout the entire life cycle of their products.

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APPENDEX

APPENDEX 1: one-year glass bottle process raw data record

1. Raw material transportation

One glass bottle with 380g mass and 300ml capacity used for soft drink packaging. I.e. Mirinda

Type of raw material	Amount used to produce 300 ml bottle (gram)	Annually purchased (ton)	Distance it is sourced from(Km)	Type of car used	One time load and No. of travel
Silica	83.17	1134.5	Mugger sheleko 87 km	Sino truck (1.1 L fuel)	20 ton (57 times)
Marble	21.48	198	Harar(526km)	Sino truck(1.1 L)	20 ton (10 times)
Lime stone	-	990	Derba(57km)	Sino truck(1.1 L)	20 ton (25 times)
Soda ash	25.81	124.25	Kenya (1365)	Trailer (2.5 L)	40 ton (3 times)
Cullet	249.5	9163.3	All part of Addis Ababa(14km)	Sino truck (1.1 L)	20 ton (458 times)

2. Raw material preparation (energy, fuel and water consumption)

Activity	Energy consumption per day	Fuel consumption	water consumption
Crasher	144 KWh	_	_
Washing	_	_	67,536 m3
Drier	374 Kwh.	15 litter/ton	_

3. Raw material mixing

Activity	Energy consumption per day
Mixing of raw material	86.4 KWh

4. Raw materials melting(Furness)

Activity	Energy consumption per day	Type of fuel used	Amount of fuel used
Melting of raw materials (Furnace)	940 KWh	Gas oil	17.5 litter/ton

5. Glass bottle production

Type of glass produced	Production amount/Year	Recycled amount/year
300ml soft drink pack	1980 ton	827.64
All bottle type	13,071.14 ton	5464 ton

6. Glass bottle distribution

Average distance it distribute(Km)	Amount distributed annually	Type of car used	Fuel consumption/Km
940	1980 ton for 300 ml bottle	Trailer	2.5 L
	13,071.14 ton for all type bottle		

7. Ambient air emission record for one ton production

Sampling point	$PM_{2.5 \mu g/m^3}$	$PM_{10\ \mu g/m^3}$	$CO_{2\ mg/m^3}$	VOC $_{mg/m^3}$
Furnace area	315	379	582	8404
Mixing area	1332	1818	1630	2455
Crusher area	1232	1987	540	1434
Dreier area	1167	1964	632	3053

APPENDEX 2: One-year plastic bottle production process raw data record

Plastic bottle with 1000ml capacity(0.040 kg mass) with mass of 37.2g PET and 2.55g HDPE.

1. Raw material transportation

Type of raw material	Annually purchased amount (ton)	Amount used to produce 1000 ml bottle	Mass of raw material packaging (ton)	Distance(Km) it is sourced from	Type of transportation	One time load(ton)	Transportation Fuel consumption /Km
PET	9800	37.572 g **0.038 Kg**	26.66	1298,865	Ship, low bed	All,222 (44 times)	All,1.1
	430.13						
HDPE	2500 **28.6**	2.575 g **0.0026** Kg	6.66	1298,865	Ship, low bed	All,222(11 times)	All,1.1
	17.0 29.46	**Total** **0.041 Kg**					

2. Bottle and cup production

Type of product	energy consumption for moulding KWH per day	energy consumption for blowing KWH per day	Amount produced per year of (ton)	Total production/day
PET bottle (1 L bottle)	359.15	416	425.87	1165.67 Kg
HDPE cup			28.6	78.36
Total: 775.15				1244.03 Kg

3. Product distribution

Average distance it distributed (Km)	Amount distributed annually(ton)	Type of car used	Transportation fuel Consumption /Km
Mekele = 937 Gondar = 669 Dessie = 386 Bure = 461 Hawassa = 281	All 1 litter PET bottle produced (425.87)	Trailer	2.5 L
	All HDPE cup produced (28.6)		
Average = 574 Km	Total = 454.47 ton		

4. Solid waste

According to (Assnakew, 2018), in Addis Ababa the annual amount of plastic waste generation is 42,705 tons and from this amount only 16,888.55 tons is collected and recycled. Only about 39.5% of plastic recycled from the total production. Therefore, from 425.87 tons of PET and 28.6 tons of HDPE produced and sold out amount of the company, the recycled amount was only 168.22 tons of PET and 11.3 tons of HDPE.

Type of waste	Amount soled per year (ton)	Mass of Amount recycled per year	Mass of raw material packaging per year	Net solid waste(sale amount plus packaging recycled)
PET bottle	425.87	168.22ton	26.66 ton	257.65 ton
HDPE cup	28.6	11.3 ton	1.79 ton	17.3 ton
Total waste produced per year				274.95 ton

APPENDEX 3: Plates

Plate 1: Functional unit of the study (one litter plastic and 300 ml glass bottle)

Plate 2: Raw material (HDPE) for plastic bottle

Plate 3: Raw material (PET) for plastic bottle with its packaging material

Plate 4: Raw material (marble) for glass bottle

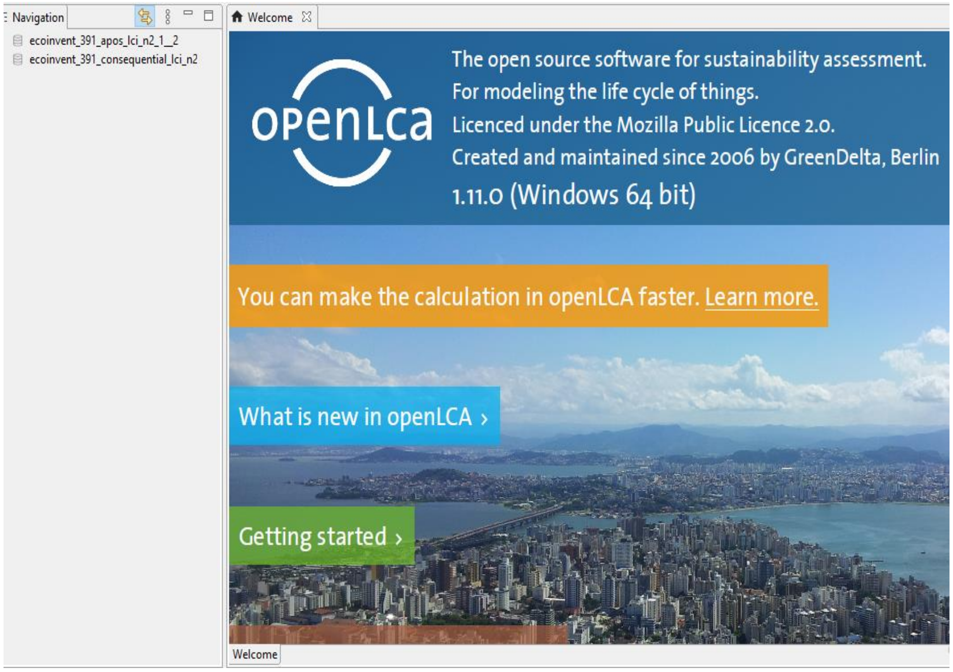
Plate 5: Raw material (Lime stone sample) for glass bottle

Plate 6 Raw material (Cullet) for glass bottle

Plate 7: Raw material (Sand) for glass bottle

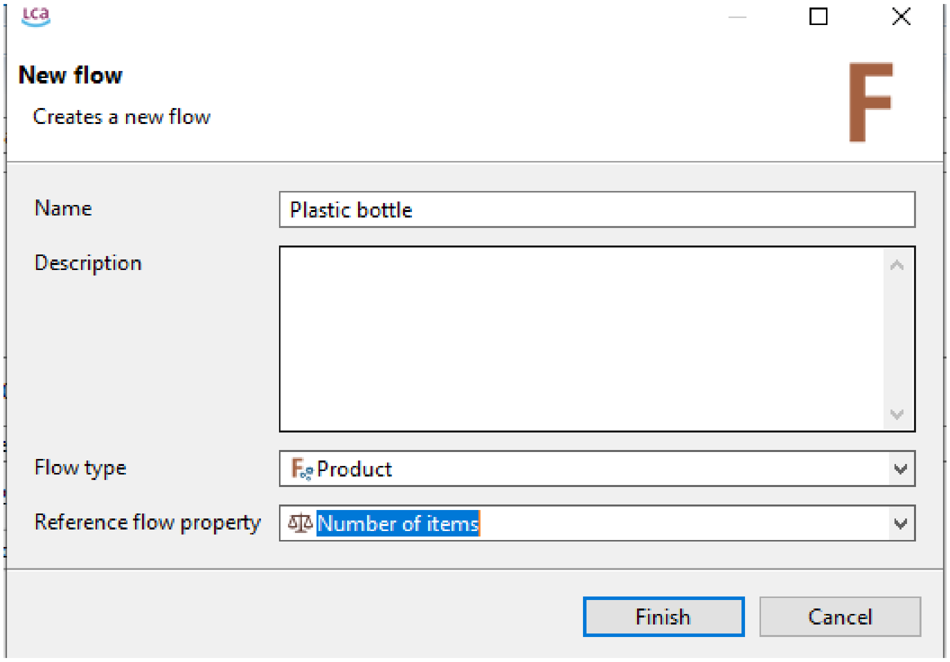
Plate 8: Emission (ambient air) recording

APPENDEX 4 Software operation process



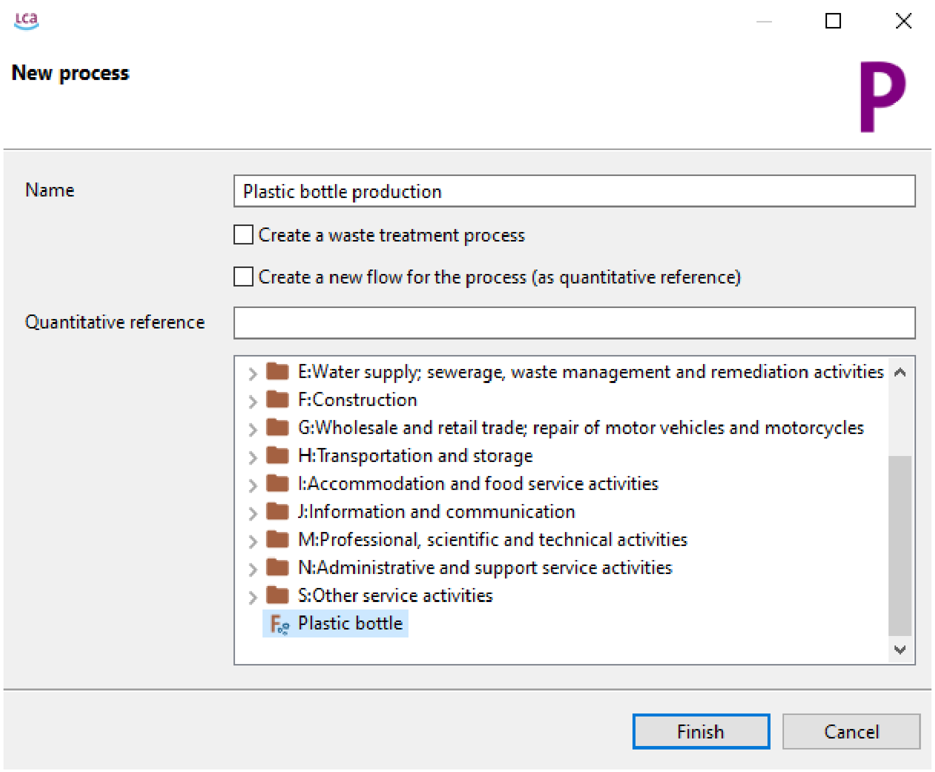
The open source software for sustainability assessment.
For modeling the life cycle of things.
Licenced under the Mozilla Public Licence 2.0.
Created and maintained since 2006 by GreenDelta, Berlin
1.11.0 (Windows 64 bit)

1. Homepage of Open LCA 1.11 software



Name: Plastic bottle
Description:
Flow type: Product
Reference flow property: Number of items

2. Creating of plastic bottle new flow



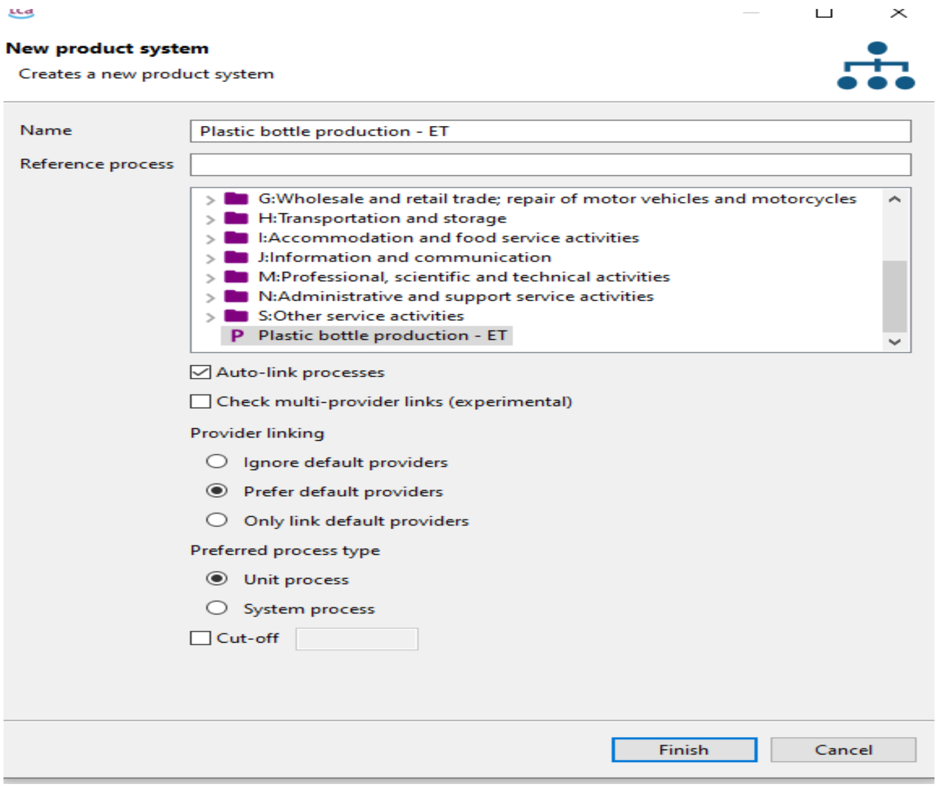
Name: Plastic bottle production

☐ Create a waste treatment process

☐ Create a new flow for the process (as quantitative reference)

Quantitative reference: Plastic bottle

3. Creating of plastic bottle new process



Name: Plastic bottle production - ET

Reference process: Plastic bottle production - ET

☑ Auto-link processes

☐ Check multi-provider links (experimental)

Provider linking

○ Ignore default providers

● Prefer default providers

○ Only link default providers

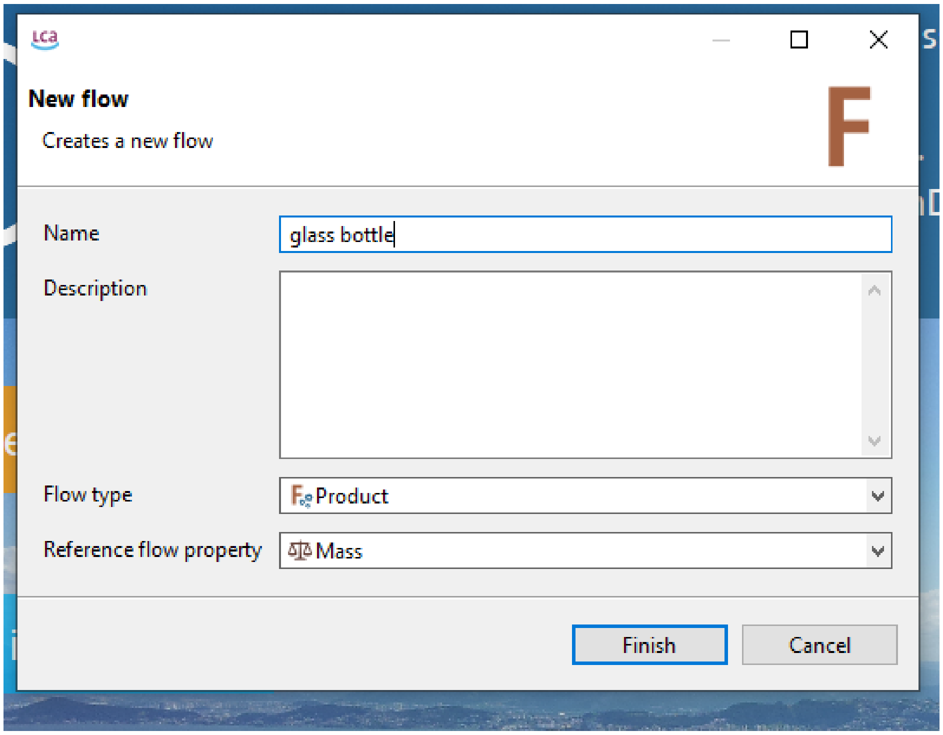
Preferred process type

● Unit process

○ System process

☐ Cut-off

4. Creating of plastic bottle product system



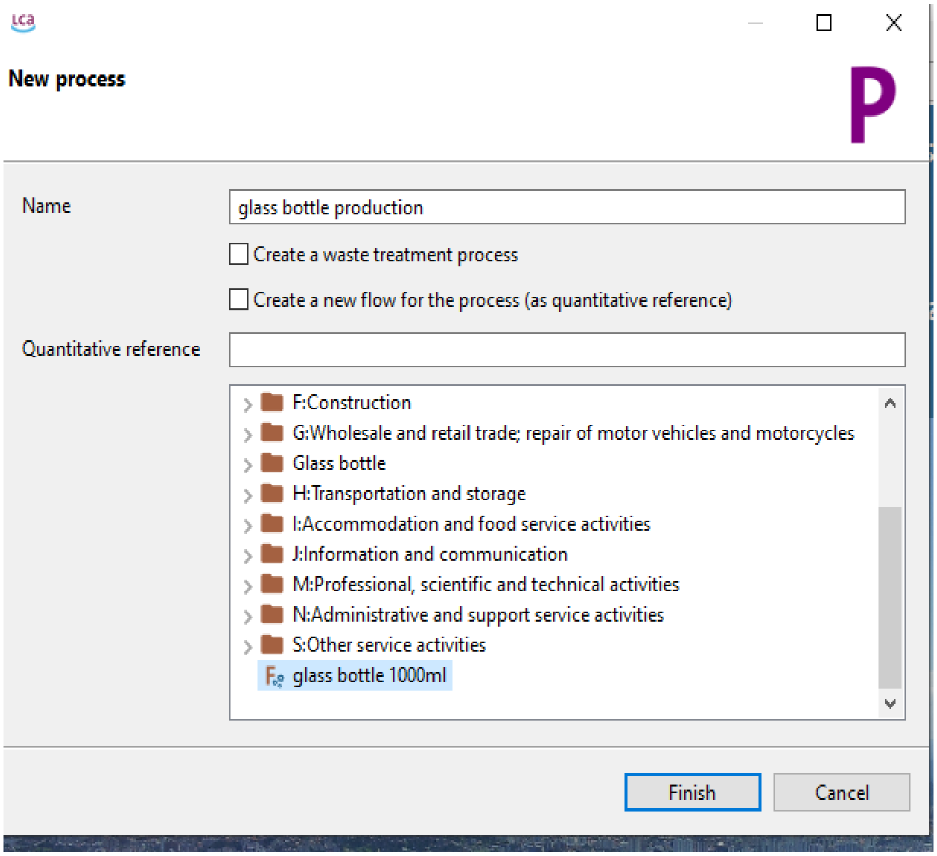
Name: glass bottle

Description:

Flow type: Product

Reference flow property: Mass

5. Creating of glass bottle new flow



Name: glass bottle production

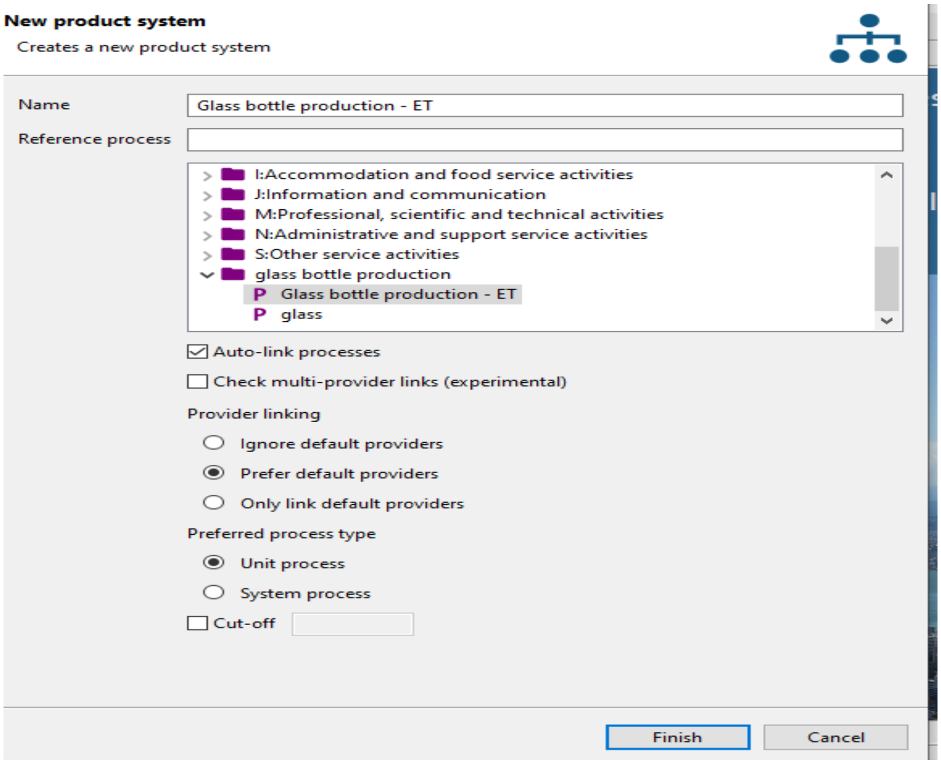
☐ Create a waste treatment process

☐ Create a new flow for the process (as quantitative reference)

Quantitative reference:

- F:Construction
- G:Wholesale and retail trade; repair of motor vehicles and motorcycles
- Glass bottle
- H:Transportation and storage
- I:Accommodation and food service activities
- J:Information and communication
- M:Professional, scientific and technical activities
- N:Administrative and support service activities
- S:Other service activities
- glass bottle 1000ml

6. Creating of glass bottle new process


New product system

Creates a new product system

Name: Glass bottle production - ET

Reference process:

- I:Accommodation and food service activities
- J:Information and communication
- M:Professional, scientific and technical activities
- N:Administrative and support service activities
- S:Other service activities
- glass bottle production
  - P Glass bottle production - ET
  - P glass

☑ Auto-link processes

☐ Check multi-provider links (experimental)

Provider linking

○ Ignore default providers

● Prefer default providers

○ Only link default providers

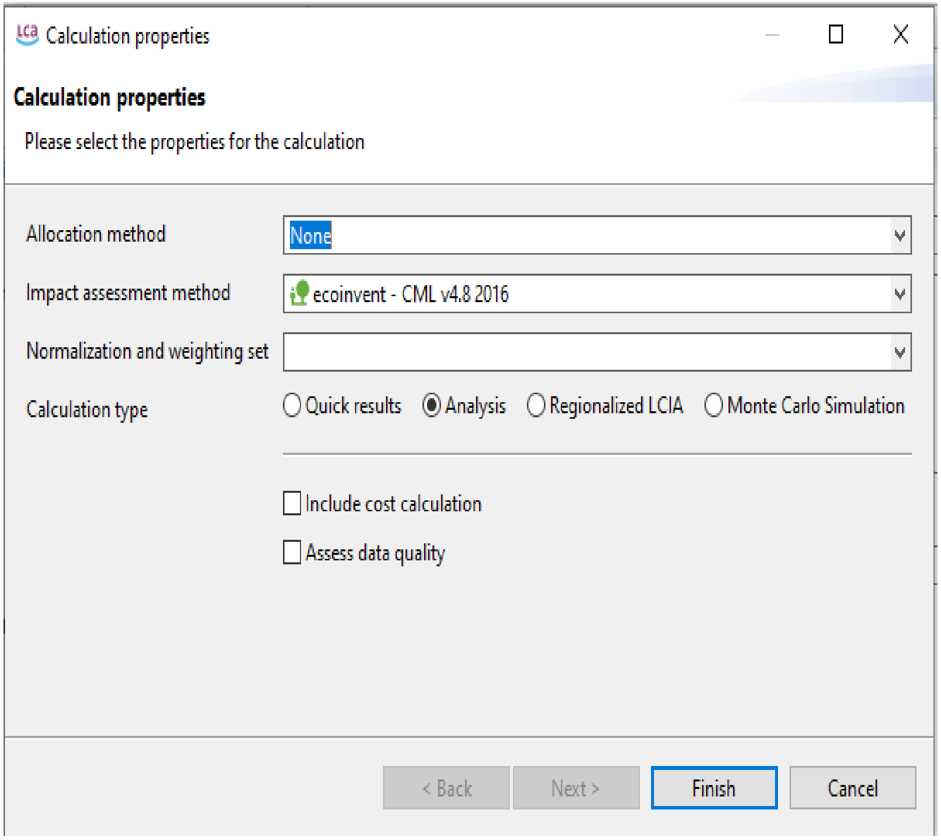
Preferred process type

● Unit process

○ System process

☐ Cut-off

7. Creating of glass bottle new product system


Calculation properties

Calculation properties

Please select the properties for the calculation

Allocation method: None

Impact assessment method: ecoinvent - CML v4.8 2016

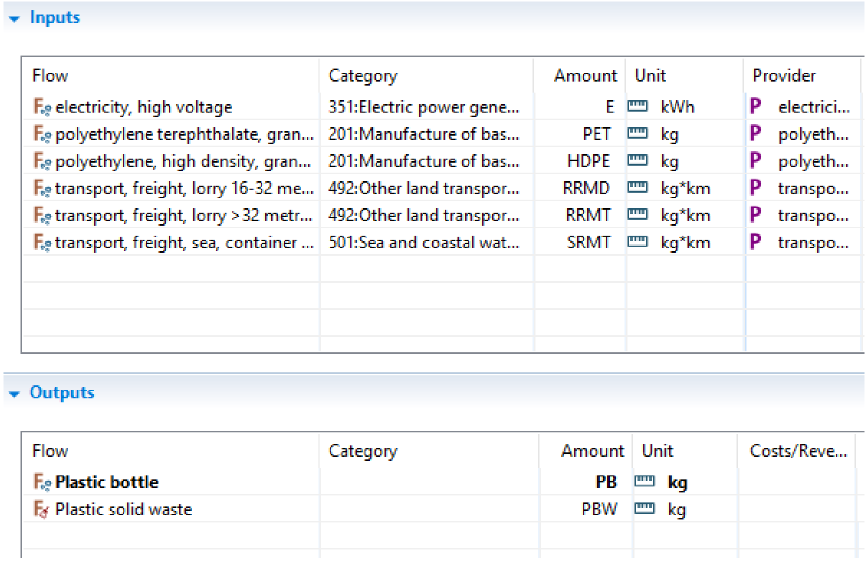
Normalization and weighting set:

Calculation type: ○ Quick results ● Analysis ○ Regionalized LCIA ○ Monte Carlo Simulation

☐ Include cost calculation

☐ Assess data quality

8. Data analysis process



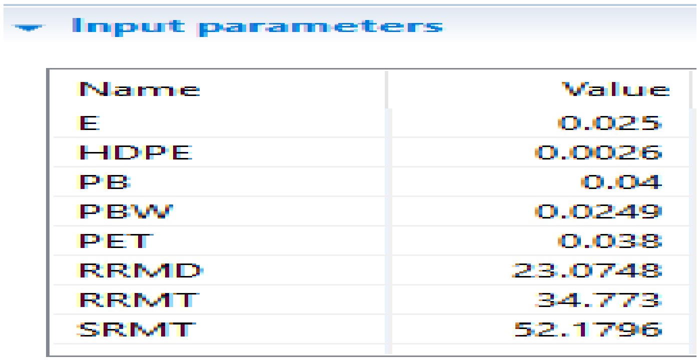
Inputs

Flow	Category	Amount	Unit	Provider
electricity, high voltage	351:Electric power gene...	E	kWh	P electrici...
polyethylene terephthalate, gran...	201:Manufacture of bas...	PET	kg	P polyeth...
polyethylene, high density, gran...	201:Manufacture of bas...	HDPE	kg	P polyeth...
transport, freight, lorry 16-32 me...	492:Other land transpor...	RRMD	kg*km	P transpo...
transport, freight, lorry >32 metr...	492:Other land transpor...	RRMT	kg*km	P transpo...
transport, freight, sea, container ...	501:Sea and coastal wat...	SRMT	kg*km	P transpo...

Outputs

Flow	Category	Amount	Unit	Costs/Reve...
Plastic bottle		**PB**	**kg**	
Plastic solid waste		PBW	kg	

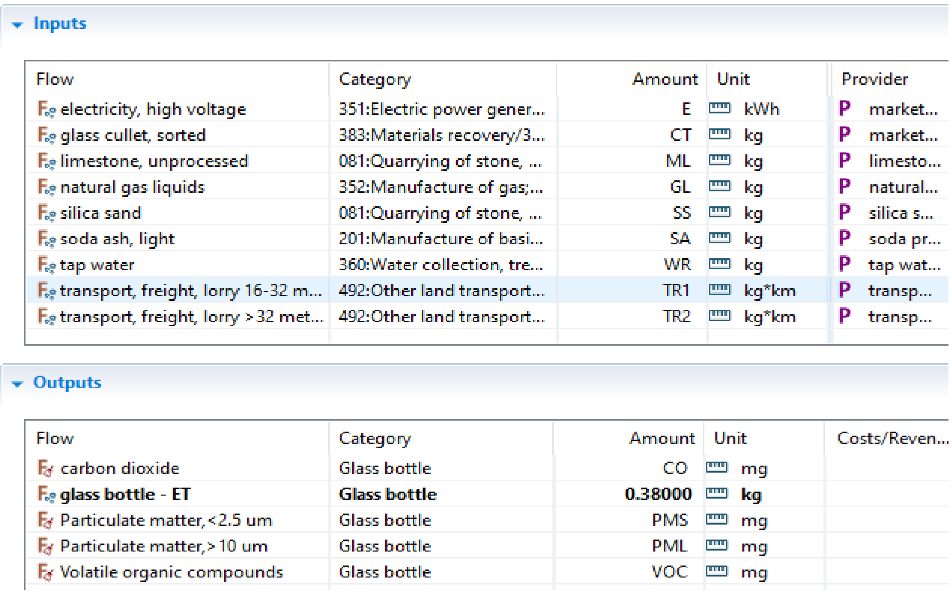
9. Input and outputs with parameter of plastic bottle



Input parameters

Name	Value
E	0.025
HDPE	0.0026
PB	0.04
PBW	0.0249
PET	0.038
RRMD	23.0748
RRMT	34.773
SRMT	52.1796

10. Value of each parameter of plastic bottle



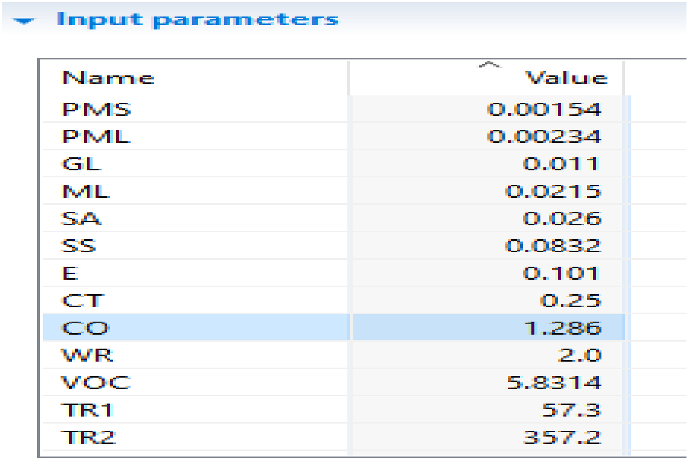
Inputs

Flow	Category	Amount	Unit	Provider
electricity, high voltage	351:Electric power gener...	E	kWh	P market...
glass cullet, sorted	383:Materials recovery/3...	CT	kg	P market...
limestone, unprocessed	081:Quarrying of stone, ...	ML	kg	P limesto...
natural gas liquids	352:Manufacture of gas;...	GL	kg	P natural...
silica sand	081:Quarrying of stone, ...	SS	kg	P silica s...
soda ash, light	201:Manufacture of basi...	SA	kg	P soda pr...
tap water	360:Water collection, tre...	WR	kg	P tap wat...
transport, freight, lorry 16-32 m...	492:Other land transport...	TR1	kg*km	P transp...
transport, freight, lorry >32 met...	492:Other land transport...	TR2	kg*km	P transp...

Outputs

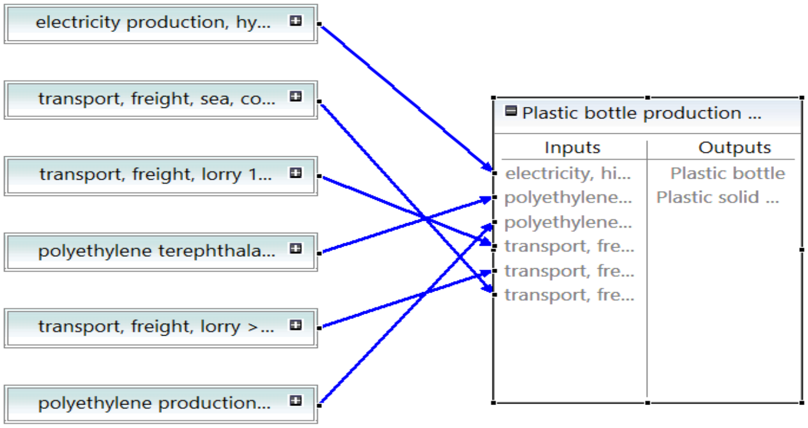
Flow	Category	Amount	Unit	Costs/Reven...
carbon dioxide	Glass bottle	CO	mg	
glass bottle - ET	**Glass bottle**	**0.38000**	**kg**	
Particulate matter, <2.5 um	Glass bottle	PMS	mg	
Particulate matter, > 10 um	Glass bottle	PML	mg	
Volatile organic compounds	Glass bottle	VOC	mg	

11. Input and outputs with parameter of glass bottle

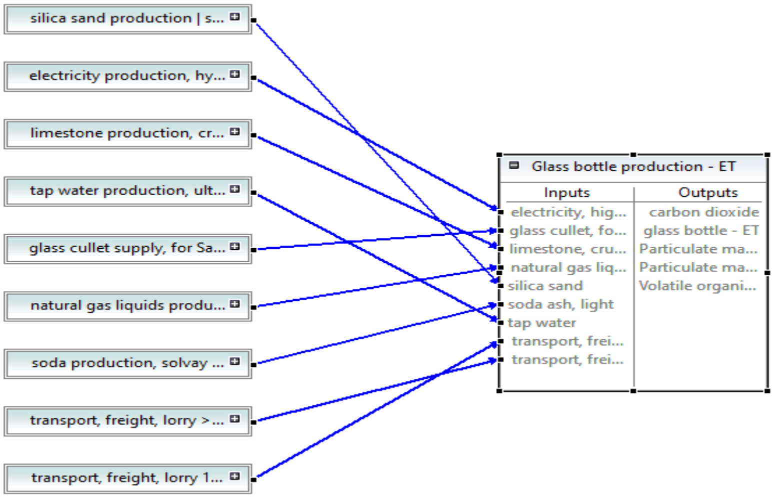


Name	Value
PMS	0.00154
PML	0.00234
GL	0.011
ML	0.0215
SA	0.026
SS	0.0832
E	0.101
CT	0.25
CO	1.286
WR	2.0
VOC	5.8314
TR1	57.3
TR2	357.2

12. Value of each parameter of glass bottle



13. Model graph of plastic bottle



14. Model graph of glass bottle