LIFE CYCLE IMPACT ASSESSMENT OF GLASS MANUFACTURING IN PAKISTAN

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ISLAMABAD

JANUARY 2023

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Design and Manufacturing Engineering

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DECLARATION

I certify that this research work titled "*Life Cycle Impact Assessment of glass manufacturing in Pakistan*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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2020-NUST-MS-DME-329671

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Name of Supervisor: Dr Shamraiz Ahmad

ACKNOWLEDGEMENTS

First and foremost, I am thankful to my Creator Allah Tahalah to have guided me throughout this research, and there is none in this world worthy of praise except Allah Tahalah.

Secondly, I am thankful to my beloved parents for supporting me in each and every journey of my life. I am thankful of the prayers of my mother, helping me rise and shine in every race of life, and my father who always stood behind me and supported me throughout my life.

Most importantly I would like to express special thanks to my supervisor Dr. Shamraiz Ahmad for his priceless help and dedication throughout my thesis. I can honestly say that I learned more under his supervision than I ever thought possible, and his dedication towards this study made me work hard every passing hour.

I would also like to pay special thanks to all the teachers and staff of SMME for their tremendous support and cooperation. I would also like to thank my organization for allowing me to continue my studies and support me throughout this course. I would like to thank my lovely friend Muhammad Ali for helping and supporting me throughout this journey.

Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents, my teachers, and my whole family whose tremendous support and cooperation led me to this wonderful accomplishment.

ABSTRACT

The production of glass packaging requires a lot of energy and resources, and as the world's population rises, particularly in emerging nations, so does the demand for glass packaging. Although developing nations are also suffering from the effects of climate change, there is relatively little study on environmental impact assessment and analysis, notably the environmental impacts brought on by the activities related to glass manufacturing. This work conducted a thorough life cycle assessment (LCA) for the production of glass packaging in Pakistan in order to close this research gap of quantification of the environmental impacts of glass packaging production. The LCA was carried out for three distinct types of glass packaging solutions (amber, flint, and green), considering 1-ton of glass as the functional unit. The creation of several scenarios allowed for the analysis of the effects and the generation of ideas for ways to lessen the negative effects of glass manufacture on the environment. The study's methodology used a cradle-to-gate approach. From the perspective of the life cycle inventory, the main data were gathered from a renowned glass industry situated in one of Pakistan's designated industrial zones, and the secondary data were obtained from the Ecoinvent database. Environmental impacts were measured at midpoint and endpoint levels utilizing the ReCiPe 2016 approach and SimaPro V 9.2 as the software tool. Results indicated that the extraction and processing of raw material had worse impacts on the environment. At plant level the consumption of natural gas for the melting purposes and electricity consumed from national grid had highest impacts on the environment. The comparison of three packaging solutions indicated that the production of green glass was more harmful to the environment, followed by the production of amber glass and flint glass came out to be more environmentally friendly among the three packaging solutions. The alternative scenarios were generated by changing the energy-mix and the cullet ratios and the results were compared with the baseline scenarios for different midpoint and endpoint impact categories. The alternative scenarios for the energy mix were also compared for different kinds of emissions to air especially the greenhouse gas emissions. The report also identified a number of significant implications. This study may serve as a guide for future research on the environmental impact of the glass packaging industry, particularly in Pakistan and other developing nations. In this sense, developing nations would work toward net-zero emissions and sustainable development goals.

Keywords: Life Cycle Assessment, Environmental Impact Assessment, Glass Manufacturing

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CHAPTER 1: INTRODUCTION

1.1 Historical Background

There has been a huge increase in the global population, and with that we are witnessing a drastic increase in the consumption of natural resources, hence leading towards their scarcity. This scenario is leading us towards climate change which is the main issue world is facing at this moment [1]. Hence there has been an increase in the awareness of these environmental concerns by the stakeholders and interests are being taken towards assessing the overall environmental burdens associated with products, services, technologies, and manufacturing facilities [2]. Similarly, the production of glass packaging containers used for food, beverages, and pharmaceutical packaging etc. has also increased over the years and is expected to reach total production of 65.42 million tons globally by the end of the year 2022 [3]. Glass packaging is usually preferred over other types of packaging because it has many superior properties for example, zero chemical interaction with food, insulating capacity, guaranteed hygiene, and in some cases its transparency [4]. Hence consumers prefer glass packaging over that of other packaging options available, and it accounts for almost 40% of total food packaging and 24% of total beverages packaging across the globe, despite its fragility and high transporting cost [3, 5].

Glass manufacturing industry is usually considered as highly resource, energy, and CO_2 intensive industry hence it has worst impacts on the environment; hence many research studies consider glass packaging most unfavorable environmental impacts when compared with that of other packaging options mainly because of their high specific weight and high amount of energy that is consumed during the production and the also during their entire life cycle [6-8].

1.2 The process of Glass Manufacturing

The glass manufacturing process differs from many other manufacturing processes because the flow of raw materials is practically continuous from the point where the raw materials are mixed until the final product is produced. The whole manufacturing process starts with the batching process where the raw materials are mixed and transferred into the gas furnace. In the gas furnace the mixture of raw materials is melted into the molten glass which is continuously supplied to the forming machines where it is shaped into the final product. Major raw materials include silica sand also known as glass sand, soda ash, limestone, feldspar, and other additions depending upon required properties. During the melting process a large amount of energy is consumed and also the process is responsible for different kind of harmful emissions to water, soil, and air hence leading towards environmental degradation and climate change [9].

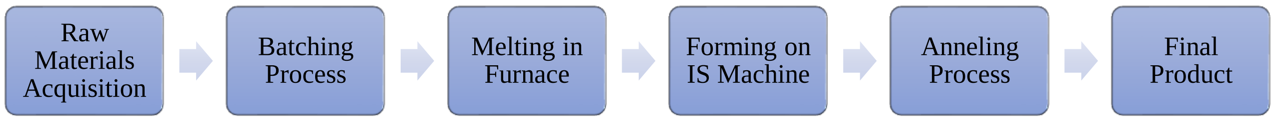

Figure 1: Process of Glass Manufacture

1.3 Environmental Impact Assessment

Environmental impacts can be defined as the negative impacts of human activities related to the use of environmental resources on natural environment. Environmental Impact Assessment (EIA) relate to the assessment and mitigation of the negative environmental impacts related to a project, process, product, or a facility prior to a decision-making process. Its early applications mainly focused on the impact analysis of our physical environment, but later on more comprehensive approaches were developed focusing on environmental as well as social impacts and cumulative effects because of their interactions. EIA supports decision making regarding environmental aspects of a very wide range of activities for example, decision about making plans like waste management plans, process installations and also location choices.

The environmental impact assessment starts with screening of the expected harmful impacts on the environment along with the estimation of their significance. Hence the screening process establishes the basis to make the decision whether EIA is required or not, and it also provides information about key impacts and how those should be analyzed. After the screening is completed, we have scoping process which identifies and selects the most important issues related to the environment and ensures that EIA is mainly focused on those important issues. Once scoping is completed the next major step is the impact analysis in which we assess and predict the impacts, examine different alternatives, and prepare mitigation and monitoring plans [10-12].

There are a variety of methods used for EIA namely, Life Cycle Assessment (LCA), A three-dimensional environmental approach, Attributional LCA method, Reliability based LCA methodology, Material Flow Analysis, Substance Flow Analysis, Carbon Footprint, Water Footprint, and Risk Assessment etc.

1.3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a well-known method used in order to assess the environmental impacts that are associated with a product, process, facility, or service throughout all the stages of their life cycle [13].

1.3.2 A three-dimensional Environmental Approach

A three-dimensional Environmental Approach attempts to direct the major sustainability issues related to the manufacturing from pollution prevention point of view, while considering technology, energy, and material as the three key components of manufacturing [14].

1.3.3 Attributional LCA method

In the Attributional LCA method the results are often demonstrated in a way so that the decisions that are based on the results will eventually yield certain quantitative benefits that are initially estimated by the attributional LCA method [15].

1.3.4 Substance Flow Analysis

Substance flow analysis is used to quantify the input/output flows and environmental impacts of either a single substance or a group of substances [16].

1.3.5 Material Flow Analysis

The material flow analysis is used to track the flow of raw materials in the economy/industry of a particular area [17].

1.3.6 Carbon Footprint

Carbon footprint evaluates direct or indirect greenhouse gas emissions into the environment that resulting from a product, service, or a certain human activity [18].

1.3.7 Water Footprint

Water footprint evaluates the environmental burdens that are linked with water as an area of protection [19].

1.3.8 Risk Assessment

Risk assessment evaluates the risk or likelihood of acute environmental impacts that may occur because of a certain activity [20].

1.4 Glass Sector of Pakistan and EIA

Pakistan's top 16 Glass Industries generate 370 million dollars sales revenue per year [21]. These industries are mainly located in Lahore, Karachi, Gujranwala, and Rawalpindi. With such a large amount of production, these industries also hold responsibilities in terms of having negative impacts on the environment. As Pakistan's energy mix mainly constitutes coal, natural gas, RFO, and RLNG hence the energy mix of Pakistan can be characterized as having negative impacts on the environment. Hence glass manufacturing sectors in Pakistan are responsible in terms of highest contribution towards climate degradation as these sectors are highly energy extensive sectors.

Recently some studies related to the environmental impacts assessment were reported from Pakistan focusing on matchstick industry [22], coal fired power plants [23], and on managing waste of hospitals [24]. But for the sectors that are responsible for consuming the majority of energy and materials in Pakistan, not a single study has been reported. Hence there is a lack of research in this field which should be the main focus of all stakeholders in Pakistan.

1.5 Problem Statement

Pakistan is one of those countries that are highly impacted due to climate change. The use of energy in the industrial sector of Pakistan mainly consists of non-renewable fossil fuels [23] hence generating worst impacts on the environment. Secondly Pakistan lacks in terms of the EIA of manufacturing sectors especially the materials and energy extensive energy sectors for example the glass manufacturing sector for which up-to our knowledge there is not even a single research study for Pakistan and also for whole of subcontinent. such studies are important and needed to analyze the environmental burdens associated with glass manufacturing in Pakistan and build inventory data for the country.

1.6 Research Objectives

This research study has following three objectives.

1. Collect and develop inventory data for the manufacturing of glass packaging in Pakistan.

2. Assess and analyze the environmental burdens linked to the glass packaging manufacturing using LCA tool.
3. Find appropriate solutions to reduce the environmental impacts associated with the manufacturing of glass packaging in Pakistan, while making sure that the recommended solution does not have additional cost associated.

1.7 Thesis Outline

This is the first chapter of this thesis, and it included a brief information about the background, process of glass manufacture, environmental impact assessment and different methods, glass sector of Pakistan, problem statement, and the main objective of this research. The next chapter is about the detailed review of literature, after that in chapter 3 detailed methodology used during this research in order to achieve the objectives have been explained. The results and discussions are presented in chapter 4, and finally in chapter 5 we have implications of this analysis and final conclusion.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

As described in the preceding chapter, multiple approaches for assessing environmental impact have recently been developed, depending on the intended application and area of protection. Because of its wide range of applications, Life Cycle Assessment (LCA) has been widely used by researchers and policymakers worldwide. Hence, this chapter provides a full introduction of LCA, its significance and application in various fields, the scope of LCA, the phases of LCA, and the methodology used to execute LCA. Furthermore, many research publications on LCA of glass packaging solutions have been presented in order to gain an understanding of its applicability in the glass sector and identify potential research gaps.

2.2 Life Cycle Assessment (LCA)

Usually, life cycle of most products is long, and almost all products have an impact on the surrounding environment. LCA is basically a method or analysis to determine the environmental burdens that are linked with almost all the life cycle stages of a product. It includes the complete process starting from raw material extraction, processing of those raw materials, manufacturing of product, distribution to the markets and then its use by the users. LCA offers a tool to analyze and compare negative environmental impacts from different material types and processes. There are three kinds of ecological hazards that are under concerns of life cycle assessment technique, the ecological hazards include human health, ecosystem quality and resource consumption. LCA also helps in the identification of opportunities to enhance and improve the environmental performance of products during their whole life cycle (i.e., from cradle to grave). It also helps in the industrial decision-making process that includes the planning, material selection, process type and design of the product. It also assists in the marketing of the product with using eco-friendly schemes for the advertisement of the product [25].

Environmental security is a major challenge for mankind nowadays as eco-system is depleting fast with the passage of time. LCA helps manufacturers and companies to manufacture eco-friendly products with the processes that are also eco-friendly in their nature. The basic purpose of implementation of LCA is the security of human environment. LCA method also helps in achieving fine quality products with fewer expenses. It leads to the reduction in cost of manufacturing by complete utilization and disposing of the used materials and products after completion of their working time. LCA has a major role in the integration of management of wastes and the pollution related subjects. The goal of LCA is primarily to compare complete data of the environmental effects related to desired products and process related in the manufacturing of those products by counting all initial and resulted materials and then assessing that how the consumption of these materials effects the environment. This information and acquired data help to select more eco-friendly materials and processes thus leading to take more informed and sound decisions [26].

LCA has several uses; for instance, it can be applied in industry for a variety of goals, such as the development of new research (62% of respondents), the support of business strategies (63% of respondents), and the design of new goods and production methods (52% of respondents). Additionally, LCA is utilized for labelling and product descriptions (11% of respondents), as well as in the education sector (46% of respondents). The importance of LCA studies has been increased as more and more companies are now applying LCA to their respective products [27].

2.3 Phases of Life Cycle Assessment

LCA can provide organizations with different opportunities to assess the environmental performance of their product, services, or manufacturing facilities. LCA consist of four main steps [28] as shown in figure 2 (1) Goal and Scope Definition (2) Analyzing Life Cycle Inventory (3) Life Cycle Impact Assessment (4) Interpreting and Analyzing the results.

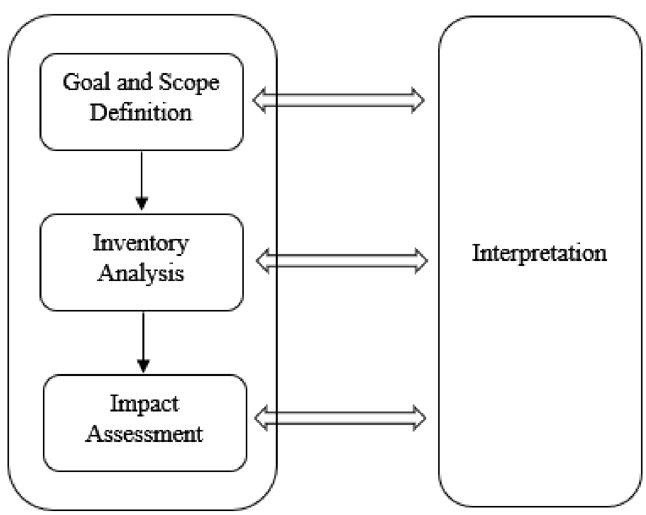

Figure 2: Four Iterative phases of Life Cycle Assessment [29]

2.3.1 Goal and Scope Definition

Goal and Scope definition is the first phase of performing and LCA, and it describes main objectives, the functional unit, different sources and collection of data, and system boundaries [30]. The LCA outcomes are frequently heavily reliant on the decisions taken during this critical stage of the study. While defining the goal of an LCA, following parameters should be properly stated.

1. The intended application of the analysis
2. All the reason for performing the analysis.
3. The intended audience of the analysis

Different goals of performing an LCA can include providing information related to the environmental impacts on an existing product, developing a new environmentally friendly product, elaboration of political strategies relating to the environment, and often for the regulation of existing product. On the other hand, following element should be considered before describing the scope of LCA study. As LCA in an iterative approach, hence the scope can be adjusted according to the information acquired during the analysis.

1. The product/process system to be studies.
2. The function and Functional Unit (FU)
3. System boundary
4. Life Cycle Impact Assessment methodology
5. Impact Categories
6. Data Requirements
7. Assumptions

2.3.1.1 Product/Process System

The definition of the product/process systems under investigation is usually the initial step in the goal and scope definition. It could be a single product or process, a series of products, a process chain, or both the product and processes within a single facility. As a result, before proceeding, it is advised that the product/process system under investigation be properly defined.

2.3.1.2 Functional Unit

The functional unit is regarded as the most essential unit of life cycle assessment because the entire study is usually centered on it. It specifies the function of the system under investigation and serves as a reference for all of the inputs and outputs to be used in the LCA analysis. The functional unit can also be utilized to investigate the contrasts between the systems under consideration. As a result, it is recommended that the functional unit be carefully and thoroughly defined before proceeding with the analysis and data collecting, etc.

2.3.1.3 System Boundary

The system boundary is used to define and identify the processes or stages of a product's life cycle that are being studied. Certain elements must be examined before deciding on the system boundary, such as the technological system and nature, time horizon, geographical area, and the boundaries between the current life cycle and all associated life cycles of other technical systems.

2.3.1.4 Life Cycle Impact Assessment Methodology

Following the definition of the system boundary, the next phase in the LCA is the selection of the methodology to be employed in the LCA. There are currently different impact assessment methods accessible, each with its own special relevance; so, the impact assessment method should be carefully evaluated according to the area of protection.

2.3.1.5 Impact Categories

The impact categories indicate the environmental implications of the processes that occur during the life cycle of a product/process or a facility. During the LCA, a considerable quantity of emission data is collected: emissions from energy production, waste production, raw material production, and so on. These emissions take various forms and formats because emissions from raw material extraction differ greatly from emissions from energy generation. As a result, the impact category aggregates various emissions into a single environmental impact. The impact categories are typically selected based on the life cycle impact assessment method used for the evaluation.

2.3.1.6 Data Requirements

Before collecting the data and proceeding with the analysis, it is recommended to first deeply understand the data required to achieve the objectives of the analysis and clearly define the sources of data used for the analysis in the goal and scope definition.

2.3.1.7 Assumptions

All the assumptions related to the product/process under the analysis should be defined in the goal and scope definition. The assumptions can be related to the input data, assessment methods, systems boundaries, or the inclusion/exclusion of life cycle stages.

2.3.2 Life Cycle Inventory Analysis (LCIA)

Quantifying inputs and outputs that are significant to the environment through the energy and mass balance is the main goal of LCIA [31]. This covers the number of resources extracted from the environment (such as minerals, energy sources, soil surface area, etc.) over the course of the life cycle of the examined good or service, as well as the emissions of pollutants into the environment. To determine and connect a system's unit processes, the inventory simply adds emissions and extractions for each unit process to previously estimated reference flows for the system's unit processes. The basics of inventory calculation are straightforward but gathering the data may take a lot of work. Fortunately, databases today combine data for a variety of processes, requiring just the processes unique to the intended applications and industries to be detailed models. It is crucial to address the challenging problem of how to allocate coproduct emissions, extractions, and byproducts because many processes produce more than one product.

2.3.3 Life Cycle Impact Assessment

It aims to evaluate the intensity and importance of the environmental impacts quantified in the life cycle inventory phase [28]. The impact assessment phase has different steps starting from the categorization of emissions into different midpoint impact categories, followed by characterization of those midpoint impacts, and endpoint damage characterization as shown in figure 3.

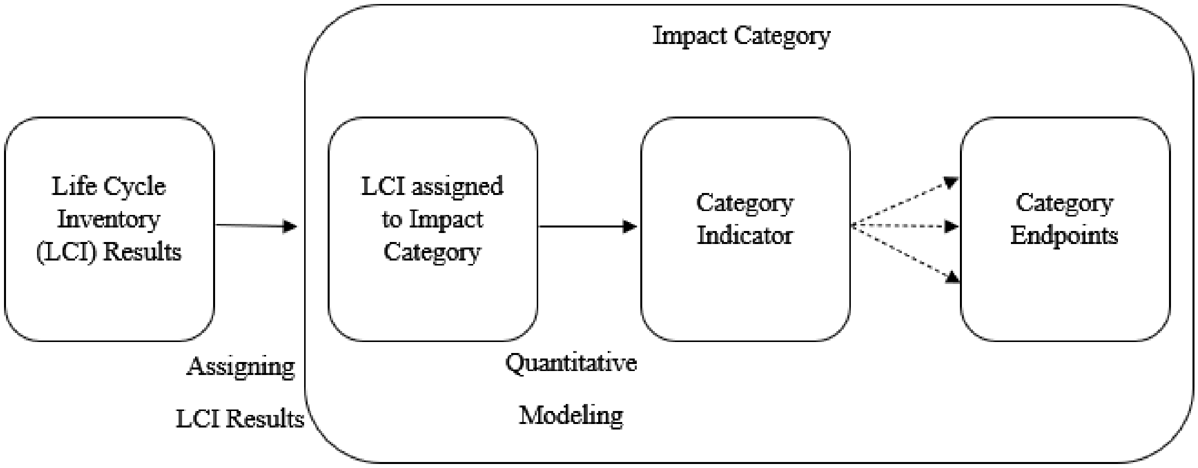

Figure 3: Steps of Life Cycle Impact Assessment

Life Cycle Impact Assessment begins by categorizing all LCI outcomes that have similar affects into an impact category at an intermediate level known as the midpoint impact category. Each and every LCI flow is then multiplied by a characterization factor in order to specify its contribution to a particular midpoint impact category. Each midpoint impact category is allocated to either one or more areas of protection (damage categories) i.e., human health, resources, and ecosystems as presented in figure 4. These damage categories are presented by a damage indicator, often known as end-point indicator. The outcomes' uncertainty grows as we progress from inventory to midpoint and from midpoint to damage results.

2.3.4 Interpretation

Interpretation is the fourth and the last phase of LCA, and its purpose is to identify the stages of complete life cycle where interventions can result in-to the reduction of impacts on the environment.

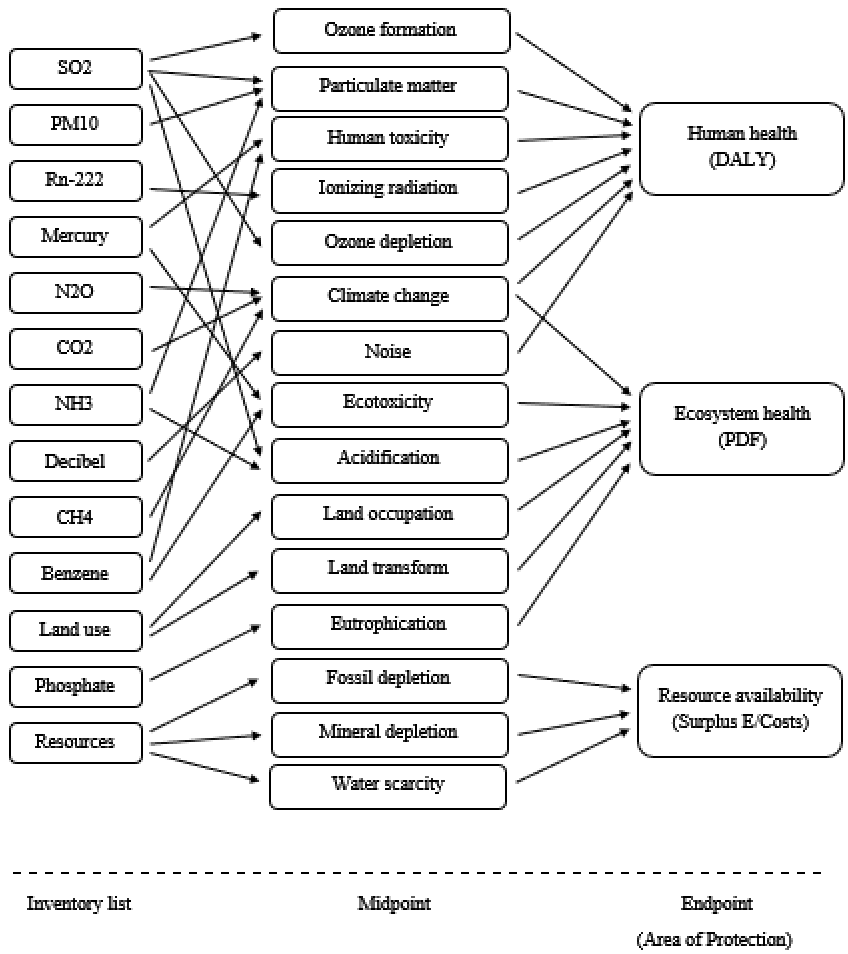

Figure 4: Description of Impact Pathways

2.4 Optional Steps in LCA

Apart from these four main steps of LCA there are three other optional steps that can help to better understand the environmental impacts.

2.4.1 Normalization

A normalizing step is undertaken to better comprehend the degree of the damage which gives the impacts per functional unit to the total impacts in that specific impact category. It is usually recommended to normalize the damage indicators instead of midpoint impacts.

2.4.2 Grouping

Grouping is a semi-quantitative process used for the prioritization of results by sorting and leading according to the area of protection, or according to the different types of emissions.

2.4.3 Weighting

In this step the scores of each impact category that is based on their relative values are weighted into a single score, in order to give a single score to better understand and compare the results for each scenario. Weighting is generally applied to the damage categories.

2.5 Impact Assessment Methods

The critical volumes method, one of the first LCA effect assessment techniques, categorized emissions by emission compartment as the first stage (air, water, and soil). This approach is no longer appropriate because it does not take into consideration the persistence or destiny (impact pathways) of pollutants. The CML (Centrum voor Milieukunde Leiden) 92 technique was the first to concentrate on the consequences of emissions and served as the foundation for numerous subsequent advancements. One of the most popular ways in Europe at one point was the CML 92 approach. The guidebook on LCA, a true cookbook of practical directions for carrying out LCA step by step, was created after it was updated to CML 2002. Following is some of the impact assessment methods used according to their area of applicability.

2.5.1 European Impact Assessment Methods

1. CML-IA baseline
2. CML-IA non-baseline
3. Ecological Scarcity 2013
4. EF 3.0 Method (adapted)
5. EF Method (adapted)
6. EN 15804+A2 method
7. Environmental Prices
8. EPD 2018
9. EPS 2015d
10. EPS 2015dx

2.5.2 North American Impact Assessment Methods

1. BEES+
2. TRACI 2.1

2.5.3 Global Impact Assessment Methods

1. Impact World+ Endpoint
2. Impact World+ Midpoint
3. ReCiPe 2016 Endpoint (E)
4. ReCiPe 2016 Endpoint (H)
5. ReCiPe 2016 Endpoint (I)
6. ReCiPe 2016 Midpoint (E)
7. ReCiPe 2016 Midpoint (H)
8. ReCiPe 2016 Midpoint (I)

Apart from these there are other impact assessment methods available that are either single issue, for water footprint only, and some of them are superseded.

2.6 Life Cycle Assessment Software

As previously stated, LCA is typically used to assess the environmental implications of a process, product, or facility, and in recent years it has gained acceptance as a technique with multiple applications, including product/process improvement, environmental labelling, and policy evaluation. Because of its numerous applications and widespread use, multiple LCA software or tools have been developed to aid in the LCA process. Expert LCA users and practitioners have generally accepted and used these tools or software. Two of the most often used LCA software tools are briefly described below.

2.6.1 SimaPro

SimaPro is a product system modelling and assessment software tool created and launched in the Netherlands by PRe-Consultants in 1990. SimaPro is a tool that collects, analyses, and reviews data on the performance of various goods, processes, and services. This software tool can be used for a variety of purposes, including sustainability reporting, product/process design, and water and carbon footprints, among others, although it is not restricted to these. One of the primary benefits of SimaPro is that it provides full access to many online databases and unit operations, which are important during environmental analysis and tracking the significant hotspots of negative environmental impacts.

2.6.2 GaBi

GaBi is a product/process systems modelling and assessment software tool that was developed and launched in 1992 by a German organization called PE International. GaBi software tool, like SimaPro, can be used for a variety of applications such as life cycle assessment, life cycle costing, life cycle working environment, and life cycle reporting, among others. This software package also includes updated content databases with in-depth details about the objects under investigation, such as cost, energy, and environmental implications. GaBi can be used to improve the sustainability performance of items by improving the decision-making process.

Many researchers and organizations have used the above impact assessment methods and software tools over the past few years to conduct life cycle assessments of glass packaging solutions and compare the environmental consequences of glass packaging solutions with alternative packing systems. Hence, a brief overview of LCA studies related to glass packaging solutions was undertaken and provided in the following part to better understand the use of LCA for glass packing solutions and to identify potential research gaps.

2.7 Review of related LCA studies

Recently the environmental impacts of glass bottles used for food, beverages or pharmaceutical packaging have been analyzed by number of studies, however all of those studies compared glass with other packaging materials [32, 33]. In those studies, glass packaging was compared in terms of environmental impacts with polymers packaging [34], plastic packaging [35], polypropylene pots for baby food [36], and different pharmaceutical packaging [32].

A lack of research was pointed out for the assessment of environmental impacts of glass production. Vellini and Savioli analyzed energy consumed during the production phase of glass with an objective to find best recycling scenario of glass using LCA methodology [37], Guiso et al. assessed and compared glass packaging with tin-plated steel cans [38], Garfi et al. assessed environmental impacts of glass bottles used for storing mineral water [39], Neto et al. highlighted the need to assess processing of cullet used for glass production [40], Freire et al. assessed the use of cullet for glass production by highlighting both the negative and positive prospect of cullet use [41], and Amienyo et al. evaluated two improvements namely use of recycled glass and less weighting to the manufacture of glass wine bottles [42]. Pulselli et al. found out that the manufacturing phase in glass supply chain has highest impacts on the environment because of extensive consumption of energy and emissions [43].

Apart from these, some glass industry associations also conducted different LCA studies in previous decade. In 2010, Glass Packaging Institute (GPI) and European Container Glass Federation (FEVE) conducted studies based on primary data of hollow glass containers using LCA methodology. The analysis of GPI was based on data from 105 different glass manufacturing facilities around North America [44]. On the other hand, the FEVE analysis was based on 200 different glass manufacturing plants across Europe [45]. Both assessments were carried out with cradle-to-cradle LCA approach, and the functional unit was considered as 1kg of glass. Potential gaps and the limitations of the FEVE study were identified later in 2012 by Finkbeiner [46]. Based on those limitations another study was conducted by FEVE in 2016 which highlighted the use of cullet in order to reduce the CO_2 emissions during glass manufacturing [47]. Table 1 gives us 15 reviewed studies about the environmental impacts of glass packaging and other packaging solutions. The description, results, and shortcomings of each study are described briefly.

Table 1: Reviewed studies about environmental impacts of glass and other packaging solutions

SR. NO.	**DESCRIPTION**	**RESULTS AND SHORTCOMINGS**	**REF**
1	Environmental impacts of three different types of pharmaceutical packaging solution (blisters, bottles, sachets) were compared using Life Cycle Assessment (LCA) for five different midpoint impact categories. Storage and delivery of same type of medicines was considered as the functional unit of this evaluation. Primary data was collected form the pharmaceutical industry located in Germany. The assessment boundaries were from cradle-to-gate.	According to the findings, blisters are the most environmentally beneficial of the three packing options for each intermediate effect category. Blisters also have the capacity to improve their environmental performance by taking specific actions. This study did not identify the environmental hotspots in the glass manufacturing process; it just compared glass with alternative packaging options.	[32]

2	This study compares the environmental impacts of traditional glass bottles with polymer bottles using LCA. The assessment boundary was taken form cradle-to-grave, and the impacts were compared for both midpoint and endpoint impact categories. Primary data was gathered from health care suppliers in USA and secondary data was gathered from Ecoinvent database.	In every impact category that was taken under consideration for the analysis, the data clearly showed that the polymer bottle outperformed the glass container in terms of environmental impact. The manufacturing phase and the transportation phase of the glass manufacturing process are primarily responsible for each and every impact category's environmental burden. This analysis excluded the highlighting of potential hotspots in the life cycle of each packaging solution and solely compared the overall effects of each packaging solution.	[33]
3	The goal of this study is to compare the environmental performance of plastic pots and glass jars used for the packaging of baby food produced by Nestle in three different countries i.e., France, Spain, and Germany considering 200g packaging size as the functional unit for the analysis. System boundaries were considered form cradle-to-grave, and the impacts were analyzed only for the midpoint impact categories using IMPACT 2002+ and CML 2001 as assessment methods.	Results indicated that in each of the countries under consideration, plastic pots perform better environmentally than glass jars. Additionally, France had greater environmental implications than Spain and Germany for each packing solution. It is challenging to identify hotspots in the lifecycle of each packaging solution because this investigation was limited to midway impacts categories and the results presented an overall analysis.	[48]
4	This research evaluated the environmental performance of hollow glass container production in Italy while undertaking two different scenarios of production. The assessment was performed using the	The findings of this study showed many environmental benefits of hollow glass containers while taking various production circumstances into account. Managers' ability to make decisions can be aided by	[49]

	primary data of the year 2017 and using secondary data from various databases using midpoint approach for 7 different impact indicators. The assessment boundary was considered from cradle-to-grave, and the functional unit was considered as 1 kg of finished hollow glass.	this analysis of many circumstances. A thorough midpoint and endpoint analysis is necessary to obtain a complete picture of the associated implications since this study only examined the impacts for 7 midpoint indicators.	
5	This study compares the environmental impacts of reusable glass bottles with polyethylene (PET) bottles used for packaging mineral water. The primary data was gathered from a mineral water company located in Italy which distributes both natural and sparkling water. The analysis was carried out on both midpoint and endpoint levels using the ReCiPe 2016 approach. The functional unit was considered as components of packaging required for a certain volume of water, and cradle-to-grave system boundaries were considered.	Results indicated that for most of impact categories under consideration PET bottles came out to be more environmentally friendly as compared to glass bottles for natural water packaging. Furthermore, in case of sparkling water the impacts of both packaging systems were almost identical. This is because of the lower distribution that occurs in case of the sparkling water. Because the variation of the important elements highlighted in the analysis determines which of the two alternative systems is the most sustainable packaging option, it is impossible to make the final conclusions and require case by case analysis.	[50]
6	To analyze different reuse percentage of glass beer bottles environmentally, this study compares impacts that are associated with returnable and non-returnable glass beer bottles. The primary data was collected form a Portuguese company against functional unit which is the delivery of	The results against the impact categories under consideration were presented for 20%, 30%, 40%, 50%, 60%, 70%, and 85% reuse of glass beer bottles. According to the study's objectives and parameters, the results may be presented to decision-makers as conclusions and suggestions. In order to	[51]

	330liters of beer to consumers. Analysis was carried out for midpoint impact categories employing cradle-to-cradle approach. A sensitivity analysis was conducted for this study's multiple reuse percentages and returnable bottle cycles.	choose the option with the highest rate of reuse and to have a more sustainable glass beer bottle system, it is necessary to analyze the economic, technological, and social implications of the options when making decisions, especially when it comes to the distribution of beer in returnable or non-returnable bottles.	
7	This study aims to determine the Life cycle processes in which an Italian glass company's economy and the environment are affected, the environmental impact caused by the system as a whole, and the production differences between the two systems under examination. Glass container production rates over a specific period of time have been identified as the functional unit for analyzing environmental effects, and secondary sources were used to collect the data. Impacts were only assessed at the midpoint level, and only impact categories with a maximum variance of 2% were considered in this study.	Results indicated that system B performs better in the life cycle cost analysis in terms of energy consumption, and in comparison, to System A, it saves a total of $1,692,942.21 over the course of a year. In comparison to System A, System B appears to have a little influence on all sustainability-related factors for the categories under examination. The method's evolution and development should link technological, economic, and environmental factors with the specific objective of further optimizing the offer, locating, and assessing additional portfolio components, or pursuing more integration. To be able to define standardization, knowledge must be deepened in order to analyze the environmental performance of process innovation.	[3]
8	In this study, the LCA is used to analyze two distinct water packaging materials, that includes glass and PET bottles. In order to	With regard to total environmental implications, the findings favored PET bottles. Due to the considerable energy	[52]

	determine the type of water packaging that has the lowest environmental impact, waste scenarios based on actual recycling rates are created. Life cycle comparisons are then conducted, taking these scenarios into account. SimaPro 8.0.1, a software designed according to the ISO 14040 LCA Standard, is used for inventory analysis, waste scenarios, assessment, and comparing system operations. The term "one piece 33 cl bottle" is used to define the functional unit, and cradle-to-gate analysis is used. This study is reported form Turkey.	usage during their production, glass bottles are not ideal in terms of their environmental performance. When the weight of the life cycle assessments of the two types of bottles are plotted against ecosystem, human health, and resource impacts, it becomes clear that PET bottles have a much smaller impact on the aforementioned parameters than glass bottles do. These costs stakeholders’ money in order to transport products to the intended destination. Only the endpoint categories were included in the analysis.	
9	This study examines the effects on the life cycle of three packaging options for premium extra-virgin olive oil: stainless-steel bottles, dimmed glass bottles, and tin-plated cans. The analysis was carried out utilizing a cradle-to-grave methodology and functional units of 0.250 L and 0.500 L containers (1L bottling capacity). Only six midpoint impact categories were evaluated for the contribution of each packing option to the impact indicators of the end product and the impact resulting from distribution to final customers. This study was reported from Italy.	The findings demonstrate that for identical sizes, dimmed glass bottles had the lowest impacts for each of the six indicators chosen, with the exception of ozone layer depletion, and stainless-steel bottles have the highest impacts for each of the other impact assessment indicators. Sensitivity study demonstrated that a breakeven point can be determined above which the impact of glass outweighs that of one of the competing packaging techniques. Packaging clearly contributes significantly to the impact of bottled oil. This contribution can be as significant as 60% of the total GW for compact container, such as a 0.100 L stainless steel bottle.	[53]

10	This study compares the environmental impacts of PET, R-PET, non-returnable glass, and returnable glass bottles using a functional unit of 1 l of pasteurized milk. A significant Italian milk processing and packaging facility provided the inventory data. The ReCiPe 2016 Midpoint (H) technique was used to estimate the results, and a marine litter indicator (MLI) was then suggested in order to assess the possibility for milk bottles to pollute the Mediterranean Sea. The assessment boundaries are considered from cradle-to-grave.	According to LCA findings, R-PET bottles contribute the least to GW, SOD, TA, FRS, WC, and HCT, with PET bottles coming in second, returnable glass bottles coming in third, and non-returnable glass bottles coming in last. Glass is the worst material for packaging since it requires a lot of energy to produce, weigh, and deliver each bottle. Returnable glass can yield some benefits, but even eight reusing of a bottle would not produce outcomes on par with PET or R-PET bottles that are used just once. Furthermore, the MLI asserts that returnable glass bottles should be the primary choice because many plastic bottles run the risk of ending up in the ocean.	[54]
11	This study assesses the environmental impact of the most popular juice, beer, and water packaging solutions on the Spanish market. Using a cradle-to-grave assessment technique, the manufacture of various packaging types and sizes was assessed together with their final disposal options (incineration, landfilling, and recycling). The packaging needed to hold 1 l of beverage served as the functional unit. The Ecoinvent v2.1 database provided environmental information on the consumption and emissions of each substance under analysis. Only GW and Cumulative Energy Demand were considered as environmental indicators.	For all the packaging choices studied, recycling was discovered to be the highly environmentally beneficial disposal choice, and depending on the packaging material, either incineration or landfilling was deemed to be the second-best choice. Plastic packaging (for sizes more than 1 l) and aseptic carton had the least negative effects on the environment. The examination of the whole life cycle of beer reveals that the impact of beer packaging is comparable to the impact of beer production, and these are the stages with the biggest impacts. In the water and juice life cycles, it was discovered that packaging had the greatest environmental impact.	[55]

12	This study analyzes how carbonated soft drinks produced and consumed in the UK impact the environment. One liter of packaged beverage volume and the entire annual UK production of carbonated beverages are considered as two functional units. The implications at the industry level have been estimated using the latter. The term "cradle-to-grave" referred to the system boundaries. Polyethylene terephthalate (PET) bottles, aluminum cans, and glass bottles, are among the packaging options for carbonated beverages that are taken into consideration. A beverage manufacturer, the CCaLC, Ecoinvent, and Gabi databases were used as sources for the data. The CML 2001 approach has been used to evaluate the environmental impacts.	According to the findings, packaging accounts for between 59 and 77% of all environmental consequences. Between 7 and 14% of the cost is made up of components, mostly sugar, and between 5% and 10% of the cost is made up of energy used in filling and packing. The potential for GW is increased by up to 33% when drinks are refrigerated at retailers. 7% of the total impacts are attributable to transportation. For the majority of consequences, including the carbon footprint, the beverage packaged in 2 l PET bottles came out to be the highly sustainable choice, while the beverage packaged in glass bottles is the least sustainable. The carbon footprint of the beverage in glass bottles would, however, be comparable to that of the beverage in aluminum cans and 0.5 l PET bottles after three reuses.	[56]
13	Using the LCA technique, this study intends to examine and compare the potential environmental effects of beverage packaging materials made of glass, aluminum (Al), and polyethylene terephthalate (PET). The 300 ml glass bottles, 330 ml aluminum cans, and 2000 ml PET bottles produced, used, and discarded in West Bank, Palestine, are the subjects of the LCA study. Seven environmental	The comparative LCA analysis found that the 300 ml glass had the largest environmental impact in the Palestinian setting, followed by the 2000 ml PET drinks bottles, the 330 ml Al beverages cans, and the 2000 ml PET beverages bottles. Additionally, as shown by the sensitivity analysis results, the environmental consequences might be greatly decreased by raising the particular recycling rates of these	[57]

	impact categories were considered while completing the LCA using the Impact 2002+ approach, based on the LCIA of data acquired from local sources. This analysis's assessment boundaries are considered from the factory gate to grave.	three packaging materials under investigation. The results may differ if we consider other midpoint and endpoint impact categories as this analysis is based on a few midpoint impacts categories.	
14	This study attempts to look into prospects for the circular economy concept implemented in the Italian wine industry. The potential environmental advantages of the Piceno wine consortium's reuse of glass bottles have been specifically quantified. The circular scenario (cleaning and reuse of bottles within the local consortium) has been compared to the regular scenario (glass recycling) using the standard Life Cycle Assessment (LCA) technique. The packing of 0.75 liters of wine in a glass bottle made from salvaged end-of-life glass bottles is the criteria of the functional unit. The assessment technique ReCiPe 2016 is chosen, undertaking only midpoint impacts into account.	Results show that recycling glass bottles has measurable positive effects across all impact categories (ReCiPe Midpoint method). The additional resources (such as electricity) utilized during the cleaning of used bottles are countered by the avoidance of the usage of new raw materials. It is important to note that the suggested reuse scenario can be applied in other geographic contexts and is not reliant on the location of the wine consortium. Similar outcomes should be possible in other wine consortiums with the same attributes and dimensions. Since only washing-related data was measured, future work should first concentrate on enhancing the quality of inventory data.	[58]
15	This study evaluates the degree to which the environmental hotspots of microbrewer beer's packaging and delivery can be reduced. Seven brewers had their packaging and distribution methods put through a life cycle assessment (LCA), which compared those methods to three mitigation options:	Findings indicate that switching from single-use glass bottles to aluminum cans or the glass bottles that can be reused will help all participating breweries reduce their impact in a variety of categories. Additional reductions are also possible if switching from small vans to big lorries is adopted for	[59]

	using steel kegs instead of PET kegs, using glass bottles that are reusable instead of the single-use glass bottles, or using aluminum cans. Small-scale producers of food and beverages, sustainability experts, and policymakers looking to find more environmentally friendly (circular) packaging and delivery methods are the intended audience. 1 L of packaged beer sold to a consumer at the point of retail is the functional unit.	the distribution to retailers. When beer is transported over small distances, employing PET keg as an alternate solution to reusable steel keg is not a environmentally friendly choice, although van transportation over long distances can result in considerable savings. The case study breweries' carbon footprints per liter of beer range from 727 to 1336 g CO2 eq., but they can be reduced by 6-27% or 3-27% by switching to aluminum cans or reusable glass bottles when beer is supplied by van, respectively.

2.8 Research Gaps

A comprehensive overview of the LCA studies discussed above for glass containers used for food, beverage, and pharmaceutical packaging are presented in table 2 based on their origin, assessment levels, type of glass packaging, assessment approach, data sources, assessment boundaries and the year of publication. The assessment boundaries showed the life cycle phases included in the analysis, and assessment levels revealed whether the assessment was based on product, process, or sector. 14 out of 15 studies originated from developed countries and only 1 study originated form Palestine [57] which is developing nation. This suggests that very little research related to the environmental impacts of glass containers and their production have been carried out in the developing nations and no study originated form the subcontinent. Furthermore, there was no study up to our knowledge which evaluated the environmental impacts of a glass sector/facility while 11 of the reviewed studies focused on the product (comparing glass with other packaging materials) and 4 studies focused on the impacts of processes involved. This indicates that the comprehensive analysis of the glass sector and industrial processes were missing in the reviewed studies. 8 studies were based on different kinds of beverages packaging, 5 were based on food packaging materials and only single study was focused on pharmaceutical packaging. Furthermore, 12 studies employed only midpoint approach, 1 study employed endpoint approach, and 2 of the 15 studies employed both midpoint and endpoint approaches to evaluate the environmental impacts. Only two studies used only the primary data for the analysis while 10 studies used both primary and secondary data for the analysis and 3 studies only used secondary data form different literature and databases. In terms of the assessment boundaries, 10 studies had cradle-to-grave boundaries and 3 studies had cradle-to-gate boundaries.

Literature review also suggest that there is no particular study that compares the environmental impacts of different types of glass used for the packaging of food, beverages, and pharmaceutical products, hence this also adds to the novelty of this analysis.

Table 2: Comprehensive overview of reviewed LCA studies

Sr. No.	Country		Assessment Levels			Type of Glass Packaging			Assessment Approach		Data Sources		Assessment Boundaries				Year	Ref
	Developed	Developing	Sector	Product	Process	Beverage	Food	Pharma	Midpoint	Endpoint	Primary	Secondary	Cradle-to-Gate	Cradle-to-Grave	Cradle-to-Cradle	Factory In Gate-To-Grave		
1	✓			✓				✓	✓		✓		✓				2022	[32]
2	✓			✓			✓		✓	✓	✓	✓		✓			2014	[33]
3	✓			✓			✓		✓		✓	✓		✓			2009	[48]
4	✓				✓		✓		✓		✓	✓		✓			2021	[49]
5	✓			✓		✓			✓	✓	✓	✓		✓			2021	[50]
6	✓			✓		✓			✓		✓	✓			✓		2001	[51]
7	✓				✓				✓			✓		✓			2019	[3]
8	✓			✓		✓				✓	✓	✓	✓				2016	[52]
9	✓			✓			✓		✓		✓	✓		✓			2016	[53]
10	✓			✓			✓		✓		✓			✓			2021	[54]
11	✓			✓		✓			✓			✓		✓			2011	[55]
12	✓				✓	✓			✓		✓	✓		✓			2013	[56]
13		✓		✓		✓			✓		✓	✓				✓	2016	[57]
14	✓				✓	✓			✓		✓	✓	✓				2019	[58]
15	✓			✓		✓			✓			✓		✓			2022	[59]
Total Score	14	1	0	11	4	8	5	1	14	3	12	13	3	10	1	1		

2.9 Summary

This chapter has described the LCA framework and previous work on the LCA of glass packaging solutions. This chapter's findings highlighted possible research gaps, the use of LCA tools in glass production and other sectors, and, most crucially, the processes required to conduct LCA. Reviewing previous work on the LCA of glass packaging solutions revealed that only developed European countries are now using LCA for the environmental impact assessment of glass sectors, with 14 of the 15 studies coming from developed countries and a single study coming from Palestine. The information acquired in this chapter enabled the development of a methodology to fill the identified research gaps.

CHAPTER 3: METHODOLOGY

The LCA framework discussed in Chapter 2 offered a solid foundation for developing a methodology for implementing LCA techniques in the glass sector in Pakistan. As a result, this chapter describes the entire methodology and steps taken from selecting a glass facility in Pakistan to defining the goal and scope of this study, life cycle inventory analysis, and life cycle impact, which includes the method of impact assessment and the levels of impact assessment.

3.1 Glass packaging production facility

A glass processing factory in Hattar, an industrial town close to Islamabad, Pakistan, was the subject of this environmental impact analysis in order to close research gaps in LCA from underdeveloped nations and for the production of glass packaging. The goals are to first determine the environmental effects of the actual (current) glass manufacturing process and then examine the environmental effects by creating three potential feasible alternative scenarios. This could aid in demonstrating the environmental effects—both good and bad—of components and energy sources and direct the company to manufacture glass packaging in a more environmentally responsible manner. The LCA technique, compliant with ISO 14040 and ISO 14044 standards, is utilized in this study to assess the environmental impacts. It is now further discussed in its major phases.

3.2 Goal and Scope Definition

The aim of this study is to evaluate the environmental impacts related to the glass manufacturing plant operating in Pakistan. The plant is located in one of the dedicated industrial zones of Pakistan with annual production equaling 90,000 to 100,000 tons. The functional unit is taken as 1 ton of glass produced and the scope of this study is cradle-to-gate excluding the transportation of raw materials as shown in figure 5 because the manufacturer has less control, and it was also difficult to access the reliable data for these phases. This included extraction and processing of raw materials, combustion of fuel and energy for melting and forming processes, and other activities within the facility until the final product is formed. The study does not consider recycling at the end of life. Impacts were evaluated considering five different parameters: Emissions and wastes produced during glass production, Raw materials used, Electricity generated on site using diesel and natural gas, energy consumed from electricity mix of Pakistan, and emission due to the consumption of natural gas during melting process.

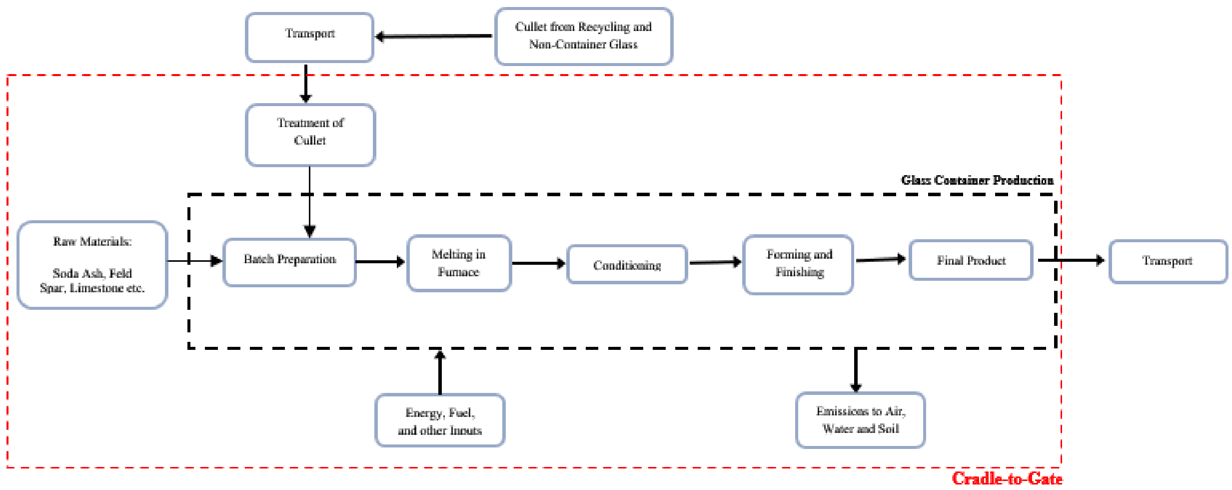

Figure 5: Impact Assessment Boundary

3.3 Life Cycle Inventory Analysis

Primary data and product information (that includes different raw materials and their quantities, different processes and parameters involved in production of glass, emissions to environment, and fuel and energy usage during production) are provided by the target glass manufacturing plant located in Pakistan for the months of November 2021, March 2022, and June 2022. Data is validated using data triangulation and average of these three months is taken for the analysis. Secondary data (including Pakistan energy mix, and cradle-to-gate materials extraction and refining) are extracted from Ecoinvent LCI database. All input/output flows that are environmental, material and energy flows are balanced in accordance with the functional unit of the analysis as presented in table 3. Emissions to air, land and water during glass production are also provided by the target industry, but the information is classified.

3.4 Life Cycle Impact Assessment

Results at midpoint impact categories and/or endpoint damage categories may be reported using the life cycle impact assessment (LCIA). The damage categories are referred to as endpoints in the environmental cause and effect chain, and the midpoint impacts are considered as ties. The midpoint impact and endpoint damages are reported in this study along with impacts at both levels. The study comprises 18 different impact categories in order to present a thorough picture of affects at midpoint level. These midpoint impact categories include; Global Warming (GW), Stratospheric Ozone Depletion (SOD), Ionizing Radiation (IR), Ozone Formation, Human Health (OF-HH), Fine Particulate Matter Formation (FPMF), Ozone Formation, Terrestrial Ecosystem (OF-TE), Terrestrial Acidification (TA), Fresh Water Eutrophication (FEW), Marine Eutrophication (ME), Terrestrial Ecotoxicity (TE), Fresh Water Ecotoxicity (FWE), Marine Ecotoxicity (MEx), Human Carcinogenic Toxicity (HCT), Human Non-Carcinogenic Toxicity (HNCT), Land Used (LU), Mineral Resource Scarcity (MRS), Fossil Resource Scarcity (FRS), and Water Consumption (WC). These midpoint impact categories are divided into three areas of protection i.e., Human Health (HH), Ecosystems, and Resources. SimaPro V 9.2 was utilized as the modelling software for this LCA study, and ReCiPe 2016, an improved version of ReCiPe 2008 that uses the hierarchist perspective, was employed as the assessment technique. Impacts can be considered using this approach at both the midpoint and endpoint levels. Figure 6 summarizes the methodology followed in this study for quick and better comprehension.

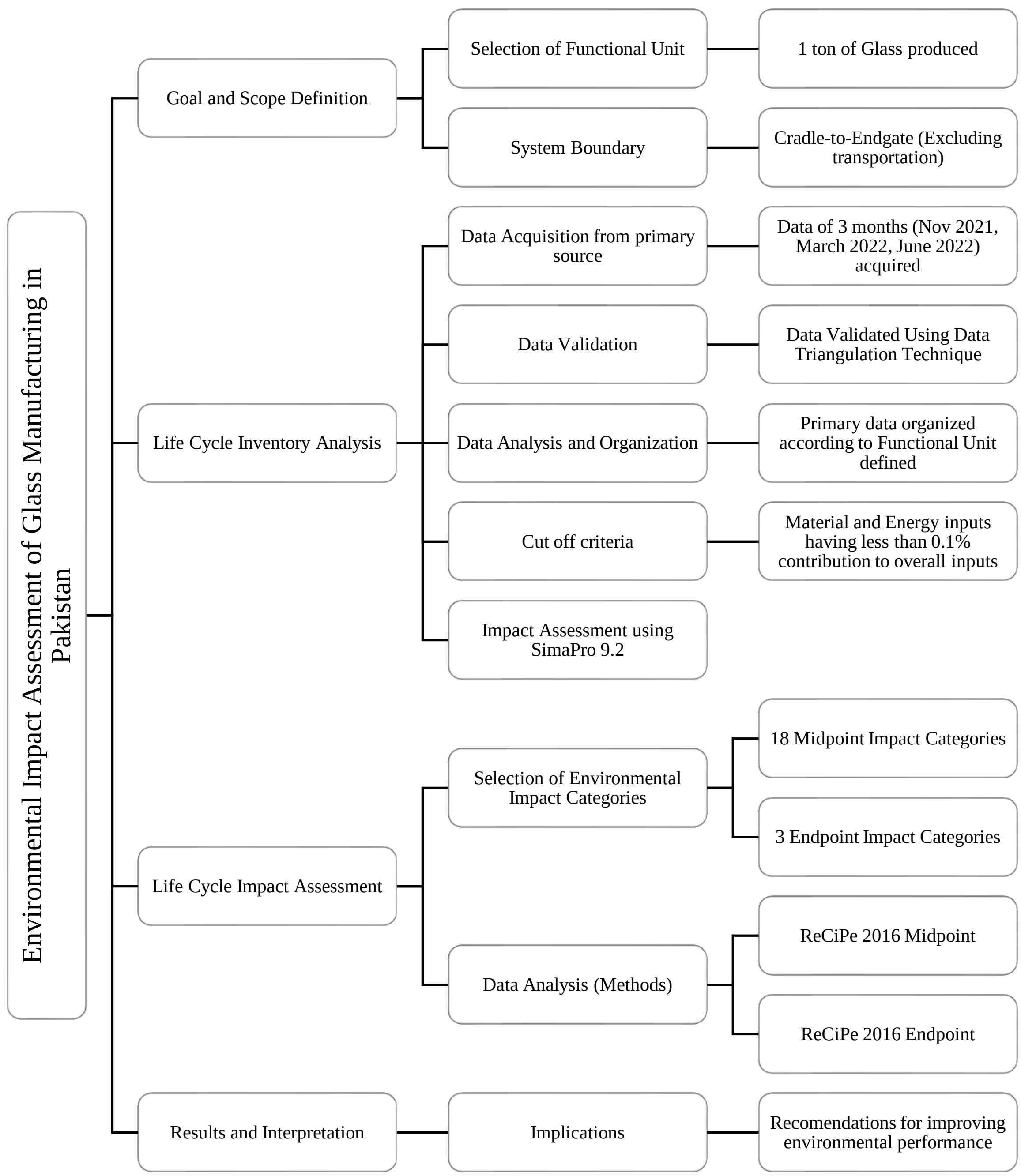

Figure 6: Complete methodology of LCA of Glass Manufacturing in Pakistan

CHAPTER 4: DATA ACQUISITION AND ANALYSIS

4.1 Target Industry

Our target industry produces three types of glass: Pharmaceutical glass containers (amber), beverages glass containers (flint and green), and food glass containers (flint/clear). For each of these glass types the manufacturing process, cullet percentage and ratio of raw materials is same except some differences in minor raw materials. For each particular type of glass, same type of cullet is used for example to produce amber glass the cullet should be from recycled amber glass. Secondly there are some minor differences in the composition of raw materials. For the production of green glass sodium di chromate is used as coloring agent, sodium nitrate is used in case of flint glass, and for amber glass nitrate, arsenic, cobalt, and coke is used but their composition is in minute quantity. The weight of end glass product also differs for each type of glass because of differences in their densities. Green has highest density while flint has lowest density.

The manufacturing process start from the batch plant where the raw material is mixed according to the desired ratio and stored in silos. After that it is transported form batch plant to the furnace dedicated silo using a conveyor belt from where it is pushed into the furnace using a batch charger and melted inside the furnace using natural gas. After that, melted glass is distributed to different forehearths in which it flows into the feeder. The distributor, forehearths and feeder all contain small burners in order to maintain the temperature of the melted glass. After that a plunger is used to push the melted glass through an orifice to make required shape of gob. The gob is distributed towards the blank side of the Individual Section (IS) machine where blank is made. Then the blank is inverted towards the blow side of IS machine where blank is blown into the desired shape of glass container. After that the container is transferred towards annealing lehr with the help of silent chain conveyors. The temperature of annealing lehr at entrance is 600^{o}C and the glass is gradually cooled (Annealed) while moving through annealing lehr towards the exit where its temperature is 25^{o}C. Finally hot/cold end coating is applied on the glass containers to make it scratch resistant and is packed for delivery to the customer.

4.2 Raw materials and LCI

Silica Sand is the main component of glass production. Other raw materials are also used to enhance certain properties like limestone which provides the stability and soda ash which is used to lower the melting point. Recycled glass (cullet) is used to increase the fusibility of glass and to prevent the loss of alkali during the reactions of raw materials. Furthermore, cullet also reduces the use of virgin raw materials and energy consumption, hence, reduces the impacts on the environment. During the production process itself water is used for cooling purposes i.e., maintaining the temperature of different machines in the working range. Natural gas and diesel are consumed for electricity generation onsite. There are a total of 7 electricity generators in the facility, 5 of which consume natural gas to generate electricity and other two consume diesel. Depending on the work load some generators are used to generate more electricity as compared to others but in total for 1 ton of glass produced, on average 3.44 MMBTU natural gas and 1.46L diesel is consumed by these generators. Electricity produced onsite along with electricity form energy mix of Pakistan is used to run machines in the manufacturing process that include conveyors, batch charger, forehearths, IS machine and annealing lehr etc.

Apart from that this electricity is also consumed during other operations within facility i.e., for Air Conditioners, and lighting etc. Energy consumed for each different type of class differs with respect to the densities, melting temperatures and sizes of glass containers. For instance, the density of green glass is more than that of flint and amber glass, hence it requires more heat to melt. Also because of differences in the densities and sizes of glass containers, each glass type has different pull i.e., number of glass containers produced in one minute. Green glass container produced to store 250 ml cold drink has a weight of 275g and its pull is 120/min. For amber glass containers produced for pharmaceutical packaging has a weight of 113g and its pull is 180/min. In case of flint/clear glass containers we have two types. Jar containers for food packaging and bottle containers for beverages packaging. Jar containers have a pull of 150/min with weight of each jar equaling 212g. Weight of flint glass bottle to store 250 ml cold drink is 275g with a pull of 140/min. So, it takes 32 minutes to produce 1 ton glass jars (flint/clear), 26 minutes to produce 1 ton of flint/clear beverages bottles, 49 minutes to produce 1 ton of amber bottles with capacity to store 120 ml of pharma, and 30 minute to produce 1 ton of green glass bottles. Hence the usage of electricity during the production and consumption of natural gas during the melting process differs for each type of glass container under consideration as mentioned in table 3.

Table 3: Life Cycle Inventory for 1 ton of glass produced at plant

Input types	Units	Values		
		Amber Glass	Flint (Clear) Glass	Green Glass
Natural Gas for process (melting)	MMBTU	2.66808	2.934887	3.290632
Natural Gas (electricity generation)	MMBTU	4.85	2.4768	2.9928
Diesel (electricity generation)	L	2.0586	1.0512	1.2702
Electricity from national grid	KWh	128.451	65.592	79.257
Glass Cullet	kg	570	570	570
EUR-flat pallet	unit	0.8	0.8	0.8
Chemical (Inorganic)	kg	18	18	18
Dolomite	kg	29	29	29
Feld Spar	kg	21.5	21.5	21.5
Graphite	g	20	1.25	1.5
Limestone	kg	41.5	41.5	41.5
Silica Sand	kg	230	230	230
Refractory Fire Clay	kg	14.3	14.3	14.3
Soda Ash	kg	70	70	70
Polyethylene HDG	kg	12.9	12.9	12.9
Water (not recycled)	kg	100	100	100
Water (recycled)	kg	1300	1300	1300
Cardboard	kg	20	20	20
Lubricating Oil	g	24	24	24
Selenium	g	-	10	-
Mixture (S, Fe, C)	kg	5	-	-
Lime (Hydrated)	kg	1	-	1.1
Portachrom	kg	-	-	1.1
Portafer	kg	1	-	-
Sodium Dichromate	kg	-	-	0.5
Sodium Nitrate	kg	1	1	-

4.3 Life Cycle Impact Assessment

The life cycle impact assessment was carried out for 18 different midpoint, and 3 endpoint impact categories using the ReCiPe 2016 method of evaluation of SimaPro software tool. First of all, the environmental impacts of three different glass packaging solutions i.e., flint (clear) glass, green glass, and amber glass were compared against both midpoint and endpoint impact categories. After that we generated two alternate scenarios, the baseline scenario which is based on the input data from the target industry, and the alternative scenario in which the energy mix of the baseline scenario was changed, and all the energy was based on energy mix of Pakistan, in order to get more insights of the environmental hotspots and point out possible solutions to reduce them. Furthermore, impacts generated due to melting process, on-site electricity production, energy mix of Pakistan, and raw materials were also compared against both midpoint and endpoint impact categories. At the end, further scenarios were generated for using different cullet ratios as raw material. The final stage of an LCA study involves interpreting the findings and evaluating various suggestions and implications.

In order to draw final conclusions, two different analyses were carried out. First analysis was based on different energy mix where two alternative scenarios were generated. **Scenario 1;** which is the baseline scenario where the energy mix is same as the primary data collected from the target industry and **Scenario 2;** in which all the electricity consumed during the production was from the national grid station of Pakistan. In order to draw conclusion, the impacts of both scenarios were compared, and a brief cost analysis was also carried out. The second analysis was based on using different cullet ratio as raw materials. For this analysis three scenarios were generated. **Scenario 1;** which is the baseline scenarios with 57% cullet as raw material, **Scenario 2;** where the percentage of recycled glass was changed to 40%, and **Scenario 3;** where the percentage of recycled glass was changed to 70%. In order to draw conclusions, impacts of all three scenarios were compared for both midpoint and endpoint impact categories, and at the end a brief cost analysis was carried out.

4.4 Summary

This chapter detailed the ways for acquiring and analyzing data from the target industry as well as from various databases. Data collection includes many visits to the target industry in Pakistan, as well as molding the acquired data utilizing mass and energy balance in accordance with the functional unit provided in Chapter 3. Table 3 presents the data acquired for the three glass packaging alternatives under consideration, and the concluding section of this chapter presents numerous possible scenarios for the analysis.

CHAPTER 5: RESULTS AND DISCUSSIONS

This chapter presents a detailed analysis of the environmental impacts for all three types of glass packaging based on the Life Cycle Assessment. The contributions of different inputs or life cycle phases were firstly assessed at the midpoint level. The endpoint level of the results was also further explored. In addition, the results were compared with those of other similar studies in order to serve as external validation and comparison. For the proper analysis three results are presented for two different scenarios. In the first scenario (baseline scenario) all the input are in line with the data gathered from the glass manufacturing facility in Pakistan. Whereas for the second scenario (alternative scenario) the electricity generated on-site by consuming natural gas and diesel has been replaced by electricity form Pakistan’s energy mix. The detail results for both scenarios are presented below. Furthermore, the impacts and outputs of both the scenarios are also compared.

5.1 Baseline Scenario

Table 4 presents the quantified midpoint impact scores of three types of glass packaging solutions. It plainly demonstrates the disparities between their overall impact scores, with green glass scoring higher in the most of impact categories than amber and flint glass. Overall, the results are consistent with previously published research that was done in other nations. However, changing energy sources, energy mixes, technological advancements, etc. are some of the reasons for the variations in the overall impact scores of some impact categories. The scores of GW, AP, and other midpoint impact categories were compared with the scores of several studies conducted for glass packaging due to shared impact categories. The results of our study had a somewhat higher value than average for those categories, which may have been caused by the difference in the energy-mix of different countries.

Table 4: Quantified impact scores at midpoint level

Impact Category	Unit	Total Impact Score		
		Amber Glass	**Flint (Clear)Glass**	**Green Glass**
GW	kg CO_2 eq	1.23×10^3	1.19×10^3	1.24×10^3
SOD	kg CFC11 eq	0.000735	0.000695	0.000677
IR	kBq Co-60 eq	30.4	26.3	28.8
OF-HH	kg No_x eq	3.64	3.41	3.62
FPMF	kg PM2.5 eq	2.54	2.42	2.53
OF-TE	kg No_x eq	3.7	3.46	3.67
TA	kg SO_2 eq	6.61	6.24	6.51
FEW	kg P eq	0.711	0.707	0.746
ME	kg N eq	0.141	0.137	0.137
TE	kg 1,4-DCB	3.66×10^3	3.92×10^3	3.89×10^3
FWE	kg 1,4-DCB	43.4	40.7	74.6
MEx	kg 1,4-DCB	56.9	53.4	95.7
HCT	kg 1,4-DCB	67.7	66	121
HNCT	kg 1,4-DCB	965	806	1.21×10^3
LU	m^2a crop eq	667	666	673
MRS	kg Cu eq	11.5	11.4	12.9
FRS	kg oil eq	302	228	253
WC	m^3	11.9	11.8	12.1

Figure 7 gives us the comparison of the impacts of each type of glass produced in Pakistan against 18 different midpoint impact categories. For most of the impact categories each glass type has almost same score, but green glass has more impacts as compared to other two glass types especially in FWE, MEx, HCT, and HNCT impact categories. On the other hand, amber glass had more impacts in SOD, IR, and ME impact categories but there is not much difference when compared to other glass types. The prominent difference for amber glass is in FRS category because of the time taken to produce 1 ton of amber glass takes much more time hence it consumes more electricity which is being generated using diesel and natural gas. The outcomes made it extremely evident what function different additives had in producing the green glass that companies often make for beverages. The analysis demonstrated that using clear glass and using fewer or no coloring additives could further lessen the environmental effects of beverage glass packaging.

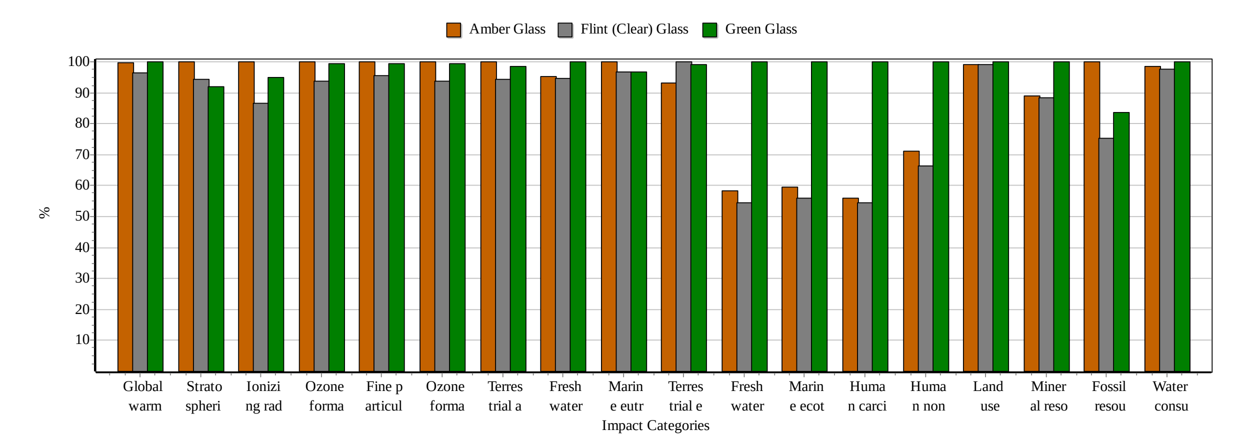

Figure 7: Midpoint impacts of three packaging glass solutions

Figure 8 gives us the normalized results at midpoint level, and it clearly shows that the production of 1 ton of green glass container has worst impacts on the environment as compared to amber glass container which comes second and flint/clear glass which turns out to be more environmentally friendly of the three types under consideration. Secondly, highest impacts arise in the HCT category for all three types of glass containers followed by FWE, and MEx.

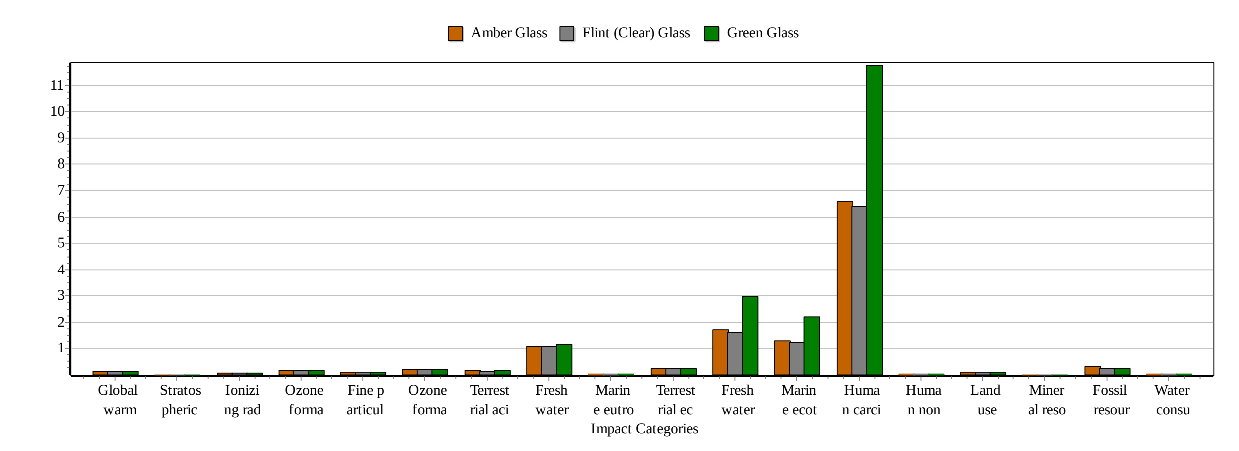

Figure 8: Midpoint impacts of three glass packaging solutions (normalized)

Figure 9 gives us a comparison of amber, flint, and green glass containers at end point level. Results show that in Human Health area of protection green glass have more impact followed by amber glass. For the ecosystems area of protection both green and amber glass have same impacts on the environment but in case of resources area of protection amber glass comes out to be having worst impacts on the environment followed by green glass. For all three area of protection flint/clear glass comes out to me most environmentally friendly among the three. The normalized results at the endpoint level indicated that the human health is the area of protection which is highly impacted by the glass production process of each type of glass followed by ecosystems as illustrated in figure 10. Furthermore, the single score at the endpoint level also gives us brief idea about the impacts of each type of glass containers understudy and results clearly indicate that green glass had the highest score followed by amber glass in terms of negative impacts on the environment as shown in figure 11. More thorough research showed that raw material extraction and processing had the greatest influence on the ecosystem, while emissions to air, water, and soil during production operations had the greatest impact on human health. Additionally, the use of natural gas and diesel for the production of power had the greatest effects on the environment. Natural gas usage during the glass melting has a considerable effect on the number of resources used.

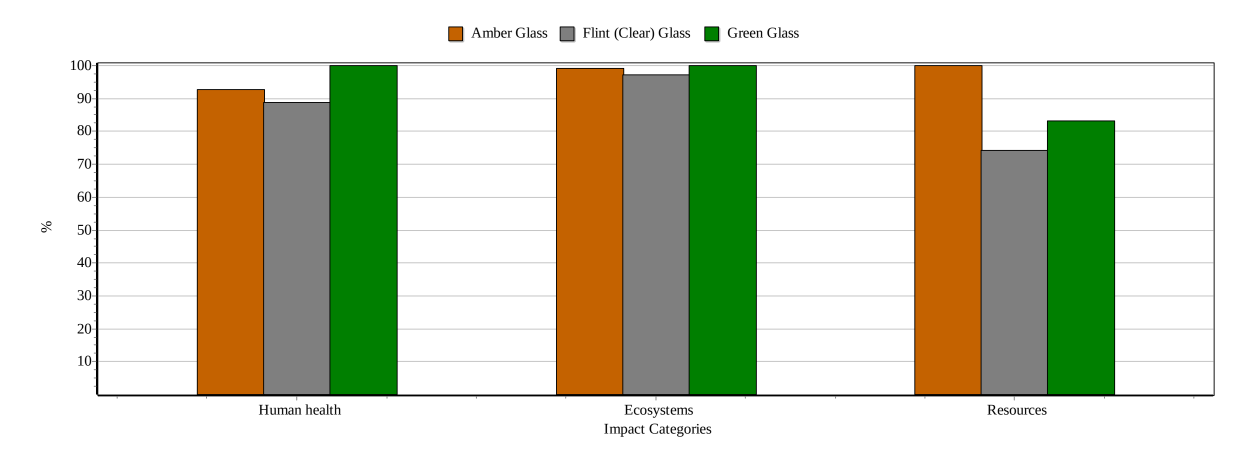

Figure 9: Endpoint impacts of three glass types

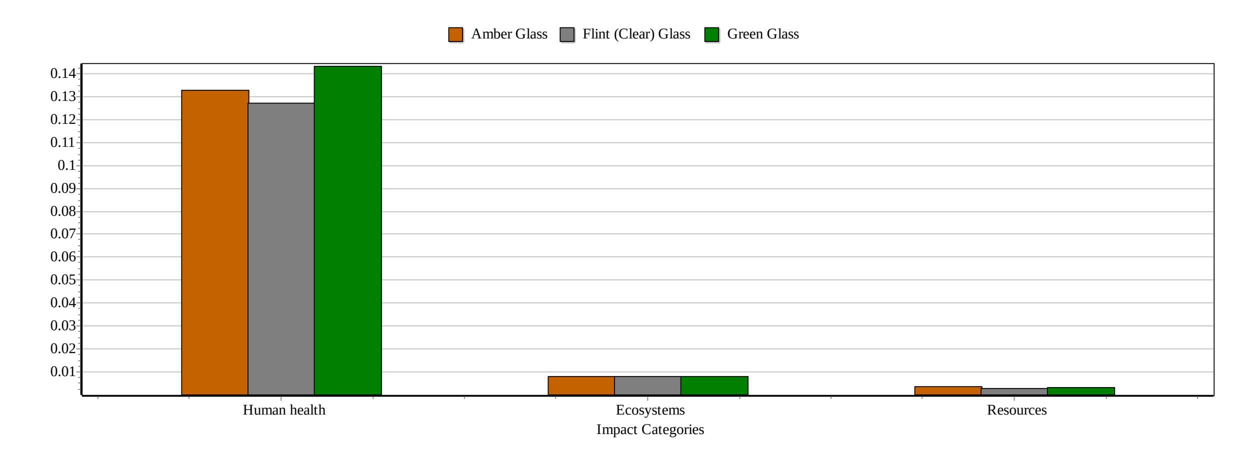

Figure 10: Endpoint Impacts of three glass types (normalized)

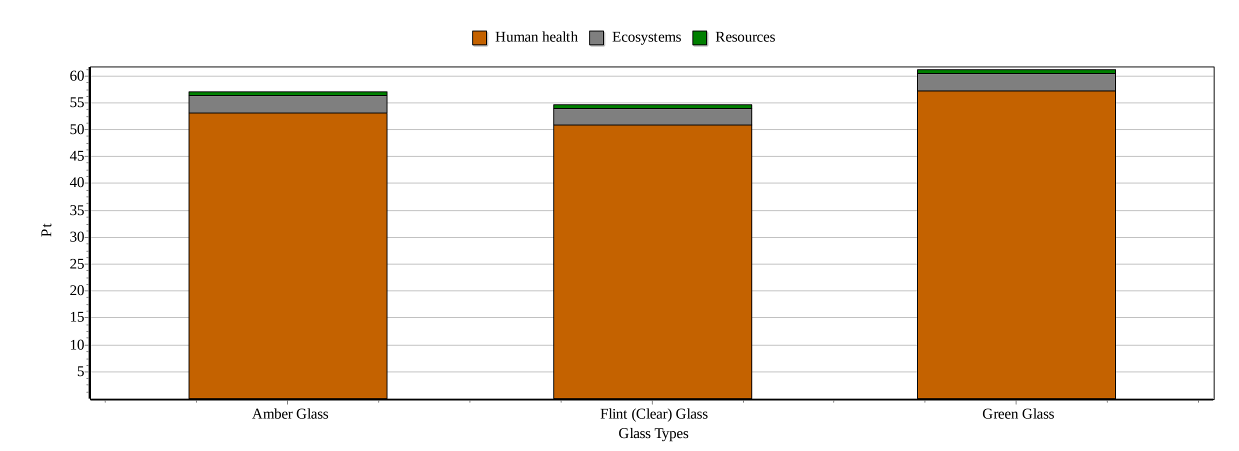

Figure 11: Endpoint Impacts of three glass types (single score)

Apart from these 12 different emissions to the air were considered for the analysis against both scenarios. These emissions constitute more than 80% of all the emissions by weight to the environment. These include carbon dioxide (CO2), methane (CH4), Nitrous oxide (N20), Dichlorodifluoromethane (CCl2F2), Chlorodifluoromethane (CHClF2), Tetrafluoromethane (CF4), Hexafluoroethane (C2F6), Sulfur Hexafluoride (SF6), Nitrogen Trifluoride (NF3), Ozone (O3), sulfur dioxide (SO2), and carbon monoxide (CO) as presented in figure 12. 10 of these 12 emissions under consideration are greenhouse gasses.

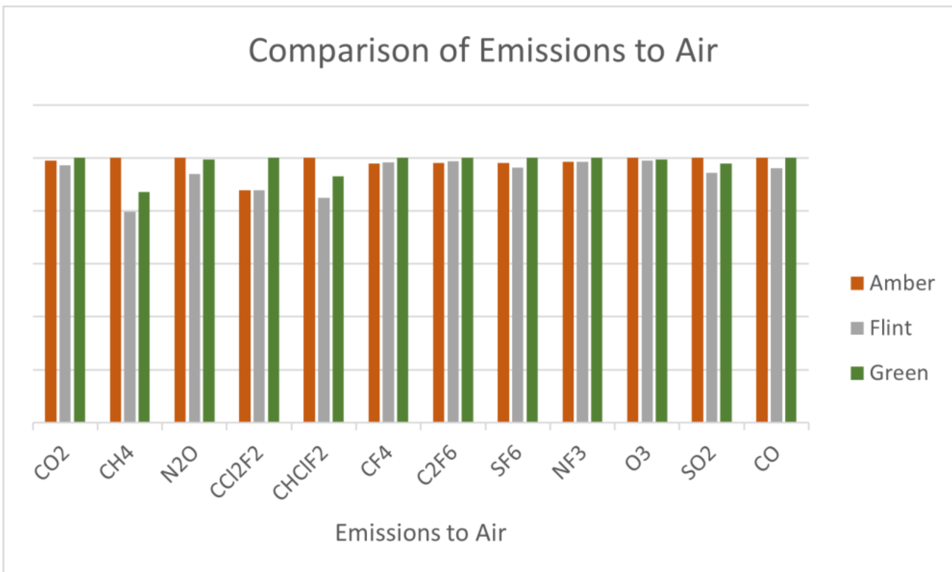

Figure 12: Quantified scores of emissions to air

Form here we can clearly see that green glass is mainly responsible for the highest emission of greenhouse gases as compared to the flint and amber glass, but amber GW score of amber glass is also very high because it emits highest amount of methane as compared to other two types and methane gas has much more impact score in GW than carbon dioxide.

The contribution of various inputs/phases to the overall environmental impacts were examined in order to gain a deeper understanding and a more thorough analysis of the findings. All of the glass kinds under consideration underwent these evaluations. However, for all three types of glass, the overall patterns of the contributions of different inputs were similar. Thus, these contributions were only shown for the flint (clear) glass type in order to keep things simple and avoid confusion by adding more figures. For each of the 18 midpoint impact categories, a comparison was conducted. This comparative analysis was conducted for four main inputs or phases, including glass melting (impacts related to the primary manufacturing process at the plant that also used natural gas), raw materials used (impacts related to all inputs and their extraction), on-site electricity generation (impacts related to gas and diesel used at the plant for electricity purposes), and electricity from the national grid (impact related to the share of electricity based on county's (Pakistan)) and electricity from the national grid. Figure 13 present the contribution of various inputs/phases at the midpoint level of assessment and figure 14 presents the contribution of those inputs/phases at the endpoint level of assessment.

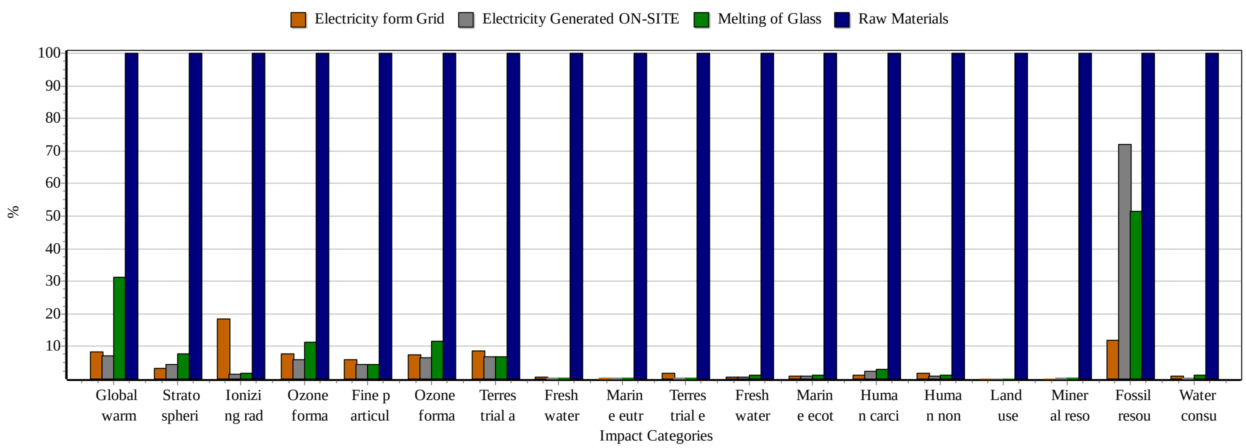

Figure 13: Contribution of various inputs/phases at midpoint level

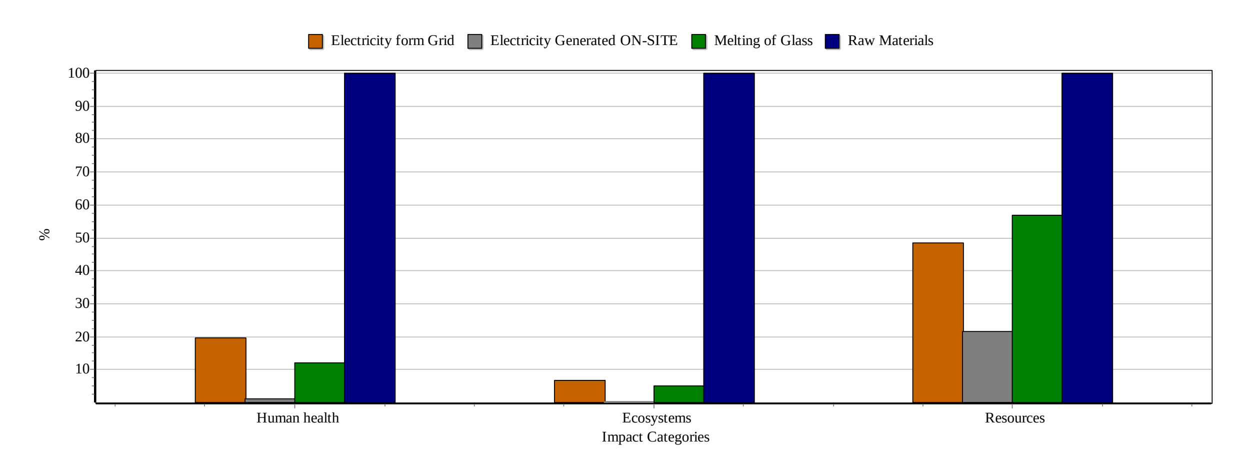

Figure 14: Contribution of various input/phases at endpoint level

Results showed that the emission related to raw materials (extraction and processing) contributed the most to the overall impacts for all impact categories. If the disposal step is disregarded, these results are consistent with benchmark studies that indicated the extraction of raw materials to be the biggest cost driver for such packaging methods. The raw materials used were having the worst impacts on the environment, followed by the manufacture of the glass (mostly melting). Other comparable investigations raised similar findings, showing that a sizable number of effects were connected to the glass packing system's manufacturing process. In addition, for comparative purposes, the share of electricity from the national grid contributed more to various effect categories than the share of electricity generated on-site, with the exception of FRS (Fossil Resource Scarcity). The on-site electrical generating used primarily fuels based on gas and diesel, so the share for FRS was larger. Despite having a very small overall percentage (in comparison to power produced locally), Pakistan's polluting energy mix was highlighted as the comparative greater contribution to impacts.

Table 5: Cost associated with different Input Variables

Glass Type	Cost Associated with Energy Consumption in PKR			
	Natural Gas for Melting	Natural Gas for Electricity	Diesel for Electricity	Electricity from Grid
Flint (Clear) Glass	3093	2610	240	2138
Green Glass	3468	3154	290	2584
Amber Glass	2812	5112	469	4187

Table 5 displays the costs associated with each input variable for each type of glass under consideration. The cost of acquiring raw materials is nearly identical for each type of glass, ranging from PKR 30,000 to 31,000. The biggest cost variation derives from energy consumption, as the energy required for each form of production is different. The cost of flint glass per ton is the lowest, while the cost of amber glass is the greatest since it takes longer to produce one ton of pharmaceutical bottles than the other two.

5.2 Alternative Scenario based on energy-mix

The results in the above section demonstrated three distinct glass packaging options' environmental effects at the level of manufacturing plants in Pakistan. Due to its status as a developing country and other factors, Pakistan's energy mix has not been as clean as that of other wealthy nations. Thus, alternative scenarios were created for each of the three types of glass packaging in order to see the impact of the national grid's energy mix. For this reason, the midpoint impacts for each of the 18 categories were computed while considering 100% national grid electricity usage. It was anticipated that there was not on-site (at the factory) gas and diesel-powered energy production. The electricity provided by the national grid satisfied all of the plant's energy needs. Similar to the baseline scenario discussed about, table 6 gives us the total impact scores for the alternative scenario against all 18 midpoint impact categories.

There has been a difference in the quantitative scores of both scenarios, but for the comparison of glass types, the characterized results are almost same. Hence, in this section we only presented a brief overview of the impacts of three glass types in the alternative scenario as presented (figures 15 to 20). The in-depth comparison of the impacts of both scenarios are presented in the next section of this chapter.

Table 6: Impact scores for alternative scenario at midpoint level

Impact Category	Unit	Total Impact Score		
		Amber Glass	Flint (Clear)Glass	Green Glass
GW	kg CO_2 eq	$1.42x10^3$	$1.29x10^3$	$1.35x10^3$
SOD	kg CFC11 eq	0.000822	0.000739	0.000731
IR	kBq Co-60 eq	58.4	40.6	46.1
OF-HH	kg No_x eq	4.11	3.65	3.91
FPMF	kg PM2.5 eq	2.81	2.56	2.69
OF-TE	kg No_x eq	4.15	3.69	3.95
TA	kg SO_2 eq	7.43	6.66	7.01
FEW	kg P eq	0.732	0.718	0.759
ME	kg N eq	0.143	0.138	0.138
TE	kg 1,4-DCB	$4.07x10^3$	$4.13x10^3$	$4.14x10^3$
FWE	kg 1,4-DCB	44.7	41.4	75.4

MEx	kg 1,4-DCB	58.8	54.4	96.8
HCT	kg 1,4-DCB	69.5	66.9	122
HNCT	kg 1,4-DCB	934	841	$1.26x10^3$
LU	m^2a crop eq	672	669	676
MRS	kg Cu eq	11.5	11.4	12.9
FRS	kg oil eq	349	200	220
WC	m^3	12.7	12.2	12.6

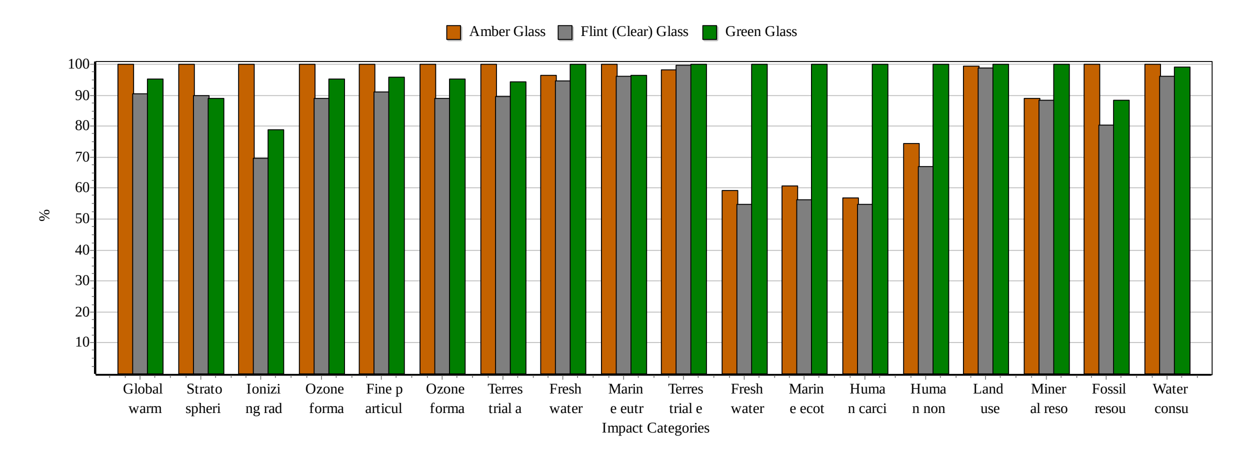

Figure 15: Midpoint impacts of three glass types (Alternative scenario)

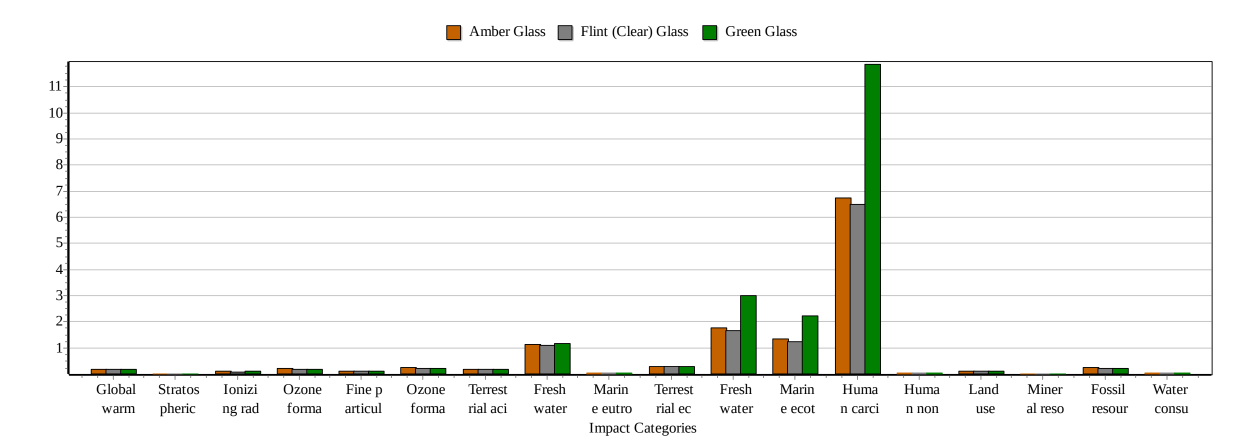

Figure 16: Normalized midpoint impacts of three glass types (Alternative scenario)

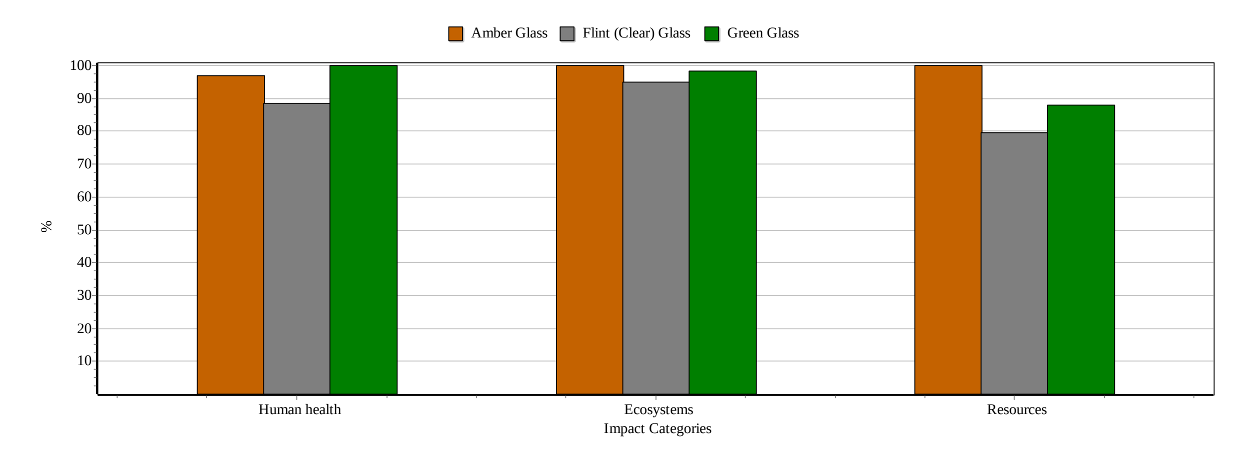

Figure 17: Endpoint impacts of three glass types (Alternative scenario)

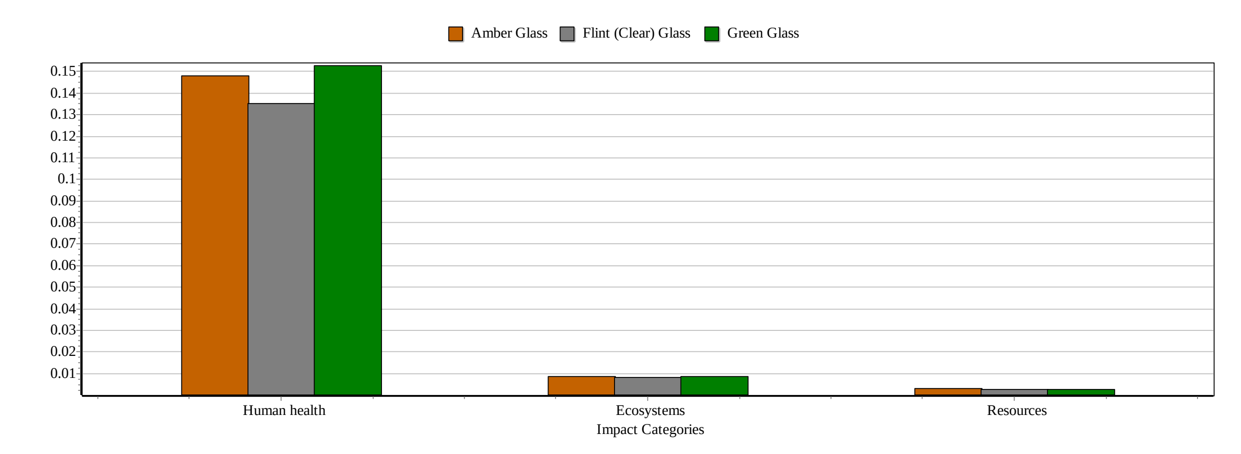

Figure 18: Normalized Endpoint impacts of three glass types (Alternative scenario)

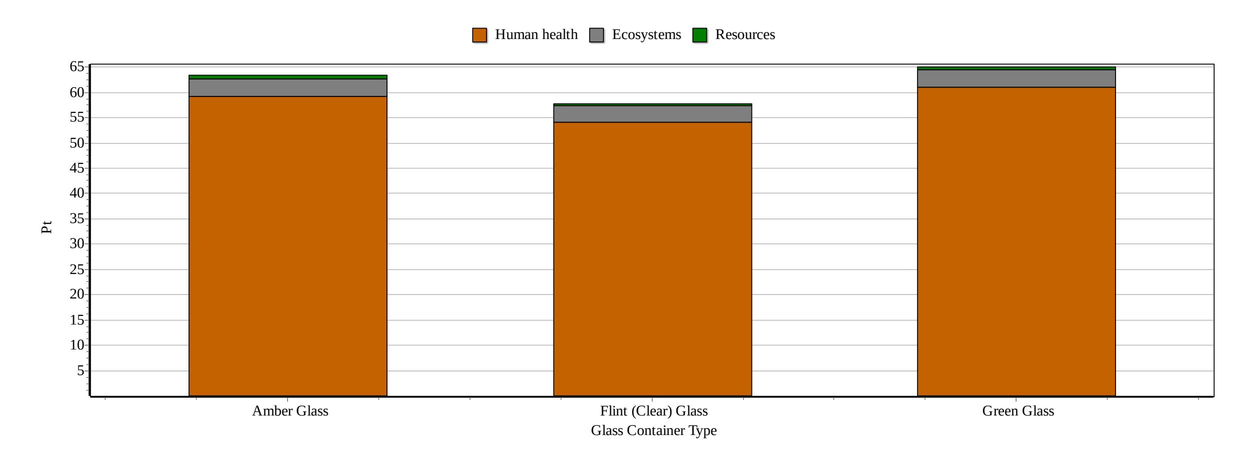

Figure 19: Endpoint Impacts of three glass types (single score, Alternative Scenario)

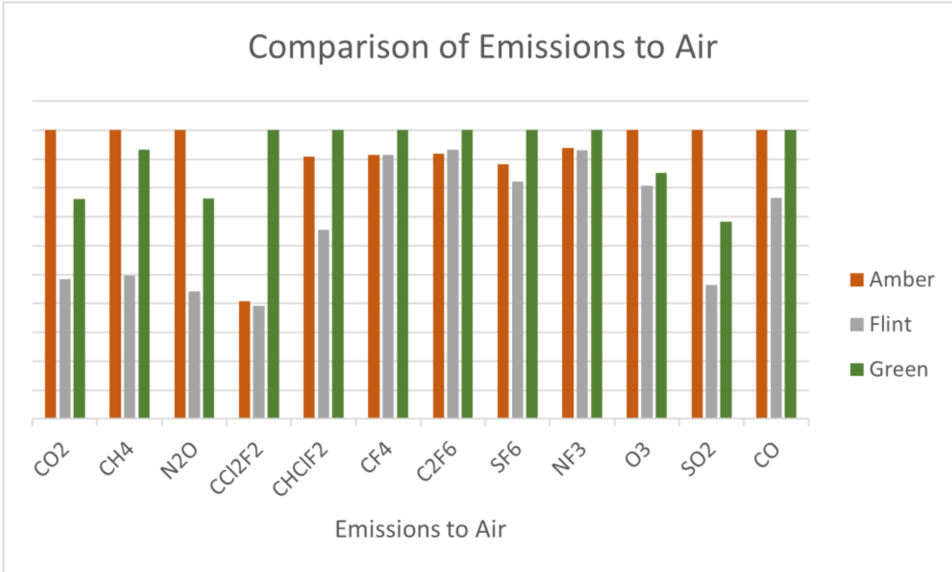

Figure 20: Quantified scores of emissions to air (Alternative Scenario)

5.3 Comparison of Baseline and Alternative Scenario

Table 7 summarizes the findings for all three glass packaging options and their alternate situations. The results for the green glass, flint glass, and amber glass were visually depicted in Figure 21, 22, and 23 respectively, where scenario 1 represents the baseline situation and scenario 2 depicts the outcomes for the alternative scenario. Based on the findings in Table 7, it was determined through the study of potential scenarios that increasing Pakistan's reliance on the national grid will have a negative environmental impact on the country's glass packaging industry. Except for a small number of effect categories like MRS, etc., all three of the glass packaging solutions under analysis had more impacts from the alternative scenarios than from the baseline scenario. These results unequivocally demonstrated the necessity for Pakistan to have a cleaner energy mix at the national level. This also showed that the consequences might be further reduced by increasing the on-site electrical production (based on gas and diesel) at the glass manufacturing plant.

Table 7: Comparison of impact scores for alternative scenarios

Impact Categories	Impact scores								
	Amber Glass			Flint (Clear) Glass			Green Glass		
	Scenario 1	Scenario 2	Percent Variation	Scenario 1	Scenario 2	Percent Variation	Scenario 1	Scenario 2	Percent Variation
GW	$1.23x10^3$	$1.42x10^3$	15.4%	$1.19x10^3$	$1.29x10^3$	8.4%	$1.24x10^3$	$1.35x10^3$	8.9%
SOD	0.000735	0.000822	11.8%	0.000695	0.000739	6.3%	0.000677	0.000731	8%
IR	30.4	58.4	92.1%	26.3	40.6	54.4%	28.8	46.1	60.1%
OF-HH	3.64	4.11	12.9%	3.41	3.65	7%	3.62	3.91	8%
FPMF	2.54	2.81	10.6%	2.42	2.56	5.8%	2.53	2.69	6.3%
OF-TE	3.7	4.15	12.1%	3.46	3.69	6.7%	3.67	3.95	7.6%
TA	6.61	7.43	12.4%	6.24	6.66	6.7%	6.51	7.01	7.7%
FEW	0.711	0.732	2.9%	0.707	0.718	1.6%	0.746	0.759	1.7%
ME	0.141	0.143	1.4%	0.137	0.138	0.73%	0.137	0.138	0.73%
TE	$3.66x10^3$	$4.07x10^3$	11.2%	$3.92x10^3$	$4.13x10^3$	5.4%	$3.89x10^3$	$4.14x10^3$	6.4%
FWE	43.4	44.7	3%	40.7	41.4	1.7%	74.6	75.4	1.1%
MEx	56.9	58.8	3.3%	53.4	54.4	1.9%	95.7	96.8	1.2%
HCT	67.7	69.5	2.7%	66	66.9	1.4%	121	122	0.83%
HNCT	965	934	-3.2%	806	841	4.3%	$1.21x10^3$	$1.26x10^3$	4.1%
LU	667	672	0.75%	666	669	0.45%	673	676	0.45%
MRS	11.5	11.5	0%	11.4	11.4	0%	12.9	12.9	0%
FRS	302	349	15.6%	228	200	-12.3%	253	220	-13%
WC	11.9	12.7	6.7%	11.8	12.2	3.4%	12.1	12.6	4.1%

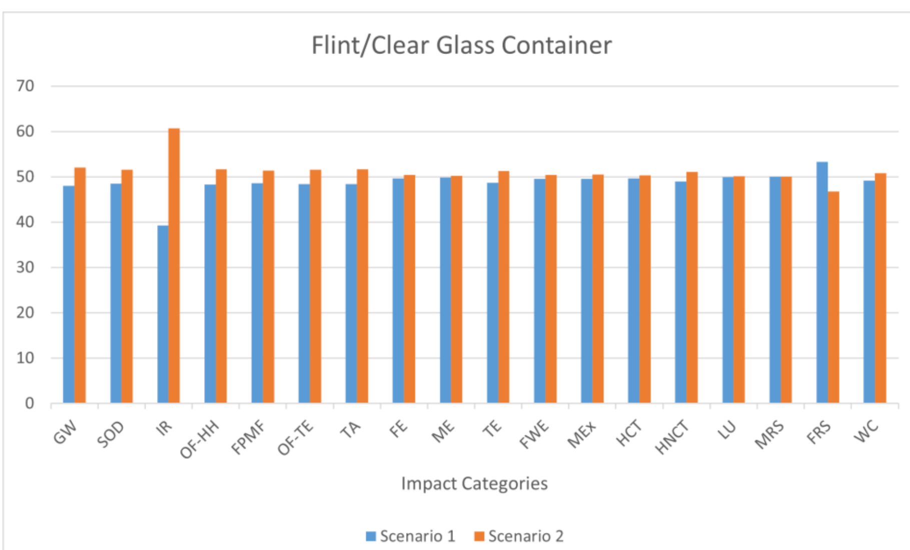

Figure 21: Comparison of impacts of both scenario for flint glass packaging

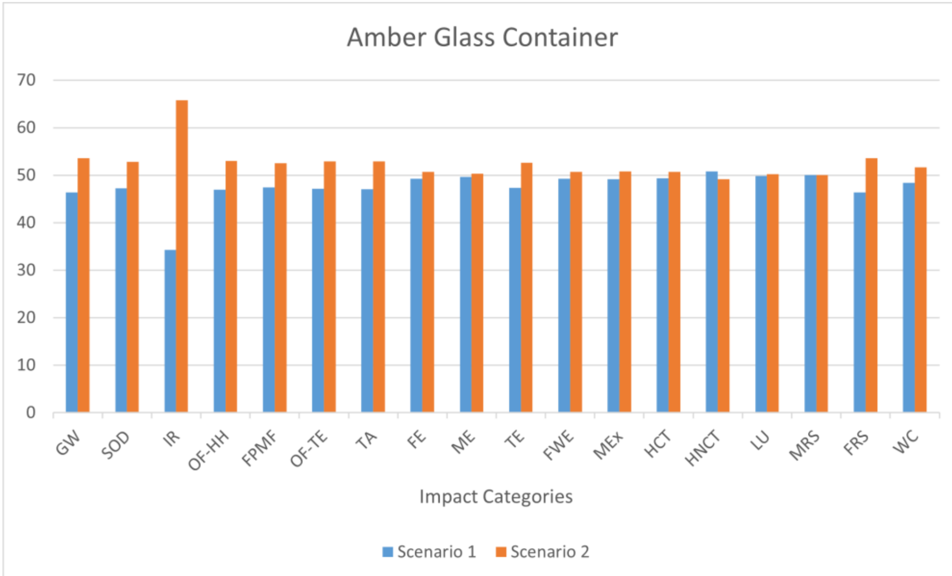

Figure 22: Comparison of impacts of both scenarios for amber glass packaging

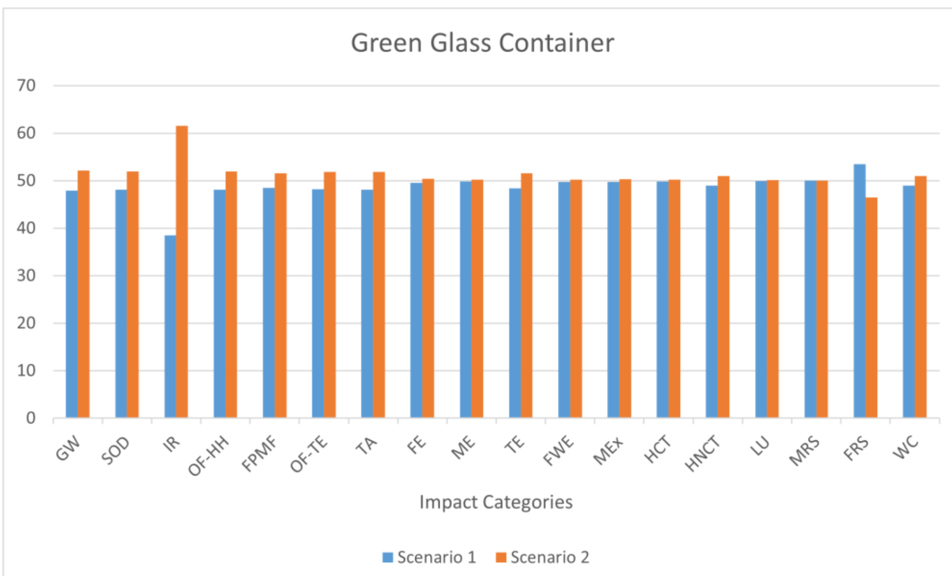

Figure 23: Comparison of impacts of both scenarios for green glass packaging

The emissions to air were also evaluated for the baseline and alternative scenarios for all three glass packaging solutions in order to further study and see the impacts, particularly the GHG, such as CO2, CH4, etc. The findings demonstrated that when electricity use was changed from the present combination to 100% national grid, CO2 emissions increased for all three types of glass. The amber glass saw the biggest rise (20%) and the flint glass saw the lowest increase (about 10%). The CO2 rise for green glass was 13%. The emission of N2O increased for all types of glass; it was 13% for amber, 7.1% for flint, and roughly 9% for green glass packing. Contrarily, when the energy supply was switched to the national grid, the emissions of CH4 decreased by 22% for green glass, 23% for flint, and 31% for amber glass. Overall, the emission of various elements, including CF4, C2F6, CO, etc., was either constant or barely varied. The amount of air emissions, particularly of GHGs, has always been of interest. These findings may therefore have significant ramifications for estimating total GHG emissions and making decisions about improving the energy mix at the plant and on a national level. The numerical values for the airborne emissions for both scenarios are presented in table 8 and figure 24, 25, and 26 gives us visual demonstration of their comparison.

Table 8: Numerical values of the airborne emissions for both scenarios

Emission To Air	Unit	Numerical Values					
		Scenario 1			Scenario 2		
		Amber Glass	Flint Glass	Green Glass	Amber Glass	Flint Glass	Green Glass
CO_2	kg	1050	1030	1060	1260	1130	1200
CH_4	kg	2.17	1.73	1.89	1.49	1.34	1.47
N_2O	kg	3.56	3.34	3.54	4.03	3.58	3.84
CCl_2F_2	mg	2.82	2.82	3.21	2.83	2.82	3.21
$CHClF_2$	mg	27.4	23.3	25.5	21.4	20.3	21.8
CF_4	mg	74.5	74.9	76.2	75.5	75.5	76.8
C_2F_6	mg	6.61	6.66	6.74	6.67	6.69	6.78
SF_6	mg	24.8	24.4	25.3	24.7	24.4	25.3
NF_3	mg	6.34×10^{-4}	6.33×10^{-4}	6.43×10^{-4}	6.35×10^{-4}	6.34×10^{-4}	6.43×10^{-4}
O_3	kg	0.0317	0.0314	0.0315	0.0338	0.0325	0.0328
SO_2	kg	5.05	4.76	4.94	5.7	5.09	5.34
CO	kg	1.05	1.01	1.05	1.07	1.02	1.07

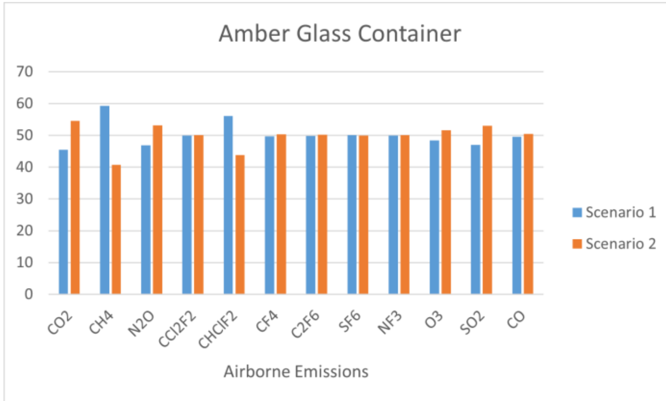

Figure 24: Comparison of emissions of both scenarios for amber glass packaging

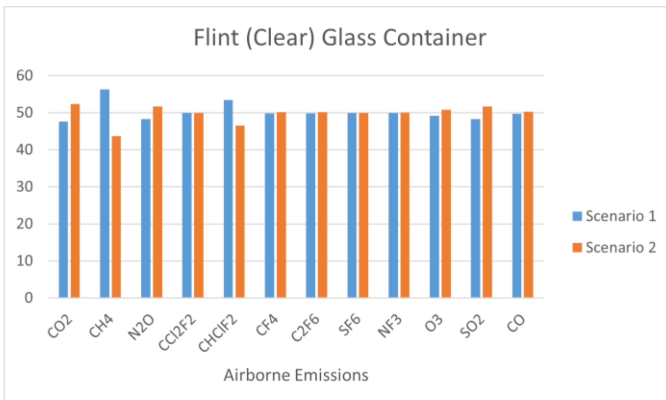

Figure 25: Comparison of emissions of both scenarios for flint glass packaging

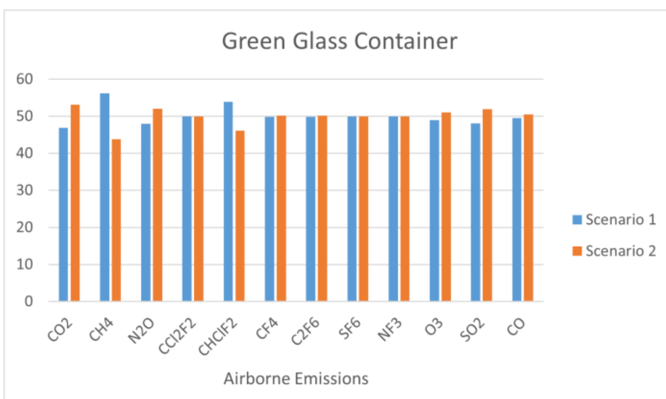

Figure 26: Comparison of emissions of both scenarios for green glass packaging

Table 9: Cost related to electricity sources for different scenarios.

Glass Type	Cost of Energy Consumption in PKR		
	Baseline Scenario	Electricity from Grid	Electricity On-Site
Container Glass	6929	13915	4966

Table 9 shows the numerical illustration of the costs associated with utilizing electricity from various sources. If the current situation at the target is replaced with an alternate scenario in which all energy utilized is from Pakistan's national grid station, not only would the environmental impacts increase, but the cost per ton of glass will also double from PKR 6929 to PKR 13915. On the other hand, if all of the required electricity is generated on-site, not only are the environmental consequences avoided, but the associated costs are lowered by about 28%.

5.4 Alternative Scenarios based on different cullet ratio

In order to compare the impact of changing the cullet ratio at the start of the whole production process the recycling scenario was created for flint glass. The scope of the analysis has also changed slightly because of the inclusion of recycling, whereas transport, use phase, and the collection of glass was still not considered for the analysis because of the involvement of several other parties. Energy and material consumed during the recycling process i.e., washing, crushing of glass into small pieces was acquired from the Ecoinvent databases because this process was separate from all the processes in the target industry. The results were compared for three alternate scenarios for the flint (clear) glass. The first scenario is the baseline scenario in which the cullet percentage is 57%. The two alternate scenarios were using 40% (first alternative scenario), and 70% cullet (second alternative scenario) as raw materials. It was assumed that the energy required for melting the raw materials is same for every cullet ratio. The numerical values for all 18 midpoint impact categories for flint glass against the three alternative scenarios are presented in table 8. The results showed that by increasing the recycled glass as raw material the environmental impacts decrease significantly. In terms of GW the baseline scenario had almost 5% less impact as compared to the first alternative scenario, whereas the second alternative scenario had almost 6% less impacts that the baseline scenario. The major difference can be spotted for the MRS and WC categories as for both of these categories the impacts for the second alternative scenario i.e., using 70% glass cullet as raw material had almost 24% less impacts than that of first alternative scenario. Figure 27 gives us visual comparison of different cullet ratios.

Table 10: Impact Score for Different Cullet Ratio

Impact Category	Unit	Cullet Ratios			Percent Change from Baseline Scenario	
		57% Cullet	40% Cullet	70% Cullet	40% Cullet	70% Cullet
GW	kg CO2 eq	917.92183	965.99888	868.21576	+5.2%	-5.4%
SOD	kg CFC11 eq	0.000329755	0.000400298	0.000259504	+21.4%	-21.3%
IR	kBq Co-60 eq	10.331828	12.362174	8.4339728	+19.6%	-18.4%
OF-HH	kg NOx eq	2.8218763	2.961003	2.6834901	+4.9%	-4.9%
FPMF	kg PM2.5 eq	1.8875148	1.9875304	1.8029016	+5.3%	-4.5%
OF-TE	kg NOx eq	2.8486618	2.9903981	2.7063614	+5%	-5%
TA	kg SO2 eq	5.3393123	5.623656	5.1199581	+5.3%	-4.1%
FE	kg P eq	0.059584771	0.076237635	0.046131326	+28%	-22.6%
ME	kg N eq	0.015496078	0.017908448	0.013439157	+15.6%	-13.2%
TE	kg 1,4-DCB	1154.9467	1321.3668	1021.0198	+14.4%	-11.6%
FWE	kg 1,4-DCB	20.542983	24.179195	17.922758	+17.7%	-12.7%
MEx	kg 1,4-DCB	26.916971	31.674567	23.468171	+17.7%	-12.8%
HCT	kg 1,4-DCB	29.911024	35.103292	25.578011	+17.4%	-14.5%
HNCT	kg 1,4-DCB	435.93903	510.19235	380.48125	+17%	-12.7%
LU	m2a crop eq	51.869208	57.527005	48.254214	+10.9%	-7%
MRS	kg Cu eq	2.5645276	3.2862385	1.8356518	+28.1%	-28.4%
FRS	kg oil eq	182.33704	195.86492	163.43001	+7.4%	-10.4%
WC	m3	3.2897309	4.4213419	2.475503	+34.4%	-24.7%

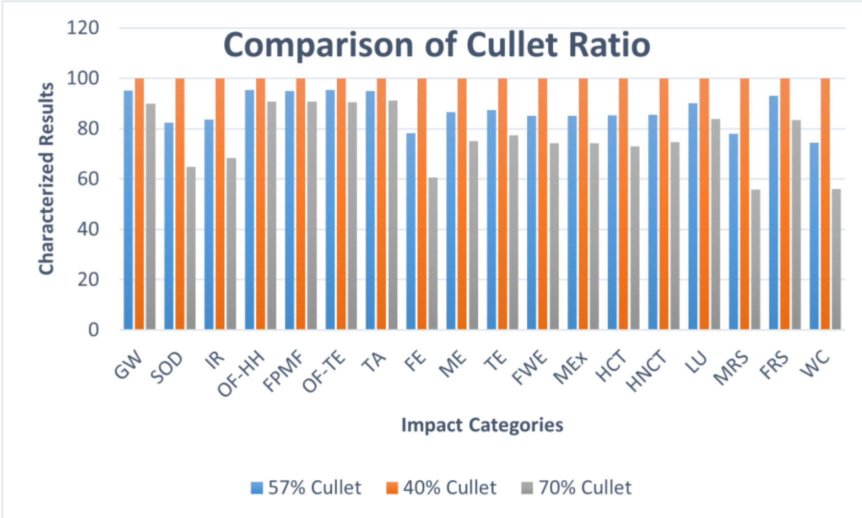

Figure 27: Comparison of Different Cullet Ratio

In order to get complete idea of the effect of changing the cullet ratio on the overall environmental impacts further analysis was carried out to illustrate the trend in the GW impact category by using different cullet ratios as raw materials. These ratios were selected as 40%, 50%, 57%, 65%, and 70% of the total raw materials. The global warming potential scores are presented in figure 28.

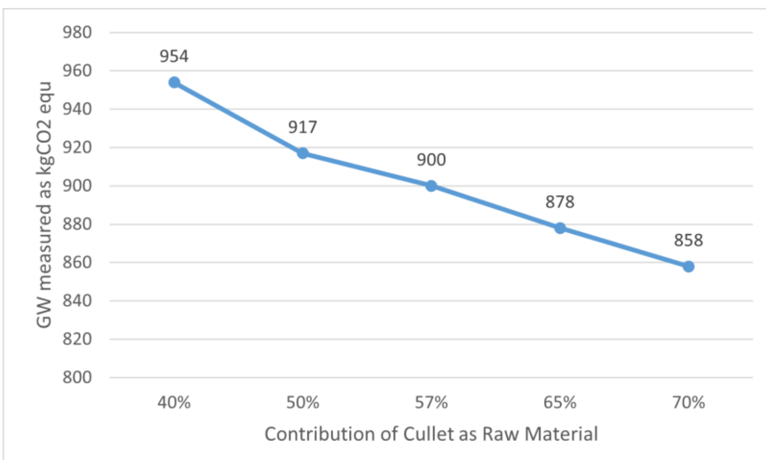

Figure 28: Trend in GW score against different cullet percentages

From figure 28 it is clearly visible that increasing the recycled glass as raw material will result in the reduction of GW score, and the overall trends is almost linear downwards when we increase the cullet ratio from 40% of total raw materials to 70%.

As a result, raising the cullet ratio as a raw material yields numerous benefits in terms of lower GW, energy savings, and reduced extraction of virgin raw materials. In theory, glass can be created entirely from cullet, but in practice, various constraints limit the ratio of glass cullet as raw material. Several defects in the glass occur as a result of contaminating inclusions within the cullet and can cause the glass container to fail at any point within the supply chain. Also the cullet can reduce the color consistency of the end product, hence depending upon the container color being produced, this has implications for the cullet use. Furthermore, due to increase in cullet process waste also increases and, in some cases, substandard products are not a proper fit for the intended purposes. Moreover, the availability or price fluctuation of sorted cullet has an impact on its utilization as a raw material in the production of glass containers [60].

Increasing the recycled glass not only decrease the environmental impact, but it also has economic benefits in terms of energy saving and little utilization of virgin raw materials.

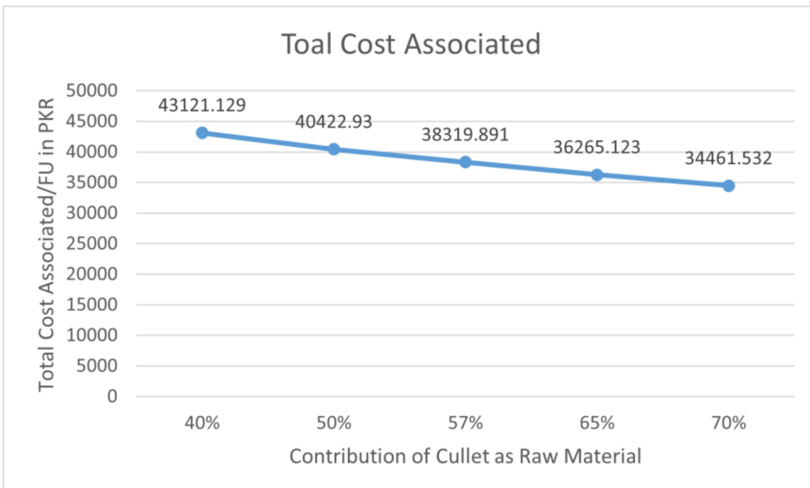

Figure 29: Total Cost Associated with Glass Production for different cullet ratio

Figure 29 gives us the illustration of total cost associated with the glass production while changing the recycled glass as raw material. In comparison with the scenario where 40% cullet is used as raw material, using 70% cullet will save almost PKR 8660. In case of baseline scenario if we change the cullet ratio to 70% then the cost associated can be reduced by almost 10% which is equal to a total of PKR 3858.

CHAPTER 6: IMPLICATIONS AND RECOMENDATIONS

As the first and only study to be based on the LCA of producing glass packaging solutions in Pakistan, it has a number of implications for all stakeholders, particularly for practitioners, decision-makers, and pertinent researchers.

The significant environmental hotspots were identified using the LCA data, comparative analysis of three glass kinds, and discussion based on different scenarios. The extraction and processing of raw materials, for instance, were discovered to be the major contributors to the environmental implications for all three forms of glass, and also increasing the recycled glass as raw material resulted in slightly lower environmental impacts. Additionally, the environmental effects of making clear glass were reduced when no additional chemicals or coloring agents were used. This obliquely implies two crucial findings. First, in order to manufacture glass packaging, practitioners and national level decision-makers must concentrate on recycling glass materials rather than using virgin resources. To do this, the government must encourage the development of a successful supply chain for the recycling of glass resources. Additionally, manufacturers and decision-makers should consider clear glass packaging for beverages rather than utilizing green glass for diverse beverage items, which has additional negative effects on the environment.

Additionally, this study evaluated the environmental effects based on the manufacturing plant's existing energy-mix (the baseline scenario) with a scenario in which all the energy is from national grid station. The outcomes showed that the alternative scenarios—which assumed that all electricity would come from the national grid—would have more negative effects on the environment. This discovery has several ramifications. First, the electricity produced at the glass manufacturing facility using gas and diesel was less polluting than electricity produced on the national grid. Therefore, from an environmental standpoint, such plants may continue to produce electricity to fulfil some of their energy needs. Second, instead of having coal-based power plants, the government and policymakers urgently need to increase the capacity of producing electricity using hydel and other renewable resources. Last but not least, this study can help researchers in related fields undertake comparable studies, particularly in underdeveloped nations. These studies may be carried out at other glass manufacturing facilities, the results could be compared to those from this study, and producers could be advised to make changes.

CHAPTER 7: CONCLUSIONS

The manufacturing sectors in developing nations use a lot of resources and produce a lot of pollutants that are very bad for the environment. However, there are very few studies that assess and examine the environmental impacts of manufacturing activities in developing countries, notably the manufacture of glass-based packaging, due to several technical and other limitations. In order to assess and compare the environmental effects of three alternative glass packaging options in a Pakistani company, this study carried out a cradle-to-gate LCA.

The first objective of this study was to collect and develop inventory data for glass manufacturing in Pakistan. Hence the primary input data was gathered from a Pakistani glass production facility located in one of the dedicated industrial zones, and secondary input data was gathered from the Ecoinvent databases. To develop the output inventory SimaPro V 9.2 was utilized for analysis using ReCiPe 2016 as an impact assessment method. The major output/emission notably the greenhouse gasses were also mapped and presented in this study.

ReCiPe 2016 method was also used to evaluate the environmental impacts associated with the glass manufacture in Pakistan, specifically with three different packaging solutions, at both midpoint and endpoint levels, using SimaPro as the software tool. The results at the midpoint level showed that various impact categories were most affected by the extraction of raw materials, followed by the glass production process, particularly the melting step. The analysis shows that, when compared, green glass was the worst packaging option, receiving higher scores at the midpoint for more impact categories. When compared to amber and flint glass varieties, the green glass had a greater influence on human health (the area of protection), according to the endpoint evaluation results. Furthermore, the cost associated with the production of amber glass bottles for pharmaceutical packaging is highest among the three, followed by green glass.

In order to find the appropriate solutions to reduce the environmental impacts associated with the glass manufacturing in Pakistan, alternative scenarios were created, and numerous implications were examined. These scenarios depicted that for better environmental performance on-site electricity production should be increased because the energy mix of Pakistan's national grid station had worst impacts because it heavily relies on the coal. In the GW impact category, it had nearly 15.4%, 8.4%, and 8.9% higher impact score in case Amber, Flint, and green glass, respectively. Furthermore, the cost of consuming all electricity from the Grid was double that of the baseline scenario. If all of the required electricity is generated on-site, the associated cost can be reduced by about 28%.

Secondly, the cullet ratio as a raw material should be increased as it reduces the use of virgin raw materials and overall impacts on the environment. If recycled glass is used as a raw material at a higher percentage than 57%, the environmental impacts for each category can be reduced, as reported approximately 5.4%, 21.3%, 18.4%, 22.6%, 28.4%, and 24.7% for the GW, SOD, IR, FE, MRS, and WC impact categories, respectively. Furthermore, the total cost associated with it will be lowered by nearly 10%, providing both environmental and economic benefits.

Overall, using flint (clear) glass without or with less coloring chemicals, using recycled resources rather than extracting virgin materials, and using a cleaner energy mix at the manufacturing facility might significantly reduce the environmental implications of glass packaging production in Pakistan, and will reduce the cost associated with the production process. Despite all of its significant ramifications, this study did not examine the end-of-life treatment of glass materials, and transportation throughout the whole supply chain.

FUTURE RESEARCH DIRECTIONS

1. This analysis is limited to a single glass sector in Pakistan. To acquire a better understanding of the environmental implications connected with glass manufacturing in Pakistan, the same research should be performed for additional glass industries situated in different parts of the country, with a different energy mix and recycling ratio.
2. The scope of this analysis was cradle-to-gate; hence it does not depict the effects associated with the entire life cycle of glass packaging solutions. As a result, it is recommended that the approach described in this study be further developed to examine the effects associated with the entire life cycle of glass packaging solutions, including the transportation and usage phases.
3. More research for the various scenarios mentioned in this study for glass sectors in other developing countries is needed to identify potential solutions for environmental sustainability.
4. More research is needed in the glass sector to compile and compare inventory data for different countries in order to discover input hotspots for different countries.
5. Developing countries such as Pakistan must adopt and apply LCA to other sectors such as cement, plastic, and steel, among others, applying methods created by other industrialized nations in order to examine and improve their respective environmental performance.

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