DEVELOPING A POLICY FRAMEWORK FOR THE DESIGN AND MANUFACTURE OF ENVIRONMENTALLY SUSTAINABLE FOOD PACKAGING

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DECLARATION OF THE CANDIDATE & SUPERVISOR

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ABSTRACT

Food packaging plays a vital role in human existence by eliminating barriers to satisfying food requirements regardless of geography. Since food is a basic requirement of all human beings, a billion-dollar industry has been developed surrounding the food supply chain. Providing protection against chemical (oxygen, moisture, carbon dioxide, etc.), physical (vibration and shock), and biological (insects, microorganisms) agents while facilitating the handling of food items in bulk or in appropriate portions for easy and efficient logistics are the primary requirements of food packaging. Concurrently, the adverse consequences of food packaging have caused higher resource consumption and waste generation. Food packaging contributes to significant plastic waste accumulated in landfills, open environments and oceans. Due to the high contribution to single-use plastic waste, organisations and nations are taking several actions to minimise the environmental burden caused by food packaging. However, limited efforts are being made to introduce systematic frameworks that could help packaging designers and policy developers to design and manufacture food packaging. This research focuses on proposing a policy framework for designing and manufacturing food packaging that oversees the triple bottom line of sustainability; environmental, economic, and social. The initial phase of the study identifies the considerations in the development of food packaging concerning rigid packaging and how sustainability could be numerically represented as a decision support tool. Multiple methods, such as public surveys, questionnaires, and focus group interviews, were used for data collection. Then, Quality Function Deployment (QFD) was used to analyse the data to identify the prioritised set of design considerations. Based on the analysis, different designs were developed and evaluated to identify the product characteristics that would influence the sustainability of food packaging. The next phase focused on developing a policy framework using the results of the from the analysis of the case studies. The design science research (DSR) method was used to develop the framework combining different food packaging aspects and graphically representing them in a diagram. The main outcome of this research is the policy framework for designing and manufacturing food packaging that integrates the three main aspects of food packaging. The proposed framework was modified and validated with expert insight, adding credibility to the research outcome.

DEDICATION

To my lovely family, who gave their best to me,

To my wife, who was with me through thin and thick,

and specially,

To all the Sri Lankans for their contribution to free education.

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LIST OF ABBREVIATIONS

AHP	Analytical Hierarchy Process
APCO	Australian Packaging Covenant Organization
DSR	Design Science Research
EoL	End-of-Life
FEA	Finite Element Analysis
FLW	Food Losses and Waste
FP	Food Packaging
FW	Food Waste
GDP	Gross Domestic Products
GHG	Green House Gas
GVW	Gross Vehicle Weight
HDPE	High-Density Polyethylene
HOQ	House of Quality
IML	In Mould Labelling
IOSP	Intelligent or Smart Packaging
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LF	Load Factor
PET	Polyethylene Terephthalate
PI	Performance Indicators
PIQET	Packaging Impact Quick Evaluation Tool
QFD	Quality Function Deployment
SPA	Sustainable Packaging Alliance
SPC	Sustainable Packaging Coalition
TBL	Triple bottom line
UN	United Nations

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1. INTRODUCTION

This chapter presents the background of the research and discusses the basics of food packaging (FP). The problems identified with the existing practices and possible actions for incorporating sustainability into local industries are also discussed. Considering the industry context, the aim and objectives are defined at the end of this chapter.

1.1. Research Background

Plastic pollution is becoming a significant issue in today's world, rendering threats to all living beings on Earth [1], [2]. Out of 6300 million tons of plastic waste produced in 2015, 79% has accumulated in landfills or leaked into the environment, threatening the living beings on land [3]. Beyond that, more than 5 trillion plastic pieces weighing over 250,000 tons are generating microplastics through fragmentation, threatening marine life [4], [5]. The widespread use, long half-life, and single-use nature are the key factors that increase the impact of plastics [6]. An exponential growth in pollution is expected in the coming decades, with the low degradation rate and the high production rate of plastics [7]–[9]. In Sri Lanka alone, 2.15 million metric tons of plastic are mismanaged yearly [10]. 80% of the western coastal area is polluted with plastics [11]. However, the amount of microplastics found in the southern coastal area is less than in other countries with similar per capita Gross Domestic Product (GDP) [12]. Therefore, authorities are exploring plastic pollution sources and seeking immediate action to narrow them down.

Food packaging is a leading contributor to plastic pollution, utilizing nearly 42% of the global plastic produced, over 141 million tons per year [13]. Additionally, the market size of over 478 billion USD shows the higher economic significance of the food packaging industry [14]. Plastic has favourable properties for food packaging, such as low cost, lightweight, high versatility, transparency, heat sealability, flexibility, and good mechanical and barrier properties [15]. Therefore, the possibility of replacing plastic with an alternative material with low pollution potential is futile. Additionally, plastic packaging may be eco-friendly compared to other materials in some instances [16]. On the contrary, substituting consumer plastic products with other materials may result in a net increase in environmental burden [9].

The pollution caused by the waste stream of food packaging is an obvious and apparent mode of pollution. The improper waste handling methods and unorganized reverse supply chain are the main reasons for the reprehensible pile of waste. Simultaneously, the design phase is highly influential in mobilizing the waste stream. Therefore, the design phase and waste stream management should be paid attention. Reducing material utilization is an apparent technique for reducing the environmental impact from the waste stream and manufacturing phase. However, food waste may increase significantly due to inadequate protection under extreme material reduction [17]. The increased food waste will escalate the overall environmental burden, which is highly undesirable.

As per the above discussion, the sustainability of FP is interconnected with multiple parameters influencing environmental impact in multiple life cycle phases. Additionally, these parameters may affect other key concerns such as consumer satisfaction, financial feasibility, and requirements of food content. Therefore, food packaging design needs holistic design thinking aggregating multiple criteria for improving the utility of food packaging while minimizing the environmental impact. As a result, sustainability concepts are being adapted into the FP industry with life cycle thinking for balancing utility and environmental burden.

1.2. Problem definition

Improving the sustainability of FP is a broadly discussed topic in literature. Adapting the circular economy principle is a main strategy for improving the sustainability of food packaging [18]. Material usage reduction through thickening the walls and adding structural elements are discussed in the literature [19]–[21]. For flexible packaging, the layer thickness has been reduced with multiple attempts [22]. Therefore, only limited measures could further reduce the material utilization with the existing technologies. Reuse is the next measure taken in terms of environmental sustainability which has certain limitations related to hygiene due to food residue contamination [23]. Even though glass containers are much easier to clean, the higher resource and energy consumption at the production and transportation phases is a main concern [24]. Recycling is highly discussed as a way of retaining the value of the material within the economy [85]. However, the difficulties in separating materials in multilayer FP, contamination of food residues, and infrastructure needed for collection, cleaning, and reprocessing limit the ability of recycling [25]–[28]. This concludes that the sustainability aspect is thought of in research incorporating circular economy within the current techno sphere up to a satisfactory level. However, some areas need to be well thought out to improve the environmental sustainability of FP. After an initial literature review, the following research gaps were identified.

1. A policy framework to bring the insights of multiple stakeholders for the design of sustainable food packaging was absent.
2. The influence of the occupied packaging volume on the environmental impact during transportation has not been mathematically modelled.
3. An assessment methodology for integrating the three key areas of sustainability of food packaging, environmental impact, functional satisfaction, and cost, was absent.

The aim and objectives were set as follows to address these research gaps.

1.3. Research aim, objectives and scope

The research aim is to develop a policy framework for the design and manufacture of sustainable food packaging. To align with the aim, five objectives were set as follows.

1. **To establish the current knowledge of food packaging technologies, policies, and practices.**

   The first objective is to identify state-of-the-art of food packaging. Additionally, authoritarian interferences are to be examined to identify the areas that should be improved for sustainability.

2. **To identify the design considerations of mostly used food packaging.**

   A set of food packaging is to be identified for further analysis based on its relevance to the study. Then, the existing design concerns are to be identified for further analysis.

3. **To conduct an environmental performance analysis of selected categories of food packaging.**

   Different packaging options are developed following a systematic design approach. Then the developed packaging options are to be analyzed based on sustainability criteria for identifying the ill-concerned aspects that could be addressed to improve sustainability.

4. **To develop a policy framework for food packaging to yield improved environmental performance while adhering to other relevant design and manufacturing considerations.**

   A framework is to be developed for guiding packaging designers and policy developers in integrating sustainability aspects in food packaging while taking insights from the analysis conducted under previous objectives.

5. **To validate the policy framework for intended environmental and other benefits.**

The developed framework is to be validated for improving recognition among the scientific community.

Research scope

Among the two types of food packaging, rigid and flexible, the study was limited to rigid food packaging. As a result of the structural integrity, rigid packaging are expected to have multiple functional attributes compared to flexible packaging. Therefore, the generalisability of rigid packaging study is higher than that of flexible packaging. Even though the number of flexible packaging units used are higher than rigid packaging, the resource consumption of a single rigid packaging is extreme to that of flexible packaging. Thus, the study of rigid packaging becomes significant when comparing resource intensity. Additionally, the number of publications that have considered the sustainability aspect of rigid FP is lower, opening up the gap for further studies. Considering all factors, the scope for case studies was narrowed down to rigid plastic food packaging.

Within rigid packaging, this thesis focuses on primary packaging, which has a higher level of utility and functionality. The assessment of the sustainability of other packaging levels (secondary, tertiary) is not included since there is more evidence in the literature. Improving the design of the primary food packaging is the main focus of this study. Structural integrity and compliance with the existing rules and regulations were considered for the case studies. Further, the adaption of measures to reduce the environmental impact of FP is discussed descriptively. Packaging-related food losses and waste is another factor that influence the environmental impact. However, the amount of food waste from each packaging option was not estimated due to the unavailability of data.

1.4. Research deliverables

The proposed framework, the main deliverables of the research, will assist the decision-making for the design and development of food packaging while adapting sustainability concepts into it. The framework could be a design-supportive guideline for packaging designers to direct the design process. Besides the sustainability aspect, the framework covers the consumer preference aspects that must be considered when designing FP. The developed food packaging designs are expected to perform better regarding environmental and financial sustainability and consumer preference.

The guidance provided for policy development is another long-term outcome of the proposed framework. There are advanced techniques practised in the food supply chain by international organizations which could be adapted to the local context. The proposed framework provides a clear image of the areas which should be strengthened in future policy development. The framework has been proposed in a modular structure with higher flexibility to accommodate these changes.

Aggregating the three main aspects of FP sustainability was another research outcome. Environmental impact, economic viability, and social well-being are the three parameters considered in developing the sustainability index. The proposed methodology assesses three parameters separately for each design option and integrates the values to get a single index for sustainability easing the decision-making process.

Above all, the research outcome expects to reduce the environmental impact induced by food packaging while improving consumer satisfaction through functional fulfilment. The short-term outcomes focus on assisting packaging designers in uncovering obscured areas in the design process. Additionally, the policy implications are expected to enhance sustainability on a long-term basis.

1.5. Thesis structure

The first chapter lays the foundation for this research. The first section of the chapter discusses the level of environmental impact caused by plastic and its contribution to food packaging. The main problems identified with the existing FP design practices and research gaps are discussed. Finally, the aim and objective that will guide the research in the following chapters are elaborated.

The second chapter was dedicated to the literature review. The technologies, the available body of knowledge, and the organizational initiatives for improving the sustainability of food packaging are elaborated. The next sections review the parameters used in assessing the sustainability of food packaging and relevant publications on the topic. Then, the measures taken to minimize the environmental impact are discussed. Finally, the applicable policy interference in making packaging sustainable and the reviewed research gaps are mentioned.

The third chapter is dedicated to the methodology. The sections combine methodology literature and how they could be adapted into this study. The development of different FP designs is discussed in detail. The last two sections of the third chapter discuss the methodology followed in developing and validating the policy framework.

The fourth chapter focuses on the analysis of the study discussing how the case studies were conducted following the methodology described in the third chapter. The values obtained under the three sustainability parameters for the two case studies are elaborated in Section 4.1 and 4.2 The final section discusses the insights from case studies that guided the policy framework's development.

Chapter 5 discusses the elements and validity of the proposed framework, which is the study's outcome. Section 5.1 presents the proposed framework and how it has addressed the identified research gaps. The following section discusses and justifies the validity of the research outcome. Chapter 6 concludes the study by summarizing the study and providing directions for future research.

Figure 1.1 illustrates the thesis structure and how each objective is fulfilled in the relevant chapters.

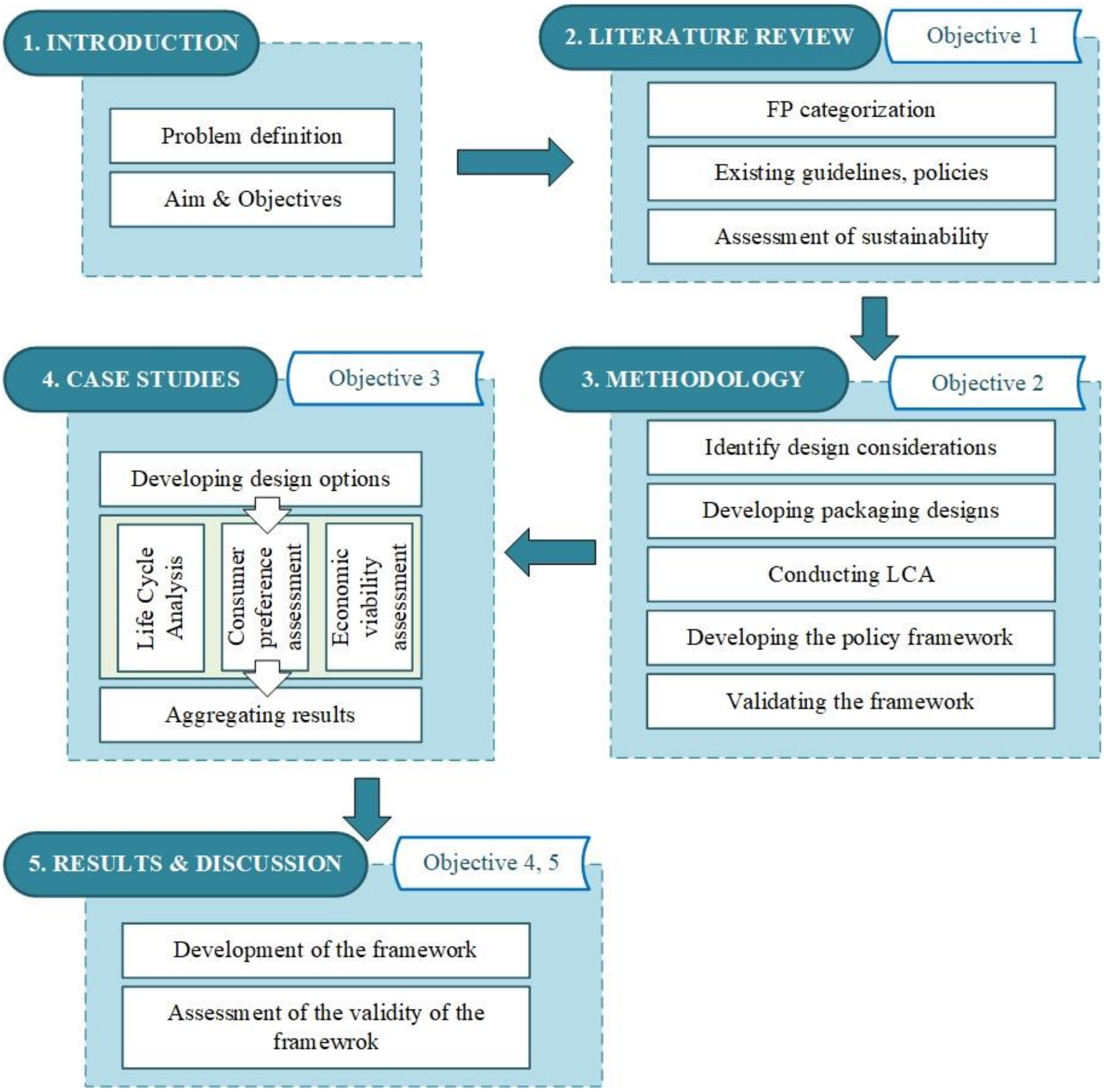


Figure 1.1: Organization of objectives with thesis structure

2. LITERATURE REVIEW

This chapter reviews the available articles that have focused on improving the sustainable aspect of food packaging. This chapter aims to identify the current body of knowledge and existing gaps through a literature review. Approximately 60 articles were reviewed discussing sustainability-related food packaging topics from 2000-2022. In addition, prevailing standards, policies, and guidelines for food packaging are also examined.

2.1. Introduction to sustainable packaging

Sustainability is defined as *"meeting the needs of the present without compromising the ability of future generations to meet their own needs"* [29]. Sustainability encompasses three different entities; environmental, social, and economic, which is known as the triple bottom line (TBL) [30], [31]. The following sections discuss the definitions of sustainable packaging, considering one or more aspects of TBL.

1. Definition by Sustainable Packaging Coalition

Sustainable Packaging Coalition (SPC) has defined sustainable packaging adhering to sustainability and industrial ecology objectives, business considerations, and strategies. The entire value chain of food packaging has been considered while seeking innovations for optimization. The definition describes the actions that relevant stakeholders could take to improve the sustainability aspect of packaging. Concerning all these facts, SPC has defined sustainable packaging as follows [32].

1. Beneficial, safe & healthy for individuals and communities throughout its life cycle
2. Meets market criteria for performance and cost
3. Is sourced, manufactured, transported, and recycled using renewable energy
4. Optimizes the use of renewable or recycled source materials
5. Is manufactured using clean production technologies and best practices
6. Is made from materials healthy throughout the life cycle
7. Is physically designed to optimize materials and energy
8. Is effectively recovered and utilized in biological and/or industrial closed-loop cycles

2. Definition by Sustainable Packaging Alliance (SPA)

SPA has defined the sustainability of packaging considering the social, economic, and functional aspects [33]. The sustainability of packaging has been defined in four levels under specific principles. This approach has addressed packaging attributes' social and environmental impacts as shown in Table 2.1.

Table 2.1: SPA's definition of sustainable packaging

Level	Principle
Society	Effective- adds economic and social value
Packaging system	Efficient-minimum use of material and energy
Packaging material	Cyclic- use of recyclable or compostable materials
Packaging component	State- nontoxic to humans and ecosystems

2.2. Food packaging categorisation and classification

Food products and packaging have been categorised for analytical purposes based on their utility, structural rigidity, and material, as discussed in the following sections [34], [35].

2.2.1 Classification based on packaging level

Food packaging is primarily categorised into four groups; primary packaging, secondary packaging, tertiary packaging, and unit load [36]. Given below are the general definitions available in publications.

1. Primary packaging

The package directly contacting the food product or product atmosphere is known as the primary package [36], [37]. In some other studies, it has been referred to as the sales unit handed over to the consumer [38]. The polymer bag contains biscuits, the inner bag of the cereal box, and the paper envelope of a tea bag are some examples of primary packages.

2. Secondary packaging

Secondary packaging or the distribution unit consists of two or more primary packaging. The main purpose is to protect the primary packaging against dirt and contaminants from soiling [36]. Additionally, the secondary packaging makes it easy to deliver primary packages by serving as a distribution unit by stockpiling the primary packages together.

3. Tertiary packaging

A tertiary package is a group of secondary packaging [39]. It may contain several primary or secondary packages. In some applications, this is known to be a "distribution package" whose primary function is to protect the product during distribution and assist in product handling.

4. Unit load

A unit load is an assembly of tertiary packaging. If the tertiary packaging is a corrugated box, several corrugated boxes are placed on a pallet and wrapped using a plastic film for easy handling, shipping, and storage. Generally, forklifts or similar equipment handle these unit loads [36].

2.2.2 Categorisation by ISO

ISO has categorised food packaging based on its structural rigidity. The "packaging whose shape remains essentially unchanged after the contents are added or removed" is known as rigid packaging according to ISO 21067-1:2016 (E) [40]. Different types of rigid packaging are given in Figure 2.1.

Figure 2.1: Rigid food packaging [41]

ISO defines flexible packaging as "whose shape is likely to change after the contents are added or removed" [40]. Flexible packaging is the most commonly used food packaging type in almost every region in the world (approx. 62% of the entire packaging industry [refer to Figure 3.2]) [42]. The main reasons for the high market share are the ability to acquire preferred barrier properties and low cost [43]–[45].

Figure 2.2: Flexible food packaging [46]

The different levels of FP could be either rigid, flexible, or semiflexible. Figure 2.3 illustrates different materials used and types of packaging according to ISO categorisation.

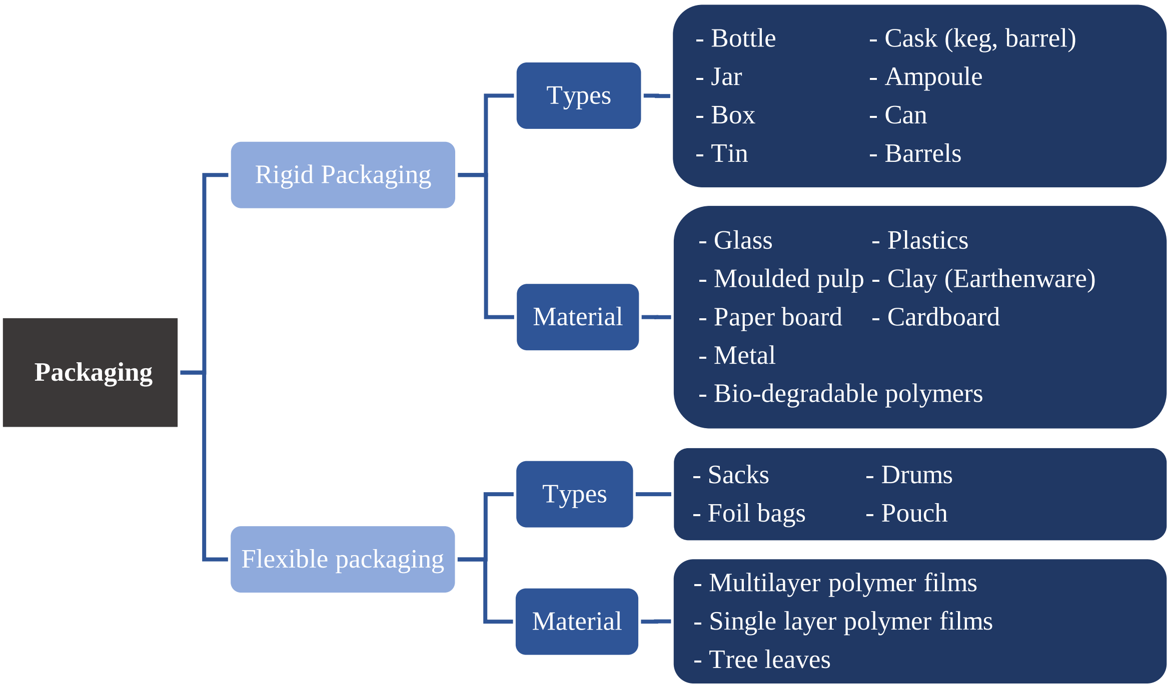


Figure 2.3: Food packaging categorization

2.3. Evidence of packaging initiations for sustainability

Organizations, countries, and communities have taken multiple measures to improve environmental sustainability. The following sections discuss the different remedies taken by them.

2.3.1 Initiations by packaging organizations

There are multiple organizations focused on guiding for improving the sustainability aspect of food packaging. SPC and Sustainable Packaging Alliance (SPA) were identified as organizations among many other institutions that integrate sustainability into packaging. Furthermore, the Australian Packaging Covenant Organization (APCO) focuses on providing guidelines for measuring the sustainability of packaging. Table 2.2 provides an introduction and the measures taken. The last column discusses the gaps that need improvement in research. The International Standards Organization (ISO) and other local authorities have focused on the health and safety concerns that must be considered in food packaging as given in Table 2.2

Table 2.2: Organizations for improving the sustainability of packaging

	Introduction	**Initiatives for Sustainability**	**Room for Improvement**
SPC [47], [48]	The organization is a membership-based collaborative that tries to make packaging more sustainable.	• Has defined sustainable packaging as discussed in Section 1 • Multiple projects are initiated to promote sustainable packaging 1. How2Recycle 2. How2Compost 3. GreenBlue Navigate	The guidelines have not highlighted policy implementation in the packaging design phase.
APCO [49], [50]	The vision is to develop a value chain that keeps packaging materials out of landfill and retains the maximum value of the country's material, energy, and labour.	• Has defined five steps for the stakeholders to improve the sustainability aspect of food packaging 1. Establish the case for improving the sustainability of the business' packaging 2. Determine what packaging is currently used across the business and its EoL 3. Identify options for improvements 4. Implement sustainable packaging initiatives 5. Track and review the progress • Initiatives from the organization 1. Introducing national sustainable targets for packaging 2. Educating people on the plastic recycling market	Measures for improving sustainability during the design phase

		3. Introducing recyclable labels for packaging	
SPA [51], [52]	Aims to arm businesses with the knowledge, tools, and skills to make informed packaging sustainability decisions that generate commercial and sustainability benefits	• Has defined KPI for the sustainability of packaging, 1. Being effective in satisfying the requirement, 2. Efficient to minimize material usage, energy, and water consumption 3. Cyclic to generate minimum waste 4. Ensuring safety • Provides an online tool to evaluate the environmental sustainability of packaging known as Packaging Impact Quick Evaluation Tool (PIQET)*	More focused on measuring sustainability instead of introducing measures for improving sustainability

* SPA is the distributor of the Packaging Impact Quick Evaluation Tool (PIQET), an online tool focused on streamlined life cycle assessment evaluating the environmental and economic aspects of packaging. However, the consumer perception has not been taken into account.

2.3.2 Food Packaging policies- local context

The underperforming waste management policy in Sri Lanka has the potential to shape its practices into a more sustainable approach. Several constructive guidelines and policies were introduced by regulatory bodies during the past few years, such as banning lunch sheets and polythene of less than 20 microns and lunch boxes made of expanded polystyrene [53], [54]. The local plastic recycling rate is closer to 30%, while the remaining is sent to landfill or leaked into the sea [55]. Thus, existing infrastructure should be developed to accommodate higher product recovery rates, including reverse supply chain, recycling, and energy recovery. Furthermore, the public should be persuaded to adhere to better waste disposal methods. In addition, developing and suggesting new packaging alternatives to increase the sustainability of existing food packaging could be identified as the foremost and prompt action that could be taken to reduce the overall impact of food packaging.

2.3.3 Related policies in the rest of the world and other national-level interferences

The European Community has introduced measures to minimize the environmental impact caused by the food packaging system. The policies are structured so that most of their responsibilities are distributed to the consumers and users to increase the effectiveness of the circular economy [56].

‘Polluter pays’ policy is followed by many countries where the costs incurred in waste management are borne by the waste producer or the waste holders [57], [58]. Belgium has introduced a tax of EUR 3.6 per *kg* of disposable cutlery on the market to minimize the waste generated [9]. In addition, there are similar taxing policies enforced by Belgium, France, Ireland, Portugal, the UK, and several other cities in the USA on single-use plastic bags [9].

Several researchers have suggested preventive measures to increase environmental sustainability besides taxing policies. Raman Sharma et al. [8] have elaborated a guideline to be followed by product purchasers for reducing the environmental impact of food and beverage packaging. On behalf of a holistic approach, this guideline provides more specific aspects which are understandable and followable even by the general public. The study proposes a list of products to be avoided and alternatives that could eliminate the environmental impact of food packaging from the customer’s perspective.

The Netherlands was identified as a country where policies have been introduced to overcome the challenges faced by the food packaging industry through extensive research. The policies extend their scope through various packaging life cycle stages, including material selection, material reduction, increasing recyclability, and waste management [59]. Even under a well-developed regulatory guideline, it has been identified that the policies are not sufficient for a transition towards the circular economy.

2.4. Factors affecting the sustainability of food packaging

The characteristics of FP influence different areas of sustainability of FP. Studies have identified the factors that are influential to the three critical areas of sustainability. The influence has been assessed using different performance indicators. The following sections will discuss the factors that are influential to each area of sustainability. Furthermore, the studies that have considered more than one parameter in assessing sustainability are elaborated in the last sub-section.

2.4.1 Factors related to the environment

The influence of the material type and quantity has been analysed in multiple studies. Results have shown that glass bottles have the highest environmental impact, followed by PET (Polyethylene Terephthalate), HDPE (High-Density Polyethylene), multilayer cartons, and bioplastic bottles in a study conducted to estimate the environmental impact of milk packaging [60]. A study estimating the environmental impact of baby food packaging has shown similar results with lower environmental impact from plastic containers [61]. Besides, the material quantity is inherently related to the environmental impact due to its resource consumption [62]–[64].

The ability to reuse and the number of reuse cycles are other factors which affect the environmental impact [24], [65]. Despite the higher initial environmental impact, glass bottles have shown less environmental impact than single-use PET bottles after 7-9 refills [24]. However, reducing environmental impact may not be significant if the reverse supply chain and the cleaning process are considered [5]. Nonetheless, a significant reduction in the environmental impact could be seen if the packaging is reused [5].

Recycling reduces virgin material consumption and supplies raw materials to the economy. Reducing energy consumption in raw material production without harmful emissions during raw material transformation is one of the main advantages of recycling in terms of environmental sustainability [66]. However, recycling may not reduce the environmental impact under every scenario since it may carry burdens related to the collecting and recycling system [24]. Furthermore, the environmental benefit gained through recycling is governed by the impact of raw material production and the impact of recycling [24]. In the case of glass, the recycling process's impact is lower than that of raw material production. As a result, glass recycling is beneficial in terms of the environment [24]. Similar conclusions have been drawn in studies stating that using recycled aluminium would save 95% of energy consumption compared with raw materials [67]. Furthermore, for PET, it has been estimated that the recycling process consumes only 3% of the total energy consumed by raw material production [68]. Thus, recyclability could be identified as a factor influencing environmental sustainability.

The geographic location or the country of consideration is another factor that influences the environmental impact. Several studies have highlighted the higher environmental impact caused by glass food packaging irrespective of the country [38]. However, plastic containers for baby food show a higher energy consumption compared to glass containers for the Spanish market due to higher transportation distance [61]. In the same scenario, glass bottles have shown higher energy consumption when the German market is considered [61]. Thus, location-specific factors such as transportation distance and country-specific factors such as energy composition become crucial factors in determining the environmental impact.

Additionally, food losses and waste (FLW) is a key factor influencing FP's environmental impact. Furthermore, the impact of transportation is discussed in detail, considering the significance of the impact of transportation in this study.

1. Food Losses and Waste

The consideration of FLW depends on the level of impact caused by the food product. In certain circumstances, FLW could be minimized through an advanced packaging design with a higher environmental impact, hence reducing the overall impact of the food packaging system. Therefore, FLWs are not considered for food items with a lower environmental impact, such as fruits and vegetables, pasta, and chips [69]. Vice versa, there are products with a higher environmental impact, such as beef, pork, poultry, and dairy products (cheese, milk, butter), where the consideration of FLW is significant in assessing the overall environmental impact [70]. Therefore, it is necessary to consider the FLW when evaluating packaging designed for these types of products [71]. However, there are practical limitations in estimating the amount of FLW and its actual environmental impact, limiting the utility of FLW in life cycle analysis (LCA). Thus, the actions to minimize the FLW are highlighted instead of estimating the FLW and their impacts [72]–[74]. The use of intelligent packaging in the food supply chain has been identified as a method to minimize food waste [75]. Additionally, improving the functional requirements to increase the ergonomic aspect of food packaging is another measure suggested for reducing the FLW [17], [76].

Approximately 10% of studies have considered the indirect environmental impact caused by food losses and waste from food packaging. Even though several studies have been conducted on sustainable food packaging, only 10.5% of the research has included FLW while 10.5% have alluded to FLW and only 79% have not considered FLW [28]. Among the studies that have considered FLW, most of them have considered a fixed percentage of purchased food being discarded for different packaging options. Somehow, when it comes to comparing different packaging options, measuring the FLW by each option is necessary to evaluate the overall environmental burden caused [71]. Despite that, most of the research assumes that the amount of food wasted by each packaging option is equal [76], [77]. Therefore, the consideration of FLW has exaggerated the eco-impact of all packaging options instead of differentiating the eco-impact between packaging options.

2. Impact of Transportation

Transportation significantly impacts the results of LCA depending on the mode and distance of transportation [51], [61]. Almost all studies have used the model which calculates the environmental impact only based on the ton.kilometer value [2], [78]–[80]. However, this conventional model has not been able to encounter the impacts caused by the lorry itself. The impact of the empty lorry is 61% of the impact caused by the fully loaded lorry [69]. Therefore, the impact of the empty lorry needs to be shared among the number of units transported. If the number of units transported is higher, then the per-unit impact would be less and vice versa. Thus, the impact of a single packaging unit is influenced by the number of items loaded into a lorry. As a result, a product transported in a partially filled lorry would carry a much higher per unit environmental impact than a completely filled lorry. This degree of filling is a geometry-related concern and, therefore could be regulated to reduce the impact caused by transportation [20]. Somehow, the geometry-related aspect has not been considered in the available literature.

The average transportation distance of a product across the country is difficult to determine accurately [79]. The accuracy of the distance travelled would be a governing parameter if two separate supply chains were to be analysed [78]. Meanwhile, if the same transportation mode is considered for all packaging options, the distance travelled would be a parameter to compare the impact between transportation and other life cycle phases [78]. Several studies have disregarded the impact caused by transportation by limiting the system boundary up to production due to the unavailability or the uncertainty of data [81].

A study conducted to evaluate the greenhouse gas (GHG) emission by packaging films has calculated the distances for each transportation based on the distance from the origin of the raw material to the production plant [82]. The results have shown that transportation would cause 15% to 45% for the different case scenarios considered. A similar study has estimated that nearly 14% of the total energy demand is caused by transportation on a cradle-to-grave basis [52]. However, in reused food packaging, transportation in reverse logistics is the key factor in determining environmental performance [24]. The literature reveals different aspects that need to be considered in conducting an LCA for estimating the environmental burden caused by transporting food packaging.

2.4.2 Factors related to social sustainability

Socially sustainable related matters are a broadly discussed topic in studies. However, these topics could be considered under two main aspects as food safety and consumer satisfaction. Under consumer satisfaction, aesthetics and functional satisfaction are discussed.

The safety and hygiene of FP is highly regulated by authorities. ISO, the main organization for introducing regulations related to FP, has provided technical specifications focused on ensuring safety and hygiene [83]. The guidelines prevailing in the Netherlands have stated four basic requirements that need to be satisfied by food contact materials; not endangering human health, not unacceptably changing the composition of food, not changing taste or texture, and manufacturing according to good manufacturing practices [84]. The use of tamper-proofing techniques to avoid malicious tampering; and adding harmful substances into the packaging to damage the retailer or customer is highlighted for preventing food-related safety and hygiene issues [85]. The aforementioned are the main factors discussed in the literature that are directly related to the safety and hygiene of FP.

Aesthetic concerns such as shape and colour are the commonly used parameters for evaluating consumer preference [154], [155]. On the other hand, the aesthetic aspects of food packaging have been identified as a factor that consumers would not consider much in their purchase decisions [90]. Therefore, the functional satisfaction of food packaging has been used for evaluating consumer preference [26]. Additionally, studies have identified that functional satisfaction directly influences consumer preference, affecting the purchase decision [91], [92]. Beyond that, other factors such as eco-friendliness also would be influential in the purchasing decision [65], [93]. Therefore, functional satisfaction could be identified as a factor which is beneficial for the consumer and for the food producer. In general, containing food, protecting and maintaining taste, communicating veracious information, stocking, distributing, and winning the customer are the basic expected functionalities [20], [26], [38], [52]. These basic functional requirements have been further elaborated and categorised by several studies specifically to identify the actual functional demand from the stakeholders.

Food waste reduction is another aspect of social sustainability which aligns with the second sustainability goal (Zero Hunger) of the UN (United Nations) [94]. Multiple causes of food waste are not influenced by the FP. A significant portion of food waste is caused by the extra amount of food being cooked for the sake of emptying the container. Packaging with a smaller food content is encouraged to avoid food losses due to this phenomenon [72]–[74]. Easy to grip, open, dose, and reclose have been suggested as functional requirements to avoid food spillage by accidents [17]. Conveying correct information about food safety is another requirement since it would minimize food spoilage. Thus, functional attributes play a major role in minimizing food waste, which is a major concern under environmental and social sustainability.

2.4.3 Factors related to financial viability

The final decision for a product will be highly governed by the cost factor at the industrial level. Therefore, it is mandatory to consider the cost aspect when designing and developing food packaging. The use of cost as a decision support parameter has been discussed in multiple studies [95], [96]. Besides, there are only a few articles available suggesting a systematic method to incorporate the cost factor into decision-making in food packaging. Those studies are described in detail in Section 2.4.4 where the costs incurred have been combined with other parameters.

Material weight has been identified as influential to cost by several researchers [15]. The material reduction would reduce the direct cost of raw materials and the cost of production, followed by the next life cycle phases [97]. In addition to minimizing the material quantity, the use of lightweight materials for food packaging is a strategy to minimize the cost of transportation [95]. For example, among glass and HDPE, the use of HDPE, which has a lower weight, has been suggested to reduce transportation costs [97].

The cost of materials is another factor which determines the cost of the food supply chain. Biodegradable materials are less favourable for packaging manufacturers due to their higher cost [37], [91]. Instead of that, plastic materials are preferred due to the low costs of raw materials despite the issues associated with the waste stream [15]. Somehow, it is essential to find the balance point between the environmental and cost factors to develop packaging with a balanced compromise between these factors.

Above all, the marketing is a dominant factor in the food industry too [65]. However, the main focus of this study is not marketing as it is mainly focused on improving the environmental sustainability of FP. Even though, consumer preference, which is a direct marketing parameter, is taken into consideration through public questionnaires results of which are presented in Section xxx.

2.4.4 Evidence of collective assessment of the above indicators

Only a few studies have solely evaluated the environmental impact or consumer preference of food packaging. Some key publications that have discussed the sustainability aspects of packaging are summarized in Table 2.3. The first three columns indicate the performance indicators that have been considered under each area of sustainability. The publications that have considered different environmental impact indicators, such as global warming potential, energy consumption, etc., are denoted as ‘environmental impact’. Furthermore, circular economy indicators such as reusability and recyclability have been listed under ‘circularity indicators’. The publications that have discussed one or more functional attributes, such as product preservation and quality maintenance, reducing food waste, resealability, convenience of use, and other functional attributes, were denoted with ‘functional satisfaction’ under social sustainability. The column named ‘sustainability’ shows whether the measures for improving sustainability have been discussed in the publication. The last column identified the publications that have numerically evaluated or analyzed one or more sustainability parameters.

Table 2.3: Summary of the literature review

Article	Environmental sustainability	Social sustainability	Economic sustainability	Sustainability	Parametric Evaluation/ Analysis
[92]	• Recyclability	• Functional satisfaction			
[99]	• ISO standards • Environmental impact	• Functional satisfaction			
[26]	• Separability of materials • Presence of material marking	• Functional satisfaction			
[100]	• Easy to dispose • Produce min. waste • Prevent food waste	• Functional satisfaction			√
[16]		• Product quality • Ergonomic entity			√
[101]	• Circular economy indicators • Environmental impact	• Reducing food waste			
[60]	• Environmental impact	• Functional satisfaction			√
[24]	• Environmental impact			√	√
[102]	• Environmental impact			√	√
[51]	• Environmental impact			√	
[103]	• Environmental impact				√
[39]	• Environmental impact	• Functional satisfaction • User-friendliness	• Cost		

[82]	• Environmental impact				√
[104]	• Environmental impact • Recyclability	• Functional satisfaction			√
[105]	• Environmental impact • Recyclability	• Functional satisfaction			√
[32]	• Environmental impact • Circularity indicators	• Functional satisfaction	• Cost	√	
[106]	• Environmental impact • Circularity indicators	• Functional satisfaction			
[107]	• Environmental impact	• Functional satisfaction	• Cost		
[108]			• Cost		√
[27]	• Environmental impact • Circularity indicators	• Functional satisfaction	• Cost	√	

As per the above summary, there are studies that have evaluated environmental, social, and financial sustainability in isolation. However, there is no evidence that all three parameters have been considered collectively in the holistic decision-support framework for FP. This would support making more comprehensive decisions on sustainable packaging designs.

2.5. Incorporating sustainability measures into food packaging

Adapting the waste hierarchy to food packaging reduces the direct environmental impacts caused by food packaging and its waste stream. Minimizing the packaging attributed FLW is an approach for reducing the indirect environmental impact. This section discusses the implementation of waste hierarchy measures and how its outcomes have contributed to minimizing the environmental impact. In consideration of FLW, different reasons for FLW and the significance of minimizing them are discussed.

2.5.1 Reducing direct environmental impact through adapting the waste hierarchy into food packaging

The waste hierarchy in the 'European Commission's Waste Framework' is a concept which could be adopted to minimize the environmental impact by reducing waste generation and resource depletion [57]. The guideline has prioritised its phases to ensure a minimum amount of influence is accounted for on the environment. Waste prevention has been given priority in the EU directive while recycling and other recovery and disposal are followed in order, as shown in Figure 2.4 [57].

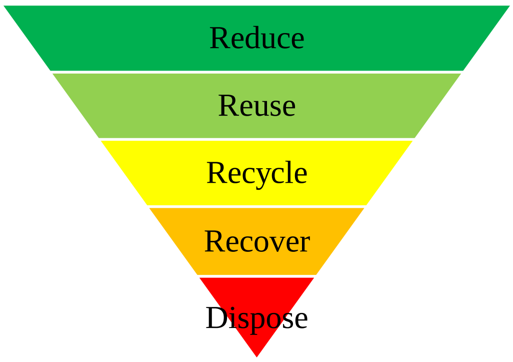


Figure 2.4: Waste hierarchy

Reduce

There are two aspects of reduction measures: food packaging material reduction, usage reduction, and food waste reduction. Material reduction is a foremost concern of packaging producers while usage reduction should be done by educating the public through awareness programmes and suitable design guidelines for packaging producers.

Reducing the amount of material used could be identified as one aspect of prevention which has shown significant results over the past few decades [18]. This would result in several incidental advantages such as; the reduction in energy consumption for manufacturing and transportation, the reduction in waste, and the cost of manufacturing [63], [64]. The weight reduction achieved in glass containers, aluminium cans, and PET bottles by 50%, 26%, and 40%, respectively, during the past few decades, shows the execution of the material reduction strategy [109]. However, excessive reduction in material usage may cause unfavourable consequences in satisfying functional requirements. The significance of not compromising the functional and safety aspects of food packaging when reducing the material quantity has been elaborated by several researchers [24], [58], [69], [109]. Therefore, the utilization of materials below the optimum limit (under-packing) and above (overpacking) are both undesirable in terms of sustainability [110].

Reuse

Reusing eliminates the necessity of a new product by satisfying the requirement of the same product that has been used once for the same purpose [111], [112]. Therefore, reusing packaging has been identified as an achievement in reducing the environmental impact [50], [67]. The possibility of reusing the food packaging is limited since the package may be contaminated with food residues and therefore need extra effort for cleaning [28], [91]. As a result, the food packaging industry focuses more on reusing secondary/ tertiary packaging, which doesn’t yield a similar issue. A plastic crate reused for 50 cycles shows 30 times less impact compared to single-use plastic crates [113]. However, the selection of a suitable reusable material is crucial since in some cases, reusing still may not be able to mitigate the environmental impact caused by the production phase. For example, a glass bottle reused 8 times may still carry a higher environmental burden compared to a single-use PET bottle [5]. Thus, introducing reusable food packaging systems needs to be done with proper environmental impact analysis justifying whether the impact could be reduced.

Recycle

Recycling reduces the escape of extracted raw materials from the economy [106]. Nearly 45% of plastic is recycled in the Netherlands, which is considered higher compared to other countries [58]. In addition, the Netherlands has declared their targets for 2025 as: achieving 100% recyclability for single-use plastics and packaging, increasing the recycling rate to 70% for single-use packaging and products, and using at least 35% of recycled material in new products [59]. On top of the national policies, the motivation of local producers to use 40% recycled material for PET water bottles could be identified as a community initiative for sustainability [58].

There are certain limitations identified in recycling food packaging. Degradation occurs in recycling is a negative phenomenon where the recycled materials tend to lose some of their chemical and physical properties [114]. Food contamination is another issue which demands extra effort for cleaning and preparing food packages for recycling [28]. Even though recycling focuses on reducing the environmental impact, it does not always mitigate the burden due to the collecting and recycling system [24]. Thus, it is necessary to conduct a case-specific life cycle analysis to estimate the real-world impact of recycling.

'Design for recycling' and 'design from recycling' are considerations related to recycling during the product development phase to ensure the circularity of the product. However, HDPE and LDPE show unpreferred mechanical properties after a few cycles of re-extrusion [115]. On the contrary, PET is a well-fitting material with low degradation, which could be reversed during the recycling process [116]. Therefore, the homogeneity of PET waste coming to recycling is not significant compared to PP and PE. However, the use of multiple types of plastic makes it difficult to recycle [115]. These concerns are discussed in the publications as are established in the industry.

Recover

Recovering energy comes next under the waste management hierarchy [57]. In this aspect, the used products are incinerated and energy is generated utilizing the heat generated which is also known as thermo valorisation [69]. However, the release of hazardous substances into the environment is a main concern in the incineration process [117]. Additionally, the possibility of implementing energy recovery facilities may be ineffective in countries with underdeveloped waste management systems [69].

Dispose

Disposal is a non-value-adding end-of-life strategy in the waste hierarchy [23]. Even though disposal is considered the least preferred method, nearly 79% of plastic out of 8,300 million tons produced between 1950 and 2015 is sent for landfilling or leaked to the environment [9]. Yet, it is preferred over incinerating garbage without energy recovery or flue gas treatment [82].

The landfill has been considered as an End-of-Life (EoL) scenario in several studies [82]. Landfilling seems to have a negligible global warming potential compared to recycling and incineration when only the direct impact is considered [82]. On the other hand, the 100% landfilling scenario had the highest environmental impact compared to 100% incineration with energy recovery, and 50%-50% incineration and landfilling [118]. Instead of the estimated environmental impact through life cycle analysis, there are apparent consequences such as contaminating water sources, air, and soil with toxic chemical substances [65], [112].

2.5.2 Reducing indirect environmental impact through reducing food losses and waste

The reduction of FLW is a widely discussed topic in minimizing the indirect environmental impact caused by FP. Food losses are defined as the deterioration of edible food through the supply chain before the consumer [106], [119]. This type of loss is caused during the processing of food items before packaging and the physical and chemical deterioration during transportation. The discard at the end consumer or retailer phase is known as food waste (FW) [106]. In several publications, FLW has been used as a general term for representing both food losses and waste.

When assessing the FLW, about 30% of the food produced piles up as waste in the distribution chain without arriving at the consumer in industrialized countries. The situation worsens in developing countries, increasing it up to 50% [20], [35]. In Sri Lanka, it has been estimated that 30% of FW is generated, equivalent to 5000 MT per day [120]. Several progressive measures have been suggested to address this issue, such as public awareness programmes, additions to educational curricula, and integration of FW prevention policies into stakeholders' agendas [120].

It is necessary to identify the reasons for FLW for minimizing them instead of quantifying them. In the UK, 29% of purchased bread is wasted since the amount of bread in the packaging is too high. Reducing the portion size to suit the consumer requirement has been suggested as a technique to avoid these events [17]. Similarly, 9% of cheese is discarded, while 77% of them are due to not using in time [17]. The majority of the milk wasted in the UK is due to excessive portion size and expiration, while only 4% is caused by packaging-related accidents [17]. Similar patterns were seen for yoghurt, where 70% of the waste is caused by expiration and the majority of fish and meat wastage is caused by excessive food preparation or not used in time [17]. The study has identified two main reasons for 'avoidable food waste', (1) a portion of the content is used from the oversized packaging and the remainder is kept in the refrigerator until it expires or deteriorates, (2) leftovers caused by excessive food preparation [17]. In addition to avoidable FLW, non-edible food components, such as preparation residues (vegetable skin, egg shells, bones) at the consumer end, are unavoidable [121]. When analysing the causes of FLW, it is apparent that these reasons could be eliminated through proper packaging sizing and improving communication that has much less concern with the physical design of the food packaging.

Studies have estimated that more than 95% of food waste occurs during the pre-consumer stages, which could have been minimized by proper protection and preservation methods during the pre-processing stage [122]. In the meantime, a study has identified that only 5-16% of food is wasted due to packaging-specific reasons while the balance is caused by behavioural factors [73]. Therefore, it is apparent that packaging-related food waste is trivial compared to the FLW caused by other factors.

2.6. Evidence of policy framework

A policy framework is a "document that sets out a set of procedures and goals, which might be used in negotiation or decision-making to guide a more detailed set of policies or to guide the ongoing maintenance of policies" [123]. In certain applications, these frameworks have been presented in a diagram for ease of illustration [124], [125]. Policy frameworks have been developed in different disciplines (specially in the IT industry) for aligning policies with national policy implementations [124]–[127]. Meanwhile, a policy framework has been developed for the adaption and management of drones for agricultural purposes [125]. Thus, these frameworks are developed to satisfy certain goals, interfering with different levels of administration. The following section briefly introduces different policy categorisations based on their level of interference and accuracy.

2.6.1 Policy hierarchy

This section discusses two different policy categorisation methods available in the literature. Policies have been categorised into six levels in one study, and the other has been categorised into four sections [128], [129]. However, both these categorisations are based on the degree of precision they represent and the information distributed. The upper hierarchy policies cover a broader range of subject matter, while the low hierarchy policies focus on functional and procedural execution. Considering the ease of understanding and the level of necessity of information, the four-level categorisation is elaborated in the following.

A four-level classification has been suggested based on the timeliness, activity, mode, organizational criterion, functionality of targets, etc. [129]. Corporate policies are the higher-level policies derived from corporate business management strategies. The task-oriented policies focus on managing tasks or process management and define methods to manage and apply the tools used. The functional policies design the usage of management functions. Finally, the low-level policies operate at the managed objects (MO) level. In some instances, it would not be easy to distinguish policies at different levels of abstraction and would be needed to split the level of execution. A graphical representation of the policy hierarchy and their degree of detail in definition, business, and technology aspects is shown in Figure 2.5.

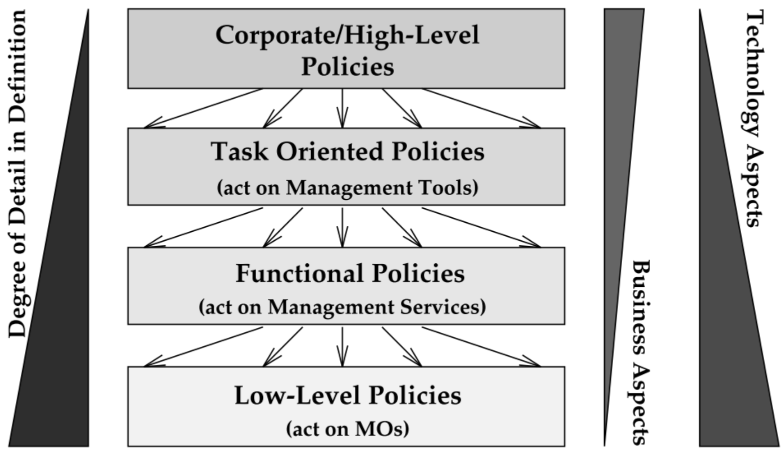


Figure 2.5: Policy hierarchy [129]

2.6.2 Existing frameworks

The design assessment framework for food packaging suggested by Yokokawa et al. encounters environmental impact and consumer preference [104]. The framework consists of three phases, where the first two phases assess the design options regarding performance criteria. The last phase aggregates the previous phases' results and compares the design's improvements. The practicality of the framework has been demonstrated by comparing four different packaging designs.

Another framework has been suggested for improving the sustainability of food packaging [130]. The framework consists of five phases, each considering the material selection, assessing the feasibility, design, and repetition. The first three phases consider design aspects, including material selection and functionality tests. It has only considered the combination of a few material types limiting the extent of the packaging designer. The last two phases focus on integrating the sustainability aspect into food packaging and continuous improvement of the packaging design iteratively. Thus, the framework has not included the financial aspect and scrutinization from external organizations.

As per the above discussion, several food packaging sustainability areas that need to be improved with proper guidance could be identified. An artefact for policy development integrating the sustainability aspect is lacking in the food packaging industry. Furthermore, multiple aspects need to be highlighted for guiding the design of food packaging as discussed under the research gap.

2.7. Research gap

The main gap identified is the **absence of a policy framework which addresses the three key factors when designing food packaging**. Regulations and standards have been enforced globally to ensure health and food safety. Somehow, no policies are imposed to maintain the balance between the three key factors that need to be considered in sustainable food packaging: environmental impact, economic aspect, and functional satisfaction. Therefore, a guideline is essential for enforcing policy development addressing sustainable food packaging development. The main target audience for this framework would be policy developers who could influence the design and manufacture of food packaging.

Three main dimensions were identified in the literature related to sustainable food packaging development; environmental/ economic sustainability and functional satisfaction. As per Table 2.3, the assessment of environmental and social sustainability has been done in several studies. However, the economic viewpoint is less considered in publications related to food packaging.

Thus, there is a **gap in the literature combining the economic aspect with other performance indicators**.

Existing studies have identified the transportation mode, weight, and travel distance as parameters influencing the environmental impact of transportation. However, the lorry itself causes a significant amount of environmental impact in addition to the transportation impact of cargo. As a result, the lorry's impact must be shared among the number of units transported. Thus, the impact per single unit transported would decrease if more items were loaded into the truck. The 3D geometry and the packaging dimensions are the key factors determining the amount of packaging that could be loaded into a truck. This phenomenon has been discussed in studies [39]. **None of the publications is available on quantifying the environmental impacts related to the occupied volume or degree of filling**.

3. METHODOLOGY

The first section discusses the research design; elaboration on the relationship between the objectives and phases of the research. Then the methodology followed in the selection of the case study is discussed. The design thinking followed for developing packaging options is mentioned in the next sections. Then, the methodology followed for assessing and aggregating the sustainability parameters is discussed. The last two sub-sections elaborate the methodology followed in developing and validating the framework.

3.1. Research design

The research was planned under five phases directly aligned with the objectives. The first phase was to understand the current knowledge and the market variation. Suitable case studies were identified through a market survey. In the second phase, design options were developed for the case studies using design tools with insights from packaging designers and customers. The next phase was to conduct a life cycle analysis (LCA) to estimate the environmental impact and how it influences the design characteristics. The fourth phase focused on identifying methods to develop a framework. The final phase was to validate the suggested frameworks through experts. These phases of the study and their relationship to each other are illustrated in Figure 3.1.

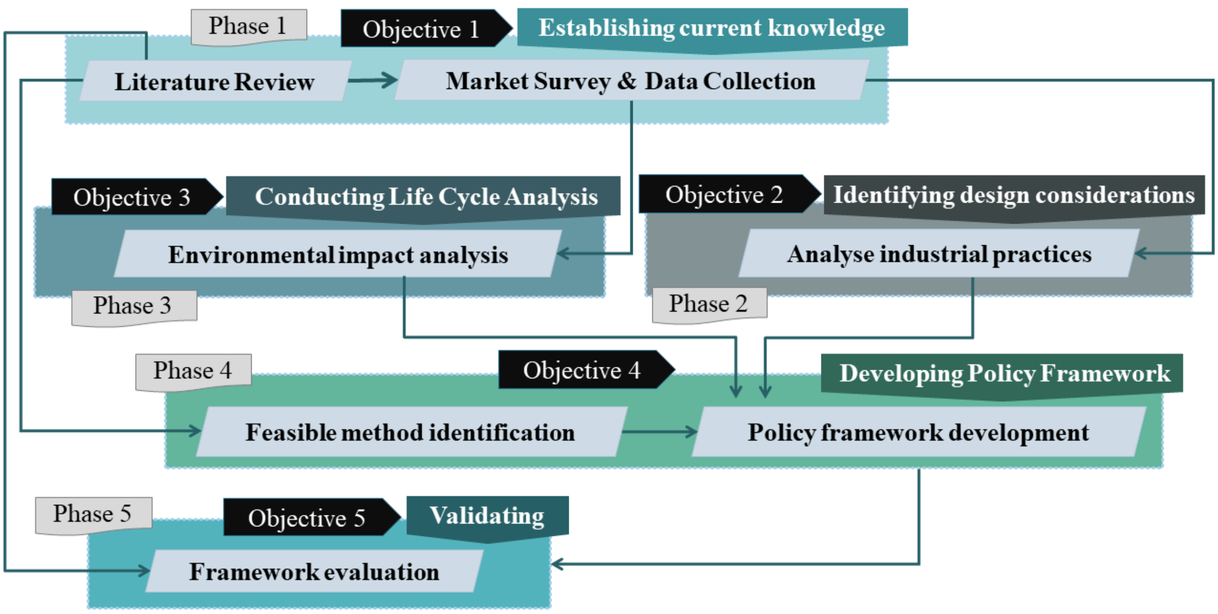


Figure 3.1: Research Design

3.2. Review methods

Google Scholar was used as the search engine for finding articles combining multiple search strings. Elsevier, Scopus, Science Direct, and Springer were the main sources of articles retrieved. Key words such as 'sustainability', 'consumer preference', and 'environmental impact' were combined with 'food packaging' to filter the pertinent articles. Approximately 515 articles were retrieved from the initial literature search that has been published since 2005. Then, the articles relevant to the design and manufacture of food packaging were retrieved by combining search strings such as 'costing', 'designing', 'manufacturing', and 'design tools' with 'food packaging', which reduced the number of articles to a reasonable number to reviewal. The forward and backward search was another technique used to find other related publications. The reviewed literature was documented using thematic coding over 15 themes: methodology, LCA, packaging material, packaging design, environmental impact, policy/ framework, costing, etc.

3.3. Case studies

Design considerations differ very much depending on the packaging type and the food content. The highly significant type of FP was considered as per the second objective due to the inability to consider the design considerations of all packaging types. The case studies were selected as the method for conducting the analysis, as discussed below.

Case studies have been used to analyse the environmental sustainability of food packaging [35], [58]. Environmental impact analysis of five different packaging designs has shown that a single packaging option would not be preferred for the three different chocolate products [26]. A similar study conducted on bacon packaging has elaborated on the differences in environmental impacts of five packaging options [131]. Additionally, several publications have elaborated on how case studies could be utilized in identifying differences in packaging-related environmental impacts [47].

Case studies have been used to identify consumer preferences for different packaging options [16]. Even for the same packaging, consumer preference has differed based on the food product. A study has considered three different products for assessing the environmental, social, and economic aspects of food packaging for ketchup, mayonnaise, and beans [97]. Rezaei et al. have elaborated that case studies could be used to assess the three dimensions of sustainability and draw conclusions on how sustainability could be improved in food packaging design [97]. Other similar publications have discussed the relationship between the design characteristics of wine bottles and consumer preferences [87].

Few characteristics of case studies showed the capability of using it as the method for identifying FP specifications related to sustainability. The ability to focus on a particular product range, convenience of the method, and accuracy of data retrieval were the most essential attributes of case studies to be considered as the main method. As described in the next section, two case studies were considered for this study. After that, the design and evaluation phases for the case studies were conducted as described in Section 3.6.

Selection of cases

Generalizability was a main concern when the selection of case studies was limited to a rigid FP category. In most occasions, flexible FP is used as single-use packaging or to contain food until its being transferred to another container for regular/domestic use. As a result, rigid FP are expected to satisfy functionalities, including reopening/reclosing beyond the functional requirement of flexible FP. Further, there are functional requirements such as maintaining the shape and withstanding loads that are related to the rigid FP-related design characteristics. Therefore, the diverse applications showed the potential of extending the study on rigid packaging towards flexible packaging.

The significance of the environmental impacts was the second reason for limiting the case studies to rigid FP. The rigid plastic category contributes to 27% of the global food packaging industry [132]. However, in the Asia-Pacific region, rigid plastic FP possesses approx. 10% of the entire food packaging industry (refer to Figure 3.2.) [42]. Even though the amount of rigid plastic packaging usage (10%) is less compared to the flexible packaging usage in this region (62%), the amount of material used for a single rigid packaging is much greater than that of flexible packaging. As a result, the resource consumption of rigid packaging systems is highly significant despite of the low market share. Therefore, the focus on reducing the environmental impact of rigid FP was considered to be significant compared to study of flexible FP.

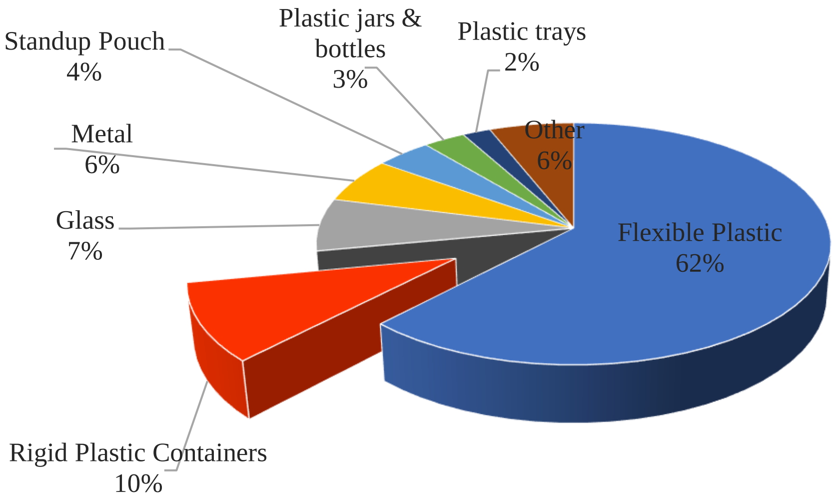


Figure 3.2: Market share for food packaging in the Asia-Pacific region [42]

The next step was to select a suitable case within the scope of rigid FP. Multiple factors were considered when selecting a case. The selected case is expected to have four essential characteristics: particularistic (the focus on a specific phenomenon), descriptive (adequately describes the phenomenon), heuristic (improved understandability of the reader), and inductive (based on inductive reasoning) [108]. The large variety of functional requirements relevant to FP was identified as a criterion for being particularistic and descriptive. The large market share and consumer base were identified as suitable criteria to sufficiently describe the phenomenon and improve understandability for the reader, respectively. Additionally, a multi-case study approach was followed to detail the rigid food packaging scope sufficiently and descriptively. The ketchup bottle and the ice cream container were selected as the two case studies for the analysis considering the variation of the functional expectation of the two cases.

The next step was to develop different designs for the case studies to analyse their performance under three parameters: functional satisfaction, environmental impact, and economic viability. Initially, the functional requirements of FP were identified and categorised. Then, the design characteristics were prioritised based on their significance of fulfilment. Finally, the designs were developed considering the features and functional requirements while taking insights from the packaging designers. The methods utilized to design the food packaging are discussed in the following sections.

3.4. Kano's theory for classifying the functional requirements

The functional attributes of food packaging have been analysed and categorised by several studies. Protecting the content, facilitating handling, and communicating are the main functional attributes, whereas several other sub-functional attributes could be listed under these [95], [26], [100], [133]. The functional requirements identified through the literature review showed different levels of significance to satisfy them. Some attributes needed to be mandatorily satisfied, while several others were not essential to be considered. Therefore, further analysis was essential to classify the functional requirements before initiating the design phase. Kano's model of attractive quality is a method to classify the functional requirements of products considering their significance of fulfilment based on consumer feedback [16]. The following paragraphs describe the four main categories of functional attributes.

'Must-be' is the first type of Kano's attributes which are mandatory to be satisfied, but the fulfilment will not increase customer satisfaction [16]. Somehow, if the packaging is unable to attain must-be attributes, consumers will be completely unsatisfied. Contain the right quantity, leakage proof, product protection, declaration of contents, and usage instructions have been identified as must-be attributes of food packaging [134], [135]. Packaging designers should be highly concerned about fulfilling 'must-be' attributes since the inability to satisfy them would be of no use and would eliminate the product from consumer consideration for purchase.

'One-dimensional' attributes cause satisfaction when accomplished and vice versa. Therefore, the level of fulfilment is a direct parameter for consumer preference. Easy to grip, easy to take out food, easy to open/ close, fit in storage, and other basic user-friendly aspects (displaying nutritional value and preservation methods, post-use processing instructions) fall under this category [90], [134], [135]. 'One-dimensional' attributes could be utilized in evaluating the degree of consumer preference since the level of fulfilment is proportionate to satisfaction.

'Attractive' qualities delight the consumers when satisfied but do not dissatisfy the consumer when not fulfilled. These are the attributes which delight the consumer facilitating additional functionalities. Resealability, reusability after use, ease of dose, secondary user-friendly attributes (ability to dispose with household waste, aesthetic appealing, providing utensils), and recyclability are some of the attractive quality attributes identified with food packaging [16], [135].

'Indifferent qualities' refer to the neutral attributes where the fulfilment or non-fulfilment does not affect customer satisfaction. The aesthetic appeal, attractive printing, and additional functions are the 'indifferent attributes' identified in packaging [134].

Generally, this classification is based on questionnaires on how each functional attribute influences consumer satisfaction. However, this is a well-established area of research in food packaging where several publications discuss the topic [16], [90], [135]. Therefore, the identified functional requirements were categorized using a literature review in Table 3.1. The identified four types of functional attributes are discussed in the following paragraph.

Table 3.1: Functional attributes

Type of the attribute	**Attributes**	**Kano's category**	**References**
Technical	Preservation	Must-be	[90], [92], [99], [133], [135]
	Contain right quantity	Must be	
	Leakage proof	Must be	
	Tamper evident	Must be	
	Hygiene and safety	Must be	
Functional	**Ability to stack, lift, and move**	Must be	[90], [92], [99], [133]
	Ability to open/ reclose	One-dimensional	
	Ability to store	One-dimensional	
	Ability to take out/ apportion	One-dimensional	
	Ability to open the seal	One-dimensional	
	Ability to handle	One-dimensional	
	Ability to dispose with household waste	Attractive	
Informative / visual	Aesthetic appealing	Indifferent/ Attractive	[26], [90], [100], [133]
	Usage instructions	Must-be	
	Post-consumption processing instructions	One-dimensional	
	Nutritional value	One-dimensional	
	Declaration of content	Must-be	
	Preservation methods	One-dimensional	

3.5. QFD for identifying and prioritising design characteristics

Identifying the relationship between the functional attributes and product features was the next step. Quality Function Deployment (QFD) is a structured approach to improve the quality of a product by identifying how customer requirements are related to product features [136]. The House of Quality (HOQ) is a tool used in QFD for illustrating information about the relationship between customer requirements (Voice of Customers-VoC) and design considerations [137].

The existing research manifests the possibility of using HOQ as an interface to improve the consumer-designer relationship by providing a numerical association between product characteristics and consumer preferences. Different customer needs, such as protection, ergonomics, communication, and logistics, have been related to different engineering characteristics in the development of FP with environmental concerns [100]. A similar study has considered packaging material, information, container shape and colour as customer attributes with respect to material characteristics, information, aesthetic and conformance [89]. Therefore, the HOQ was selected as the design support tool, and the methodology followed to develop HOQ is described in the following sections.

The main components of HOQ: customer requirements, product requirements, relationship matrix, correlation matrix, product comparison matrix, and engineering competitive assessment are presented in Figure 3.3 [138].

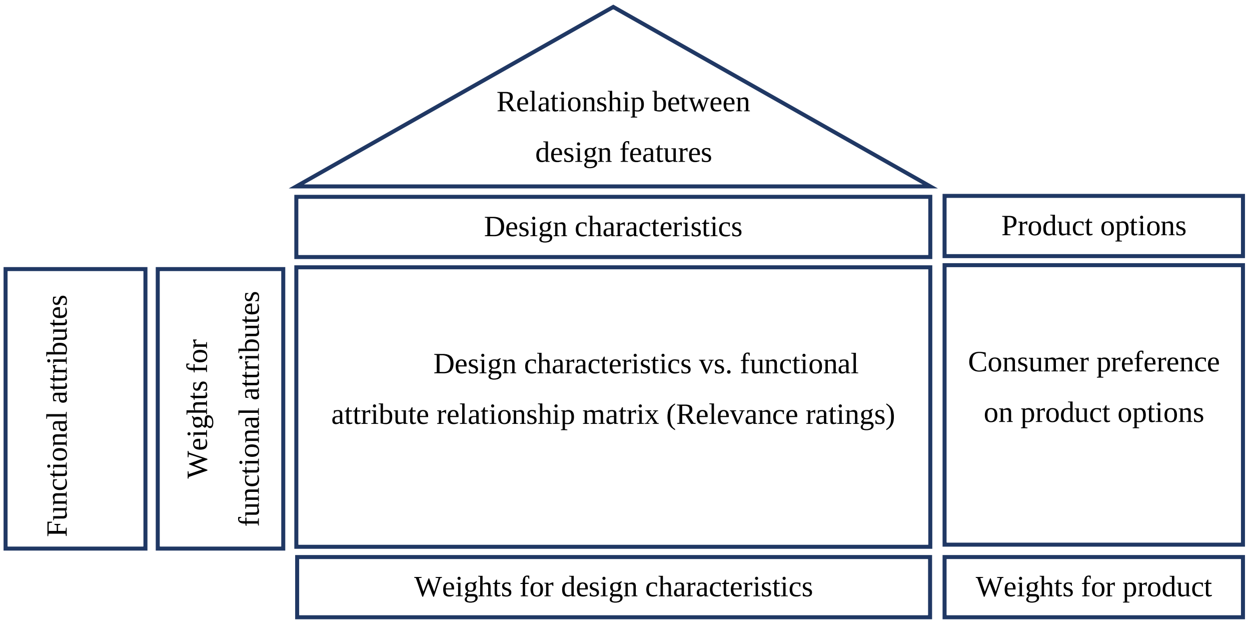


Figure 3.3: Components of House of Quality

3.5.1 Feature identification

Packaging features are the specific qualities which are aligned to fulfil the expected functionalities [133]. The features are unique for a specific context, while the functions are more general for a range of products [133]. The number of publications on packaging features is limited in the literature.

The material type, structure of the packaging film, shape, and weight of the packaging have been identified as features of a milk carton [99]. A similar study has identified the packaging material, information on the packaging, container shape, and colour as packaging features [89]. However, all these studies have selected a set of features that are unique for the considered packaging option. Therefore, it was essential to identify product-specific packaging features through discussions with industrial personnel for the case studies.

In addition to the literature review, several other features were identified through discussions with experts in the field. The lid/cap, body, seal, and label were the common components identified with the rigid FP. Among them, the label was not considered in this study since it does not facilitate physical functionality other than communication and marketing. Subsequently, the packaging design phase in this study focuses on satisfying physical functional requirements; thus, different labels were not considered. It was assumed that a similar label was used for all packaging designs. The features of the remaining components are listed in Table 3.2.

Table 3.2: The features of FP components

Component	Features
Cap/ lid	Material
	Closure mechanism
Body	Material
	Shape
	Dimensions
	Strength/ thickness
Seal	Type/ shape
	Material

3.5.2 Assigning weights for functional attributes

The next step was to prioritise the identified features (refer to Table 3.2) for initiating the design process. 'Must-be' attributes were mandatory to be satisfied while 'One-dimensional' attributes were chosen to be the functional attributes in HOQ since they are proportionate to user satisfaction, directly influencing the purchase decision and consumer satisfaction [90]. After identifying the functional attributes, a questionnaire was used to collect data for assigning weights.

'Questionnaire-A' was developed to collect data to assign weights for the functional attributes. The ranking method was used to assign weights on consumer perspective to the identified 'one-dimensional' attributes. The respondents were asked to rank the functional requirements based on their significance in the purchasing decision and use phase. A closed-ended questionnaire was prepared on deriving quantitative data using an online platform – 'SurveyHero'. The questionnaire was distributed among the public via social networking platforms and email in September 2021, and 102 responses were collected (the questionnaire is attached to Appendix A). It was not mandatory to rank all the functional requirements and could leave the ones that were not being considered. Therefore, the number of items in each response was not equal. The weighting score for each functional requirement was calculated using the following equation.

$$Score\ for\ r^{th} attribute\ (S_r) = \sum_{i=1}^{\#\ of\ responses} (Max.nu.of\ responses\ in\ the\ i^{th} response - Rank\ of\ the\ r^{th}\ attribute\ in\ the\ i^{th} response + 1) \quad (1)$$

There are a few advantages and disadvantages identified with the ranking method. Unlike the Likert Scale, the ranking method minimizes the possibility of assigning equal values to the options available [100]. Therefore, it would allow differing levels of significance for different functional attributes without assigning equal values to each attribute. Moreover, this method would allow the respondents to think thoroughly before ranking, providing more precise outputs. Somehow, the inability to rate two or multiple options with the same level is a drawback identified. Additionally, in the ranking method, it was assumed that the difference between adjacent ranks is equal, which is another shortcoming. Besides, it was assumed that the aggregation of outcomes from many respondents would reduce the limitations' influence and provide similar weights and different levels of significance when necessary.

Next, the weight for each attribute was calculated as a percentage using the following equation.

$$Weight\ for\ r^{th}\ attribute\ (W_r) = \frac{Score\ for\ the\ r^{th}\ attribute}{\sum S_r}\ \% \quad (2)$$

The calculated weight for each attribute was used to rank the functional attributes.

3.5.3 Correlating design characteristics and packaging functions

The next step was to identify the level of relationship between the functional requirements and design features. Semi-structured interviews conducted through virtual communication platforms were used for data collection. Industrial experts and academics specialising in packaging design were contacted individually for the two case studies. A questionnaire guided the semi-structured interviews throughout the expected data collection scope as given in Appendix B. Meanwhile, other useful information related to the design of the packaging was discussed. The industrial personnel were chosen since they have practical knowledge and experience working with food packaging for several years. It was able to contact only a few food packaging designers since the number of experts is limited within the industry. In addition, the packaging developed years ago has been continued; hence, the designers were out of reach for the companies.

The respondents were asked to quantify the relationship between each functional attribute and the design feature. For example, they were asked to rate each feature in Table 3.2, based on their significance in ease of opening and reclosing the packaging. The responses were collected using numerical values; 0, 1, 3, and 9. These values represent the degree of relationship where 0 stands for not related, 1 for weakly related, 3 for related, and 9 for strongly related [89], [136]. The collected responses were averaged to get a representative value (relevance rating) for each attribute.

The technical priority score indicating each design characteristic's significance was calculated. The responses from the industry experts were used to calculate the technical priority score using the following equation.

$$\begin{aligned} &Weight\ for\ the\ r^{th} design\ feature\ (W_r) \\ &= \sum_{i=0}^{n} (weight\ for\ the\ i^{th}\ functional\ attribute \\ &\times relevance\ rating\ for\ i^{th}\ functional\ attribute\ ) \end{aligned} \quad (3)$$

Then the HOQ was developed to prioritise the design features that needed to be considered in the design phase.

3.6. Developing food packaging designs

SolidWorks 2016 was used as the modelling software for creating 3D models. The available ISO standards were adhered to when selecting food-grade materials. The design constraints, guidelines, and techniques practised by the packaging designers were also followed to meet the existing industrial standards. In addition, all the component designs were developed such that they could be produced with the existing manufacturing facilities in the country [130], [139]. The results from the HOQ were used to determine the essential factors to consider during the design process. The 'Must-be' attributes are identified in Section 3.4, such as food preservation, leakage proofing, and pilfer proofing, were considered during the design phase since dissatisfaction with these attributes will eliminate the packaging from consumer consideration. In addition, the following aspects were considered in the food packaging design phase.

3.6.1 Assuring the structural integrity

The ability to withstand the external forces induced on the container is essential to be considered from the packaging producers' standpoint. Therefore, FEA was used as the method for assessing the structural rigidity using the methodology described in the paper published under this study "A comparative analysis of the environmental and structural performance of PET bottle designs in Sri Lanka" which has been attached in the annexes [140].

3.6.2 Minimizing food losses and waste

Designing FP design to minimize the FLW is a synthesis of several techniques. Consumer-specific attributes such as consumer needs, habits, attitudes, and economic conditions are required to identify the causes of FLW [17]. For instance, offering large food quantities in restaurants, oversized food preparation in households, and not being used in time have been identified as reasons for FLW [17], [141]. However, the possibility of reducing these consumer-influenced FLWs is minimal through this study's proper food packaging design.

Multiple measures could be taken to reduce packaging-related FLW. Knowledge of food preservation is essential since FLW may occur due to different product-specific reasons. For example, there are food items such as cheese that require different barrier properties for preservation depending on the type of cheese [23]. Further measures for reducing the FLW were found by referring to the literature. Easy to empty and containing the desired quantity have been identified as desired characteristics for FLW reduction in a study conducted to analyse two packaging types for minced meat [71]. Similar studies have identified mechanical protection, resealability, easy to open, grip, and dose as strategies for reducing FLW [17], [76]. The measures suggested by experts and available publications (refer to Section 2.5.2) assisted in the design phase for reducing the FLW.

3.7. Evaluating packaging designs

The developed packaging designs were evaluated to fulfil the third objective of this research. The environmental impact, functional satisfaction, and financial costs were identified as the three parameters that would define the sustainability of food packaging based on literature as discussed in Table 2.3 This section discusses the methods followed to estimate the influence of the three parameters.

3.7.1 LCA for assessing the environmental impact

Life cycle analysis (LCA) has been utilized to estimate the environmental impact of the food packaging industry [2]. The LCA is conducted in four steps such as goal and scope definition, life cycle inventory, life cycle assessment, and life cycle interpretation [60], [131]. The methods followed for executing these steps are discussed in the following sections.

1. Goal and scope definition

The goal of this LCA was to compare the environmental impacts of different food packaging designs. To meet the goal, all the life cycle phases of food packaging were identified through a literature review and discussions with industry experts (refer to Figure 3.4). Generally, the scope is defined considering the material flow's start and end points. Under the cradle-to-gate boundary system, the impacts from raw material extraction to the factory gate are considered [142], [143]. Exceptions could be found where the transportation from the factory to the retail shops is also considered under cradle-to-gate [139], [144].

The disposal scenarios were not considered in the system boundary due to the unavailability of data for the local context. Therefore, the impacts from production to waste management or recycling are considered as cradle-to-grave or cradle-to-cradle [145]. The cradle-to-grave aspect was considered for encompassing all the environmental impacts through the entire life cycle of the food packaging. However, a few life cycle phases of the product and the packaging were not considered since the environmental impact from these phases does not help differentiate the environmental impact of different packaging.

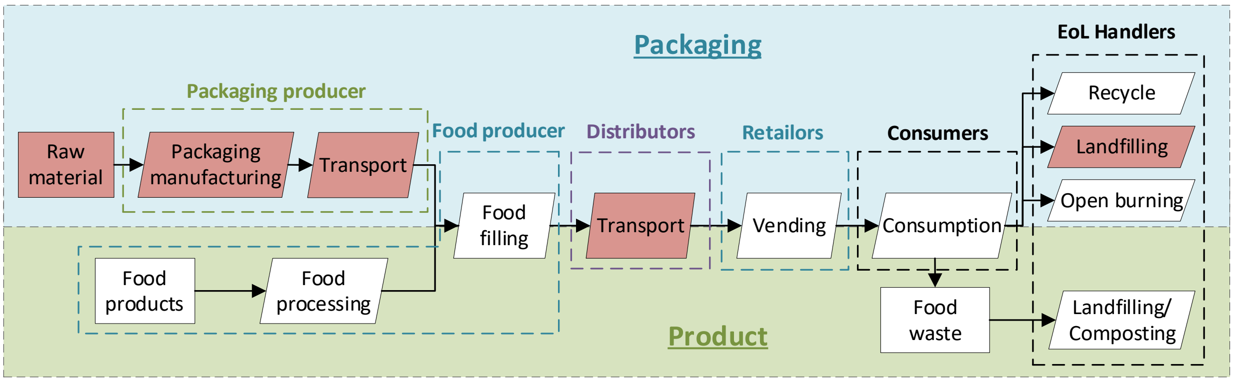


Figure 3.4: System boundary considered for the LCA (the elements considered for the LCA system boundary are highlighted in maroon colour)

The food filling, vending, and consumption phases were not considered in this study, with the assumption that the impact yield in these phases is equal for all packaging designs. In addition, there were practical limitations in determining accurate LCI data for these phases. Only the landfilling was considered as the EoL due to the large portion of plastic being sent to landfilling and the unavailability of data. Researchers have followed similar approaches in situations where the data was unavailable or uncertain [60], [144].

The functional unit quantifies the satisfied function of a product or a service used as a reference for comparing different options in LCA [146]. The functional unit has been defined in two different ways in food-related LCA. In some cases, the amount of food transported to the user has been considered [20], [68], while the number of packaging is considered as the functional unit in some other studies [28], [78], [131]. In this study, 'delivering a certain amount of food' was considered as the functional unit since all the packaging options for a case study contained the same amount of food [147]. More specifically, the delivery of 400 ml was considered for the ketchup bottle, and for the ice cream container, the delivery of 1*l* of ice cream was considered.

2. Life cycle inventory

The life cycle inventory (LCI) consists of the material and energy use, environmental discharge, and waste associated with each phase for calculating environmental impact [148]. There are different methods to collect data for the LCI. Referring to available articles, collecting data from resource persons, and measuring or calculating the actual values are some of the methods [60], [71], [103]. In this study, the weight of each packaging component was calculated using the developed 3D model from SolidWorks. The development of the life cycle inventory for the transportation phase was performed considering the packaging volume, as discussed in Section 5.

The environmental impact of food waste (FW) due to FP was not incorporated in this study due to difficulties in data collection concerning each packaging option. The LCA could have been conducted considering a similar amount of FW on every option instead of evaluating FW caused by each packaging. This approach was not followed during the analysis since it would not differentiate the environmental impact from each option rather than exaggerating the impact from all the packaging options with a similar amount.

3. Life cycle assessment

The life cycle assessment has been conducted using available databases such as openLCA, Ecoinvent, and United States Life cycle Inventory (USLCI) [91]. The ecoinvent is a widely used database available at SimaPro software [79]. There are multiple software such as; SimaPro, Gabi, OpenLCA, Team, and Gemis to model the life cycle impact [91]. However, the SimaPro 9.0 was used for this study considering data relevant to global from the Eco-invent data base.

4. Life cycle interpretation

The impact categories available in life cycle databases are commonly used to interpret the environmental impact. Different performance indicators (PI) used in studies are summarised in Table 3.3.

Table 3.3: Performance indicators (PI) used to interpret the environmental impact

Criteria	Reference
GHG emission	[79] , [141], [143]–[147]
Climate change	[102], [153], [154]
Energy consumption	[61], [66], [102], [109], [112], [148]
Stratospheric ozone depletion	[18], [69], [102], [131], [154], [155]
Particulate matter	[102], [154]
Human toxicity	[154]–[156]
Photochemical ozone formation	[18], [102], [155], [156]
Acidification	[18], [71], [102], [154]
Eutrophication	[18], [102], [156]
Land use	[102], [156]
Water resource depletion/ toxicity	[102], [154]–[156]
Mineral, fossil & resource depletion	[102], [155], [156]
Solid waste	[148]

Some studies have only considered one parameter, while other researchers have considered multiple indicators. However, an environmental impact indicator is expected to have the following characteristics to be used as an effective environmental impact indicator [157].

1. Being a representative of the environmental conditions
2. Simplicity
3. Responsivity to environmental and human-related activities
4. Ability to refer to a value to get an idea of the impact being done
5. Technical viability
6. Grounding in international standards

The GHG emission was selected as the indicative impact parameter in this study. The greenhouse gas (GHG) emission has been efficiently involved in representing the eco-performance [20], [66], [79]. In addition, the parameter meets all six attributes, enabling it to be used for this study.

5. Impact of occupied volume in transportation

The concern of occupied volume discussed in this section directly influences the LCI at the distributor level in Figure 3.4. However, this is presented separately, considering the significant work done in developing the model for incorporating occupied volume.

In the case of a lorry, the total impact of transportation is an accumulation of the impact from the empty lorry and the impact from the weight of the cargo. As a result, every single unit carries a portion of the impact of the empty lorry. Thus, when calculating the actual transportation impact of a single unit, the impact of the empty lorry should be divided among the transported units. Therefore, the number of packaging units transported in the lorry becomes a governing factor for determining the actual environmental impact of a single unit.

The number of packaging units loaded into the lorry is governed by the occupied volume of the packaging and the maximum loading capacity of the lorry. In this research, it was assumed that the weight of the cargo does not exceed the maximum allowable limit. Practically, packaging units are loaded adjacent to each other. However, due to the shape, a void space is left between the packaging units. Therefore, the packaging occupies a higher volume in the space in addition to the actual volume of the packaging. This imaginary occupied volume, which includes the actual packaging volume and void space, is illustrated in Figure 3.5.

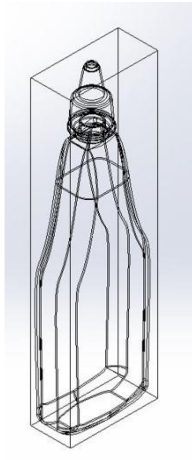


Figure 3.5: The occupied volume is shown in the cuboid

If the volume of the void spaces could be reduced, the number of packaging transported in a single lorry would be increased. As discussed in the above paragraph, the increased number of units will reduce the environmental impact per unit. The model for estimating the environmental impact was developed based on this argument.

A previous study has estimated that an empty lorry would account for 61% of the environmental impact caused by a fully loaded lorry. The remaining 39% would linearly accumulate to 61% based on the load on the lorry [69]. The study has developed an equation to calculate the overall environmental impact of lorry transportation with respect to the load factor (LF), the ratio between the weight carried by the lorry vs. the weight capacity of the lorry. The weight of the content was not accounted for in calculating the weight carried by the lorry since the content was not considered within the scope of the LCA.

$$E = 0.61 * IFLL + 0.39 * LF * IFLL \quad (4)$$

$$E - Environmental\ impact\ from\ transportation$$

$$LF = \frac{\text{the weight carried by the lorry}}{\text{full weight capacity of the lorry}}$$

$$IFLL - Impact\ from\ Fully\ Loaded\ Lorry$$

$$Envi.impact\ from\ a\ partially\ filled\ lorry = IFLL * (0.61 + 0.39 * LF) \quad (5)$$

$N - nu.of\ total\ items\ to\ be\ transported$

$n\ (= \frac{V}{v}) -\ nu.of\ items\ that\ could\ be\ transported\ by\ a\ single\ lorry$

$V -$ $volumetric\ capacity\ of\ the\ lorry$

$v -$ $occupied\ volume\ of\ the\ packaging$

$m -$ $weight\ of\ the\ packaging\ (without\ the\ product)$

$M -$ $load\ capacity\ of\ the\ lorry$

$$Load\ factor(LF) = \frac{\text{the weight carried by the lorry}}{\text{full weight capacity of the lorry}}$$
$$= \frac{m * n}{M}$$

(Since only the packaging is considered, the weight of the content was neglected)

$$Number\ of\ turns = \frac{N}{n}$$

$$Accumulated\ environmental\ impact = Nu.of\ turns\ \times Impact\ from\ a\ single\ turn$$

$= \frac{N}{n} \times (0.61 * IFLL + 0.39 * LF \cdot IFLL)$ (Assuming all the lorries are filled and not fully loaded)

$$Resultant\ environmental\ impact\ from\ one\ unit$$
$$= \frac{Accumulated\ environmental\ impact}{N}$$
$$= \frac{0.61 * IFLL + 0.39 * LF * IFLL}{n}$$
$$= \frac{IFLL}{n} * \left(0.61 + 0.39 * \frac{m * n}{M}\right)$$
$$= IFLL * \left(0.61 * \frac{v}{V} + 0.39 * \frac{m}{M}\right) \quad (6)$$

Equation 6 provides the relationship between the occupied volume of the packaging and the environmental impact. The impact from transportation was calculated using the suggested mathematical model considering the occupied volume and the weight of the packaging. The empty food packaging needed to be transported 50 *km* from the packaging manufacturer to the food producer. In addition, it was considered that the packaging is transported 150 *km* from the filling point to the retail shops. Therefore, it was estimated that single packaging would travel 200 *km* in total for both scenarios. These values were obtained during the discussions with the packaging designers. It was assumed that the lorries were completely filled. In this study, it was made sure that the fully packed lorry does not exceed the weight capacity of the lorry. During the return trip, the lorries transport some other goods, and therefore, the return trip was excluded from the system. The mostly used type of lorry by the companies was considered as the transportation mode. The load space of the lorry was approx. 17.5 m^3 and the gross vehicle weight (GVW) was 4.9 tons. The emission data for Euro-3 graded lorries were considered for the analysis. In addition, the environmental impact from the transportation was calculated using the conventional equation with the ton.kilometer value to compare the two models and the results are shown in Figure 4.24 and Figure 4.25.

3.7.2 Questionnaire for assessing consumer preference

Surveys and questionnaires have been widely used to estimate the consumer viewpoint on a product by several researchers [158]. The questionnaire has been used in a study conducted to identify consumer preference for different milk desserts [86]. User preference over different design features has been analysed for metal tins and polyethylene terephthalate (PET) bottles [19]. Consumer perceptions of different design characteristics have been identified through a questionnaire [92]. Moreover, some studies have evaluated consumer choice over different packaging designs and eco-friendliness. Most of these studies have considered simple case scenarios where the preference for a packaging design has been questioned directly. Data analysis tools have been used for complex cases where multiple factors affect the preference [159]. It is difficult to assess a large number of design options at once since it would confuse the respondents. Additionally, when multiple designs are available for different components, an additional analysis method for compiling the data collected is essential. In similar situations, conjoint analysis has been deployed in aggregating data collected through a questionnaire for calculating a single weight for a considered product [87], [160].

'Questionnaire B' (refer to Appendix C) was prepared to identify functional satisfaction over different component designs. Ninety-six (96) responses were received from December 2021 to January 2022. The respondents were asked which component design they would prefer considering each 'one-dimensional' functional attribute. For example, the respondents were asked which cap/ lid they would prefer considering the ease of opening and closing. Respondents were asked to assume that the price and the content inside the packaging are the same to minimize the biases caused by brand consciousness and price concerns.

After collecting data using ‘Questionnaire-B’, conjoint analysis was used to estimate a numerical value to represent functional satisfaction over each packaging option. The conjoint analysis has been used as a method to aggregate results from the survey to identify the preference for a certain product [104]. First, the functional attributes have been assigned an importance rating, and it has been combined with the consumer preference over different packaging options as given in the following set of equations. In the second case study, only a few distinctive design options were developed. Therefore, a simple questionnaire identifying the functional satisfaction of each option was sufficient without further analysis using conjoint analysis. The consumer preference for the k^{th} packaging option was calculated based on the results from the survey as shown in Equation 7.

$$Functional\ satisfaction\ score\ for\ k^{th}\ component\ design\ (P_k)$$
$$= \sum_{r=1}^{\#\ of\ attributes} N_{r,k} \times W_r \tag{7}$$

$$N_{r,k} = Number\ of\ responses\ in\ favor\ of\ k^{th}\ packaging\ option\ under\ r^{th}\ attribute$$

After calculating P_k, the results were normalized following the methodology discussed in Section 3.7.4.

3.7.3 Analytical approach for cost estimations

There are several research suggesting methods to estimate the cost of a product. However, the purpose of this research was not to discuss cost-attributed financial influences in detail. Therefore, a simple, accurate, and reliable method for estimating the cost of the packaging was chosen. The analytical approach is a broadly discussed method in cost estimation. This method breaks the product into basic units such as material, operation, and activities. Then the incurred cost for each unit is accumulated [161]. The cost breakdown was done using the information provided by the industrial experts and was supported by the literature.

The cost has been divided into sections in research that have developed a cost estimation model for food packaging [108]. This study has considered the direct costs and overhead costs of food packaging. However, the component disintegration was limited only to direct costs since data was unavailable for indirect costs and other unquantifiable components discussed in publications. The considered components in cost estimation are highlighted in pink colour in Figure 3.6.

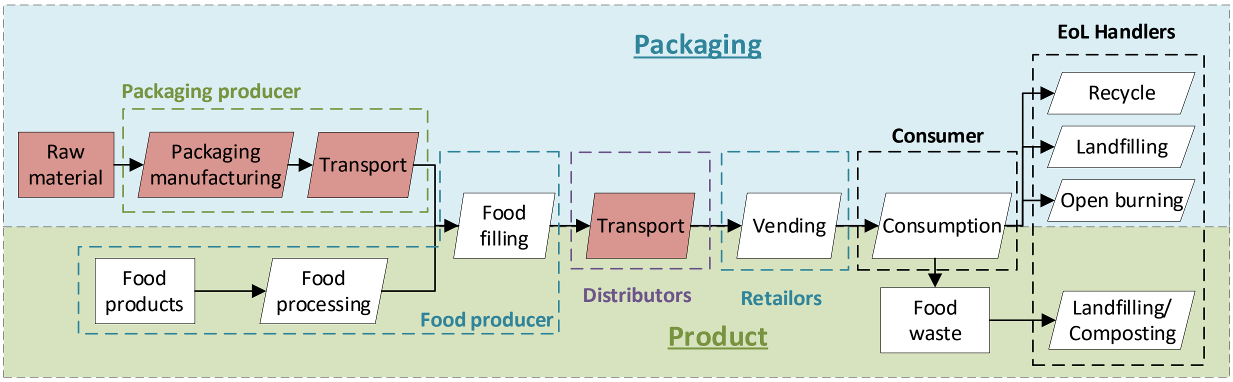


Figure 3.6: Cost components considered (the elements considered for the LCA system boundary are highlighted in maroon colour)

The cost of materials, labour, and manufacturing were the three main cost components identified at the production level [108]. The cost of labour was a vague parameter to be determined. However, since most of the machines are fully automated, the cost of labour has not been considered significant by the packaging manufactures. The cost of waste handling and recycling was not considered within the scope of cost estimation due to the unavailability of data.

The costs incurred in transportation were included in the study with a novel approach incorporating the occupied volume of the packaging. A similar approach was found in literature where the influence of the number of units transported in a lorry has been considered in cost estimation [162]. The occupied volume of the packaging was adapted to estimate the cost of transportation in a way similar to the estimation of environmental impacts. In this model, the cost of transportation per unit was calculated based on the number of items transported in the lorry incorporating the concept of occupied volume. The suggested model is represented in Equation 8.

$$\text{Cost}_{\text{Transport}} = \frac{\text{No. of kilometers} \times \text{Cost per km for the lorry}}{\text{Nu of units in the lorry}}$$

$$\text{Cost}_{\text{Transport}} = \frac{\text{No. of kilometers} \times \text{Cost per km for the lorry}}{V} \times v \qquad (8)$$

V- volumetric capacity of the lorry (load space)

v- occupied volume of the packaging

The cost of each component was collected from the packaging manufacturing companies as given in Table 3.4.

Table 3.4: Cost of items

Cost item	Cost
PET material	1,400 USD/ ton
HDPE material	1,600 USD/ ton)
PP material	1,450 (USD/ ton)
Transportation	0.6 (USD/ *km*.lorry)

After calculating the total cost, results were normalized following the method described in Section 3.7.4.

3.7.4 Interpreting sustainability using a single index

The three different parameters could not be aggregated using a simple aggregation method since the behaviour of the parameters is preferred in two different ways. Lower values are desirable for environmental impact and financial cost; for consumer preference, higher values are expected. Thus, it was necessary to normalize them to compare on a single platform. The following mathematical equations were used to normalise the calculated values of the three parameters on a higher-the-better basis [163].

The equation for normalising the higher-the-better parameters:

$$N_i^g = \frac{X_i}{X_{max}^g} \tag{9}$$

The equation for normalising the lower-the-better parameters:

$$N_i^g = \frac{X_{min}^g}{X_i^g} \tag{10}$$

N_i^g - normalised value for the i^{th} option under g^{th}criteria

X_i^g - value of the i^{th} option under g^{th} criteria

X_{min}^g, X_{max}^g - minimum and maximum value in the data set under g^{th} criteria

Fuzzy Analytical Hierarchy Process (FAHP) for aggregating three performance indicators

After normalizing the results, it was necessary to aggregate them to represent sustainability in a single index for easy comparison. The Analytical Hierarchy Process (AHP) is used to rank options by taking insights from different experts and decision-makers [164], [165]. First, weights are assigned to multiple criteria through pair-wise comparison [166]. Then, different options are evaluated based on the weights assigned to each criterion. Further, the consistency of the results is calculated to ensure the outcome's validity.

Fuzzy AHP (FAHP) is an advanced version of AHP that considers the decision-maker’s fuzziness. In this method, lower and upper bound values are assigned instead of assigning a single value for the priority. There are several methods, such as triangular, trapezoidal, interval, and fuzzy numbers, to determine the lower and upper bound values [167]. The triangular method, a straightforward and reliable way, was used in this study for determining the fuzzy numbers, as given in Table 3.5.

Table 3.5: Linguistic variables for pair-wise comparison of each criterion [168]

Linguistic variable	**Fuzzy scale**
Extremely strong	(9,9,9)
Intermediate	(7,8,9)
Very strong	(6,7,8)
Intermediate	(5,6,7)
Strong	(4,5,6)
Intermediate	(3,4,5)
Moderately strong	(2,3,4)
Intermediate	(1,2,3)
Equally strong	(1,1,1)

The next step was to develop the pairwise comparison metrics and calculate the weights. Comparison data between criteria were obtained through interviews with four academics using the data recording sheet given in Table 3.6.

Table 3.6: Table used for recording data during interviews to facilitate AHP

Name of the respondent:

	Functional satisfaction	Environmental impact	Cost
Functional satisfaction	(1,1,1)		
Environmental impact		(1,1,1)	
Cost			(1,1,1)

At first, two criteria were selected, and the respondent was asked which criteria they considered most. Then the significance of that criterion over the other criterion was obtained in numerical scale ranging from 1 to 9 (refer to Table 3.5). Three pair-wise comparisons were questioned since there were only three parameters to be considered as shown in Table 3.6. After collecting responses, a pairwise comparison matrix was developed with fuzzy sets for each response. Then, the obtained responses were normalized using Equation 11 [168].

$d_{i,j}^{k}$ − fuzzy set of the k^{th} respondent's preference of i^{th} criterion over j^{th}criterion

a^k, b^k, c^k − lower, middle, and upper fuzzy numbers for the k^{th} response

f − the total number of responses received

n − the total number of criterion

$$d_{i,j} = \left(a_{i,j}, b_{i,j}, c_{i,j}\right) \quad where\ a_{i,j} = (a^1 \times a^2 \times \dots \times a^f)^{1/f}, \tag{11}$$

$$b_{i,j} = (b^1 \times b^2 \times \dots \times b^f)^{1/f}, c_{i,j} = (c^1 \times c^2 \times \dots \times c^f)^{1/f}$$

The developed pair-wise comparison matrix is shown in Equation 12.

$$Pair - wise\ comparison\ matrix = \left[\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix}\right] \tag{12}$$

The developed pair-wise comparison matrix is given in Table 3.7.

Table 3.7: Normalized comparison matrix for FAHP

	Functional satisfaction	**Environmental impact**	**Cost**
Functional satisfaction	$(1 \quad 1 \quad 1)$	$(2 \quad 2.2 \quad 2.4)$	$(3.2 \quad 4.2 \quad 5.3)$
Environmental impact	$\left(\frac{1}{2.4} \quad \frac{1}{2.2} \quad \frac{1}{2}\right)$	$(1 \quad 1 \quad 1)$	$(1.4 \quad 2.4 \quad 3.5)$
Cost	$\left(\frac{1}{5.3} \quad \frac{1}{4.2} \quad \frac{1}{3.2}\right)$	$\left(\frac{1}{3.5} \quad \frac{1}{2.4} \quad \frac{1}{1.4}\right)$	$(1 \quad 1 \quad 1)$

After that, the methodology suggested by Ayhan M.B. was followed to calculate weights for each criterion, as illustrated below [169].

1. First, the geometric mean of fuzzy values was calculated, as shown in Equation 13.

$$r_i = \left(\prod_{j=1}^{n} d_{ij}\right)^{1/n} \quad i = 1,2, \dots, n \tag{13}$$

Sample calculation conducted for 'Functional satisfaction' is given below.

1. $\boldsymbol{r_i = \left(\prod_{j=1}^{n} d_{ij}\right)^{1/n}} =$

$$[(\mathbf{1 \times 2 \times 3.2})^{\mathbf{1/3}} \quad (\mathbf{1 \times 2.2 \times 4.2})^{\mathbf{1/3}} \quad (\mathbf{1 \times 2.4 \times 5.3})^{\mathbf{1/3}}]$$

$$= [\mathbf{1.85} \quad \mathbf{2.12} \quad \mathbf{2.35}]$$

The summation of $\boldsymbol{r_i}$ was calculated, and the reciprocal was obtained. Then they were reordered in ascending order as given in in Table 3.8.

Table 3.8: Geometric mean of fuzzy comparison values

Criteria	$\boldsymbol{r_i}$		
Functional satisfaction	1.85	2.12	2.35
Environmental impact	0.83	1.03	1.20
Cost	0.38	0.46	0.61
Total	3.06	3.61	4.16
Power of -1	0.33	0.28	0.24
Increasing order	0.24	0.28	0.33

2. Next, the fuzzy weights of criterion $\boldsymbol{i}$ ($\boldsymbol{w_i}$) was calculated using Equation 14.

$$w_i = r_i \times (r_1, r_2, \dots r_n)^{-1} \qquad (14)$$

$$=(lw_i, mw_i, uw_i)$$

The values are given in Table 3.9.

Table 3.9: Fuzzy weights for each criterion

Criteria	$\boldsymbol{w_i}$		
Functional satisfaction	0.44	0.59	0.77
Environmental impact	0.20	0.29	0.39
Cost	0.09	0.13	0.20

3. The fuzzy triangular numbers were de-fuzzified using Equation 15.

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \qquad (15)$$

4. The weights were normalized to obtain criteria weight (CW) by applying Equation 16.

$$CW_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \qquad (16)$$

The de-fuzzified and normalized values are given in Table 3.10.

Table 3.10: Weights for each criterion

Criteria	M_i	CW_i
Functional satisfaction	0.60	0.58
Environmental impact	0.29	0.28
Cost	0.14	0.13

5. The sustainability index value was obtained using the following Equation 17.

$$Sustainability\ index\ value\ for\ y^{th} design\ option = \sum_{1}^{3} CW_i \times N_y^i \tag{17}$$

The sustainability index values were obtained as discussed in Section 4.1.4. and Section 4.2.4. for the two cases respectively.

3.8. Approach to developing the policy framework

A predefined set of instructions or methodologies is unavailable for framework development [170]. However, some studies have used design science research (DSR) as an approach to policy framework development [125]. DSR is "*a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative artefacts, thereby contributing new knowledge to the body of scientific evidence*" [171]. The main aim of DSR is "*to create knowledge and understanding of a problem through the building and the application of an artefact*" [172]. It develops artefacts that can be applied to solve real-world problems or enhance organizational efficacy [124], [172]. This is a well-established method in developing information technology artefacts associated with information systems but there are events where it has also been used for other applications to assist framework development [172].

The DSR combines the knowledge base and application environment to formulate artefacts as shown in Figure 3.7. The artefact is developed considering the business needs of the environment while making use of knowledge from related subject areas. The formulation of the artefact is an iterative process between assessment and refinement. The knowledge improved through the outcome is transferred to the knowledge base, and the artefact influences the environment.

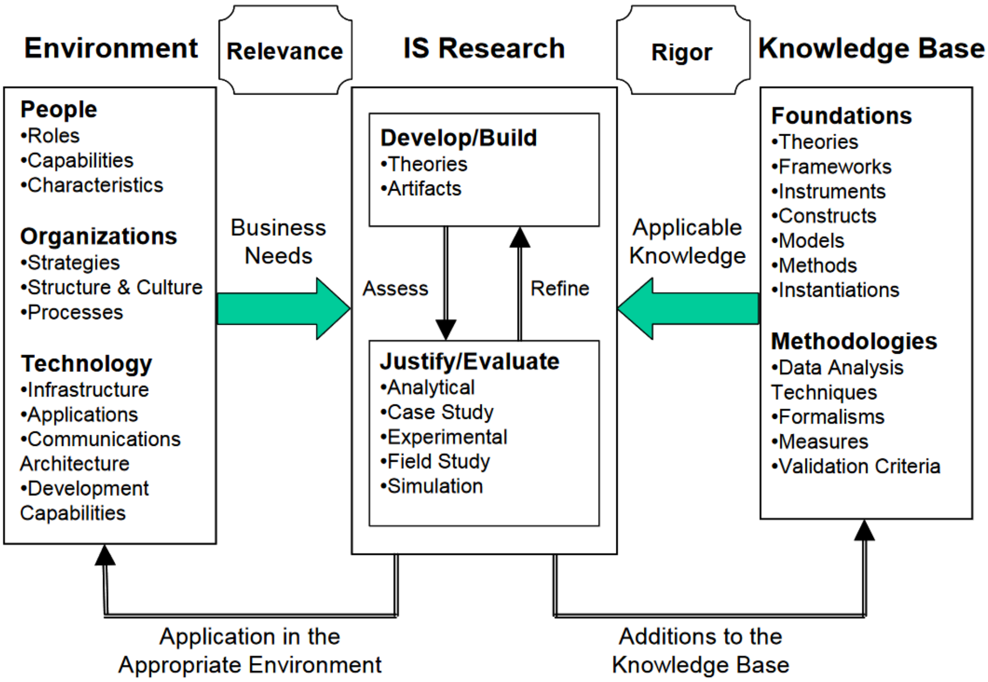


Figure 3.7: DSR framework [173]

The iterative trial-and-error method was used with tools and theories to develop the framework. The insights from the results obtained from this research and available literature were used as the foundation for the framework. In addition, existing frameworks (refer to Section 2.6.2.) were assisted in sketching the structure in the development phase. Several brainstorming sessions were conducted to optimize the framework before validating it through external personal.

3.9. Validating the framework- Delphi method

The framework was developed to provide a structure for the authorities to formulate policies and develop sustainable food packaging. After developing the framework, it was necessary to ensure that the framework could deliver the expected outcomes for acceptance among the scientific community [174]. Validation of quantitative research is a well-established area of knowledge. Generally, quantitative research could be validated using the results obtained through statistical analysis. In qualitative research, it could vary depending on the researcher's interpretation, the construction and the reflection of information [174]. Due to the lack of clarity and consensus on the method, the validation of qualitative research has been debated by researchers [175]. Referring to relevant literature, validation against experts' opinions and processual validation are some of the most common methods suggested [174], [175].

In qualitative research, the framework validation is a grey area. Referring to appropriate literature has been suggested as the obvious way of validation [176]. The second way is to refer to one or more experts for their criticism. The implicit knowledge acquired over years of experience is a reliable way of framework validation [176]. Therefore, validation through the expert's perspective is expected to provide more credibility to the validation process [176]. The Delphi method is a systematic approach which uses experts' perceptions for the validation process. In the Delphi method, multiple evaluation criteria are refined through literature and are used to validate the artefact against experts' perspectives. However, referring to multiple methods, such as both the literature and experts' perspectives, could be identified as a method for improved validity [177].

In this research, the experts' opinion was used to validate the framework based on several criteria. As the first step, the suitable criteria were selected (refer to Section 3.9.1) and then the validity was assessed through the experts' perspective, as discussed in Section 0

3.9.1 Identification of validation criteria

Identifying criteria for validating qualitative research is challenging due to the criteria's proliferation, uncertainty, and subjectivity [175]. Thus, only a limited number of publications have systematically analysed criteria for the validation process. Different validation and evaluation criteria utilized in management accounting have been explicitly discussed under three different categories [175]. The classification is based on their approach to validation: adopting classic criteria, adopting alternative criteria, and abandoning common evaluation criteria. Among them, the first two types of validation criteria are elaborated in Table 3.11 and the third type is discussed in the following paragraph.

Table 3.11: Evaluation criteria in literature

Evaluation criterion	Description
Criteria Type I- Adopting a classic approach	
Internal validity	Ensures that all phases of the research are accurate and acceptable and deliver the intended outcome
External validity	Assuring the ability to apply the research findings to other situations
Construct validity	The assessment of the operation ability of the theory developed.
Reliability	Ability to deliver the same results on several trials
Generalizability	Ability to extend the idea for general applications
Criteria Type II- Adopting alternative criteria	
Credibility	The observations and data are sufficient to make claims
Conformability	Research findings are linked with the data in an easily understandable way
Transferability	Applicability of the concept/ findings with other applications
Plausibility	The validity of the logical approach to draw conclusions

Abandoning common evaluation criteria is the third type of validation criterion, which was not included in the above table since no list of criteria was identified. In this approach, the use of a case-specific unique set of criteria is encouraged since the selection of criteria is a very subjective matter for each study [175]. However, available publications suggest suitable criteria and methodological approaches that are adaptable to this study.

Another research has elaborated the validity of qualitative research under four main criteria: credibility, transferability, dependability, and confirmability [178]. Credibility stands for the research's internal validity, which ensures the proper utilization of methods in the data collection phase. Under credibility, the measures that could be taken to improve the quality of data sources and the data collection process are discussed. Transferability refers to the extent to which the research findings apply to other situations. Dependability is a measure of the consistency of the results. Confirmability measures the isolation of the researcher’s perspective from the results. Moreover, the study illustrates the remedies that could be formulated in the research design phase, mainly focusing on validating results. However, credibility and transferability are two areas that could be further extended in validating the conclusion.

In this study, the validation process was carried out under two sections due to the complexity of validating the proposed framework, which has multiple phases (refer to Chapter 5). The first set of criteria was selected to assure the validity of each phase, while the second set of criteria validated the overall framework. The identified set of criteria for validating each phase is given in Table 3.12 and the criteria for validating the overall framework is given in Table 3.13.

Table 3.12: Validation criteria used for validating each phase of the proposed framework

Criteria for each phase
Covers all the aspects to be considered
Proposed stages are logical
Proposed stages are practical

Table 3.13: Validation criteria used for validating the overall framework

Criteria for the overall framework
The phases are in order and systematically guide the user
Sufficiently addresses the areas to improve environmental sustainability
Sufficiently addresses the areas to improve financial/ social sustainability
Provide sufficient guidance for packaging designers and policy developers

3.9.2 Assessment of validity- Questionnaire

There are several techniques for assessing the validity of the research using the aforementioned criteria. Triangulation is the most general and common approach for validating the outcomes of qualitative research [179], [180]. In this case, the real-world validation of a framework of this scale may need to be done years after implementation. Additionally, such a validation process may need extensive resources and time, which is not practical within the scope of this study. Therefore, the Delphi method was selected as the suitable technique for evaluating the framework through the perception of external reviewers.

The Delphi method suggests an approach for validation through experts' perception eliminating the necessity of a long-term validation process [181]. In this method, the experts' opinions are collected iteratively to achieve a convergence of opinions [182]. The method consists of several stages as the selection of an expert panel, design of the questionnaire and scoring method, execution of iterative data collection rounds, and data analysis [182]. The number of iterations may depend on the purpose of the research, and generally, two or three iterations are sufficient

[182]. The expert panel should be selected carefully since they influence the validation quality. Therefore, the selected experts are expected to meet several requirements; knowledge of the field, the willingness to participate, and availability for data collection [183]. A panel of industry experts were identified through focused group networks, adhering to the aforementioned criteria. Then, their opinion about the validity of the framework under each criterion was collected.

In this study, the initial validation phase was focused on collecting qualitative data for major changes, while the next phase was a mixed method (qualitative and quantitative) for assessing the level of acceptance using the Likert scale and text. Several brainstorming sessions were conducted within the research team and academics from other departments to refine the proposed framework. The resource person brought up multiple constructive measures that were implemented during this initial validation phase. The final evaluation was conducted with academics from different countries to get their feedback to identify the aspects which need further attention in the proposed framework. The reviews from external specialists were assisted in validating the proposed framework. A questionnaire was prepared using GoogleForm to collect experts' opinions on the validity under different criteria. The developed questionnaire is given in Annex D. 42 academic experts from different countries were identified through their publications related to the sustainability of food packaging. They were requested to fill out the GoogleForm by sending an email and a detailed description of the proposed framework. Six responses were collected for the questionnaire; three were through emails and three were from discussions with experts. The number of experts seems to be insufficient compared to a public survey. However, in the case of a focused group, the quality of data collected is assessed by the quality of the expert panel instead of the number of respondents [182].

The modifications suggested at the final evaluation were reviewed and acceptable ones were implemented. Then, the revised version was sent for evaluation again. In total, the proposed framework was iteratively modified and validated 3 times in the final stage improving the validity of the proposed framework.

4. CASE STUDY ANALYSIS AND RESULTS

This chapter focuses on identifying the parameters for developing the framework. The first two sections of this chapter elaborate on how the suggested methodology in Chapter 3 was used for developing and evaluating the designs for the two case studies: ketchup bottles and ice cream containers. The last section analyses the outcomes of the case studies, which assisted in the development of the proposed framework.

4.1. Case 1- Ketchup bottle

The ketchup bottles were selected as the first case study, as discussed in Section 3.3. The ketchup bottles should facilitate several functional requirements showing a higher capability. In addition, it is a common product showing a higher market share and convenience for the public. A range of ketchup bottles is available in the market in different materials and sizes manufactured by multiple producers. Ketchup bottles are available in different sizes ranging from 400 *ml* to 200 *ml* and single portion sachet packets with 15 *g*. In addition, there are plastic cans from 1 *kg* to 4.5 *kg* and 400 *g* multilayer catering packs for large-scale applications (restaurants). Thus, a vast range of products and applications were seen with ketchup products which qualify it to be used as a case study.

4.1.1 Classifying functional requirements of ketchup bottles

Initially, it was necessary to identify the functional attributes of ketchup bottles and develop a questionnaire to prioritise them. Fifteen functional attributes were screened under technical, facilitate handling and communication categories for the ketchup bottles, as shown in Figure 4.1. The functional attributes were categorised based on Kano's theory, and each attribute is highlighted with a different colour based on Kano's classification.

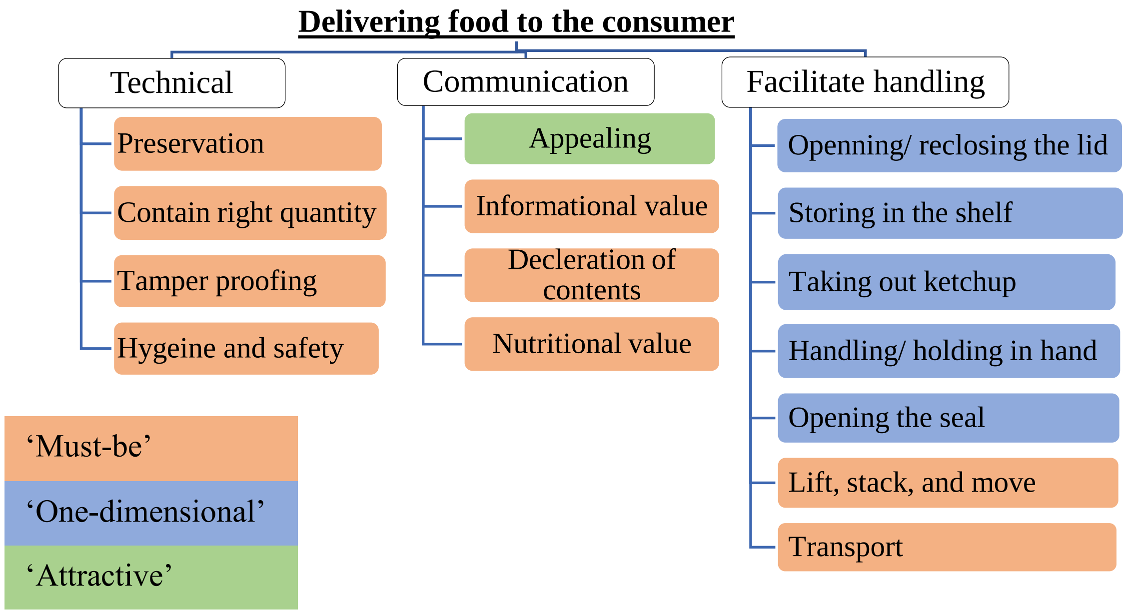


Figure 4.1: Functional attributes of ketchup bottles

The weight of each functional attribute was estimated through the rank assigned by the public based on 'Questionnaire-A' as discussed in Section 3.7.2 (see Appendix A for the questionnaire). The 'Must be' attributes were mandatory for the product to be eligible to appear in the market because non-fulfilment of 'Must-be' attributes will eliminate the product from consumer consideration. Thus, only 'One-dimensional' attributes were considered in assessing functional satisfaction considering its high influence on consumer satisfaction. The questionnaire results were used to rate the functional attributes of ketchup bottles as shown in Table 4.1.

Table 4.1: Assigning weights to functional attributes for ketchup bottles based on Questionnaire-A

Attribute	**Score**	**Weight (%)**
Taking out sauce	255	26.32
Closing/ opening the lid	210	21.67
Handling/ holding	188	19.40
Storing	165	17.03
Opening the seal	151	15.58

4.1.2 Identifying and prioritising features/ characteristics

Initially, the packaging components were identified as lid/ cap, body, seal, and label. The label was eliminated from this study under design considerations since it only satisfies a non-physical functional requirement. Somehow, displaying essential information to the customer and consumer is highlighted which is beyond the scope of the study. For the cap/lid, the closure mechanism and the material were the two identified characteristics/ features related to the lid/cap. For the body, the material, shape, dimensions, and strength/ thickness were the features. The shape and the dimensions showed a higher relationship since the enclosed volume is directly related to the shape and the dimensions. There were a few different types of seals in the market. However, the two different features were the seal type, the technique used for sealing and the material used. Overall, for the three main components considered in the study, eight different features/ characteristics were identified for the ketchup bottles.

The next step was prioritising features/ characteristics based on their influence to satisfy functional requirements. The HOQ described in Section 3.5.3 was used for prioritising the design features. The relationship matrix between the design features and the functional attributes was developed with the responses from the packaging designers. Semi-structured interviews were guided with the questionnaire (refer to Appendix B) on data collection for the relationship matrix. A Likert scale was used to rate the significance level of the relationship between the features and functions. The packaging designers were contacted through the ketchup producers. Somehow, only one manufacturer had a food packaging designer as an employee in their company and no other had since the packaging designs were developed generations ago. Thus, an academic was contacted via video conferencing technology to get input on the functional-feature relationship. The feature-function relationship matrix was developed with the responses from the resource person as shown in Table 4.2. The resource persons shared their knowledge and experience on the design constraints and guidelines, which assisted in designing packaging component options useful in developing packaging designs.

Table 4.2: Prioritised design features for ketchup bottles with feature-function relationships

Functional attributes \ Features	Weight for each attribute (%)	Lid/ cap		Body				Seal	
		Material	**Closure mechanism**	**Material**	**Shape**	**Dimensions**	**Strength/ Thickness**	**Type/ Shape**	**Material**
Opening/ closing	26	3	9	9	3	3	9		
Handling	21			1	9	9	3		
Storing	19			1	3	3			
Opening the seal	17			1	1	1		9	9
Emptying the container	15	9	9	3	3	3	3		
Weights for features		187	315	318	368	368	342	153	153
Priority rating		6	5	4	1	1	3	7	7

4.1.3 Designing packaging options

The body of the packaging was identified as the component which needs to be considered most compared to the lid/ cap and the seal. The shape and the dimensions of the body had the highest importance score notifying the importance of paying more attention to these two factors when designing the body. The lid/ cap scored the next highest, followed by the seal.

Designing the lid

Ketchup falls under the non-perishable food category, which could be stored for months if stored carefully. Thus, extra attention should be paid to tightly fitting the lid/ cap to preserve the content. There were two design suggestions available for cap/ lid design. The cap, which is completely removed when opening the bottle is in Figure 4.3, and the partially opening flip-flop caps are given in Figure 4.2). In the flip-flop caps, the upper part of the cap is hinged to the lower part, and the lower part is threaded to the bottle body. Since the cap is not entirely removed, the content touches the cap when flowing out. Thus, the cap should be designed with shapes to minimize the resistance to flow. In addition, a material with a lower friction coefficient such as HDPE is preferred to allow ketchup to flow without sticking to the cap.

Figure 4.2: Partially opening flip-flop caps

The other type of cap is completely removed when opening. A thread is used to tighten the cap so the user can remove it by turning it. Thus, the designer only needs to consider the ease of turning/ removing the cap and sealing the content inside securely once it's closed. Polypropylene (PP) was identified as a suitable material alternation for this application after discussions with packaging designers.

Figure 4.3: Completely removable threaded caps

Designing the body

The angles of the bottle neck are determined to create a continuous flow over the body wall without any disturbances for dispensing. The dimensions of the bottle are determined such that it is very convenient to hold in hand and contain the right quantity. The flexibility to squeeze the body is another consideration since taking out ketchup by squeezing the bottle is necessary. The strength of the bottle should hold the content without deforming. In some applications, ribs are used to provide additional structural rigidity. Somehow, horizontal ribs with sharp edges are not preferred inside the bottle, which could interrupt the ketchup flow. Vertical ribs could have been utilised to strengthen the bottle since any external utensil is not to be used to take out the content.

In cases where a spoon or a knife is used for taking out the content, vertical ribs should be used carefully such that it does not obstruct emptying the content.

Several factors were considered when selecting Polyethylene terephthalate (PET) as the suitable material for the ketchup bottle. PET is the most used material for plastic ketchup bottles in Sri Lanka. The ability to create intricate shapes using blow moulding, which is an existing technology in Sri Lanka, was a plus point on PET. In addition, PET is the most recycled material globally and locally, which highlights the competence of suggesting a more suited waste processing technique.

The thickness of the body is the other factor which determines the strength influencing the material quantity and flexibility. If the thickness is reduced excessively, it will not be able to withstand the forces under stacking and will not return to the initial shape after squeezing. In addition, during the interviews, the packaging designers recommended a minimum thickness of 0.4 *mm* to avoid warping during manufacturing. The vertical load acting on the bottle was determined based on the expected stacking height. The finite element analysis (FEA) was used to verify that the bottle design can withstand the forces induced on the top surface under the minimum manufacturable thickness. A stacking height of 4 *m* was determined for the ketchup bottles based on the input from packaging manufacturers, and the forces acting on the top surface of the bottles were determined. The forces were calculated as 76 *N*, 73 *N*, 101 *N*, and 131 *N* for the four options. The total deformation of each bottle design is shown in Figure 4.4.

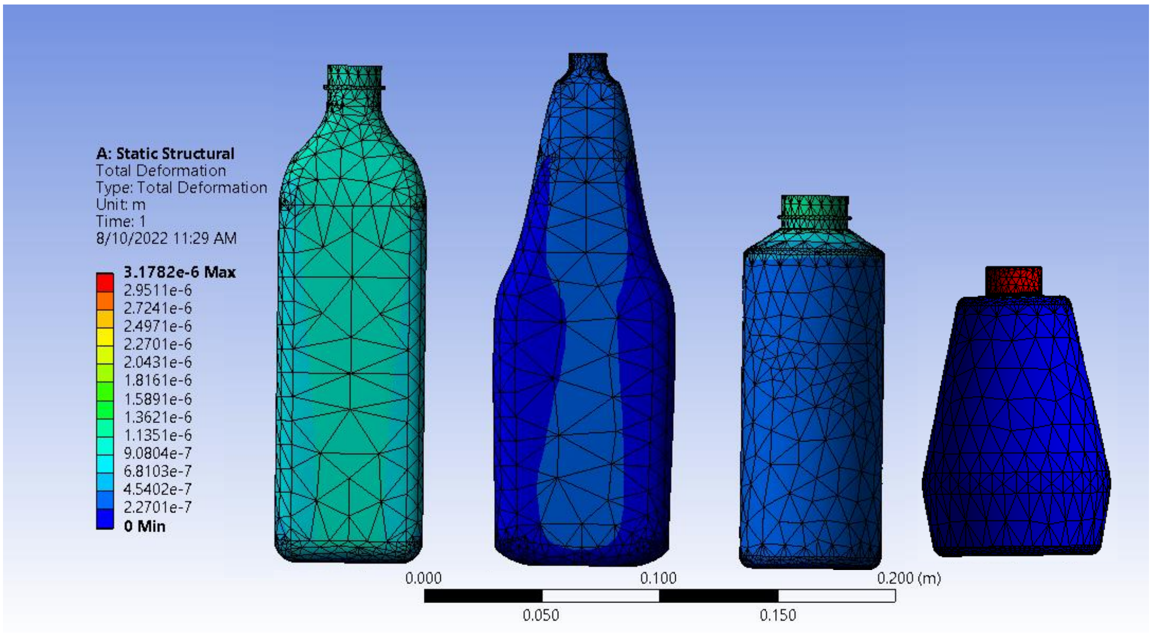


Figure 4.4: Total deformation of ketchup bottles under top loading

The maximum deformation in the analysis was less than 0.004 *mm* which is negligible. Meanwhile, the maximum stress induced in the bottle body was also less than the yield stress. Therefore, it was concluded that the bottles could withstand the external forces acting on the bottles.

In addition, the diameter of the opening is another concern which determines the ease of taking out ketchup. The diameter was determined based on the expected functionality and the physical parameters of the content inside. It was supposed to be large enough for ketchup to come out easily and small enough not to flow out the content suddenly if the bottle was turned upside down accidentally.

After considering all the factors above, four different body designs and three different cap designs were developed inspired by the existing products in the local/ international market and online websites. The design options were named as $Op_{i,j}$ where i stands for the component and j is a number assigned for the design option. Each cap design was combined with the bottle body to develop a complete packaging design resulting in 12 packaging options in total. The developed packaging designs and the specifications of the components are as follows in Table 4.3. The developed packaging options numbered 1 to 12 for easy discussion. 'Option 5' was the available ketchup bottle design in the market which was used as the reference to compare the functional satisfaction, environmental impact, and cost.

Table 4.3: Component combinations for packaging options

			Body			
			$Op_{Body,1}$ PET (33.5 g)	$Op_{Body,2}$ PET (36.2 g)	$Op_{Body,3}$ PET (29.6 g)	$Op_{Body,4}$ PET (27.3 g)
						
Cap	$Op_{Cap,1}$ PP (3.0 g)		Option 1	Option 4	Option 7	Option 10
Cap	$Op_{Cap,2}$ LDPE (4.1 g)		Option 2	Option 5*	Option 8	Option 11
Cap	$Op_{Cap,3}$ LDPE (9.2 g)		Option 3	Option 6	Option 9	Option 12

* *'Option 5' was available in the market and was considered the benchmark for evaluating the other packaging.*

4.1.4 Calculating the sustainability index

The identification of environmental, social, and financial sustainability using the results obtained for functional satisfaction, environmental impact, and cost are the main areas discussed in this section. Finally, the results were normalized and aggregated following the method described in Section 3.7.4.

1. Environmental impact

The data required to develop the LCI were acquired from the SolidWorks models (Table 4.4).

Table 4.4: LCI for ketchup bottles

	Material Weight (g)		kg.km value
	PET	PP	
Option 1	33.5	3.0	43.8
Option 2	33.5	4.1	49.9
Option 3	33.5	9.2	47.3
Option 4	36.2	3.0	56.4
Option 5	36.2	4.1	64.1
Option 6	36.2	9.2	60.5
Option 7	29.6	3.0	49.5
Option 8	29.6	4.1	58.0
Option 9	29.6	9.2	53.9
Option 10	27.3	3.0	69.4
Option 11	27.3	4.1	84.8
Option 12	27.3	9.2	76.8

The environmental impact was calculated under 18 categories. Figure 4.5 shows that 'Option 6' has the highest impact under almost all impact categories, and 'Option 10,11' has the minimum impact under the majority of impact categories.

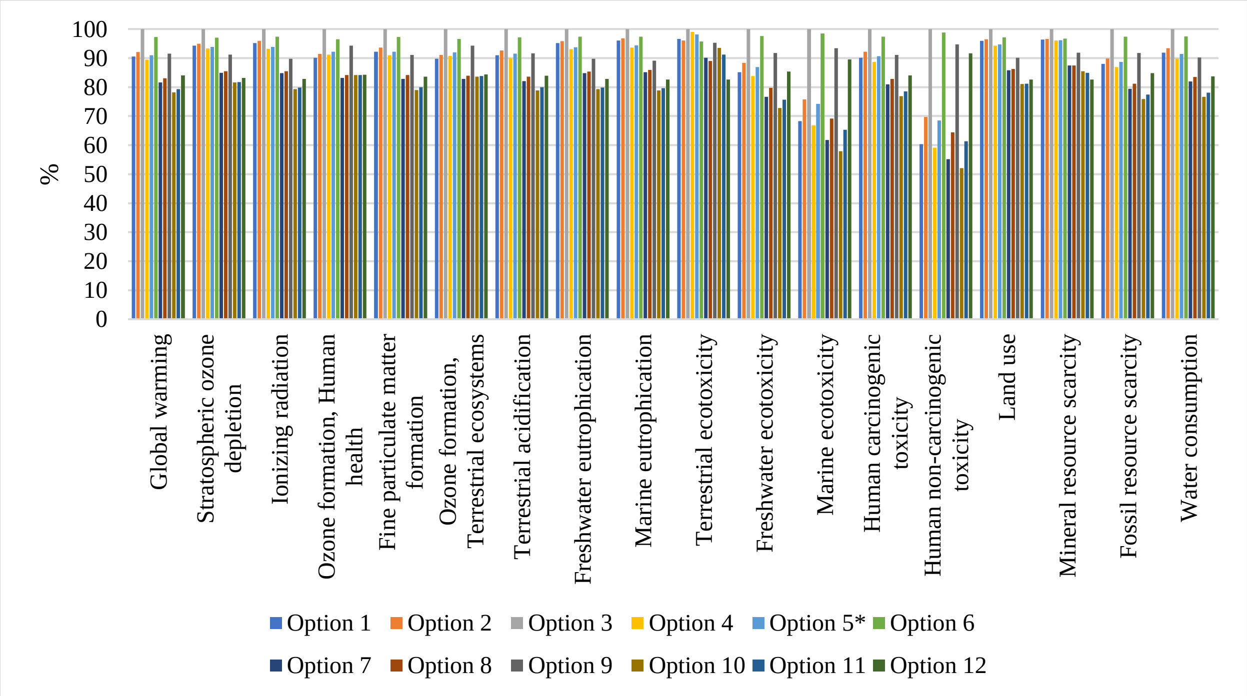


Figure 4.5: Environmental impact from ketchup bottle design options

Due to the difficulty of analyzing all the factors at the same time, global warming potential (GWP) was considered as the representative category. The GWP for a single packaging unit is given in Figure 4.6. It was much easier to represent the impact of all the packaging options under one single parameter for convenience for analytical purposes.

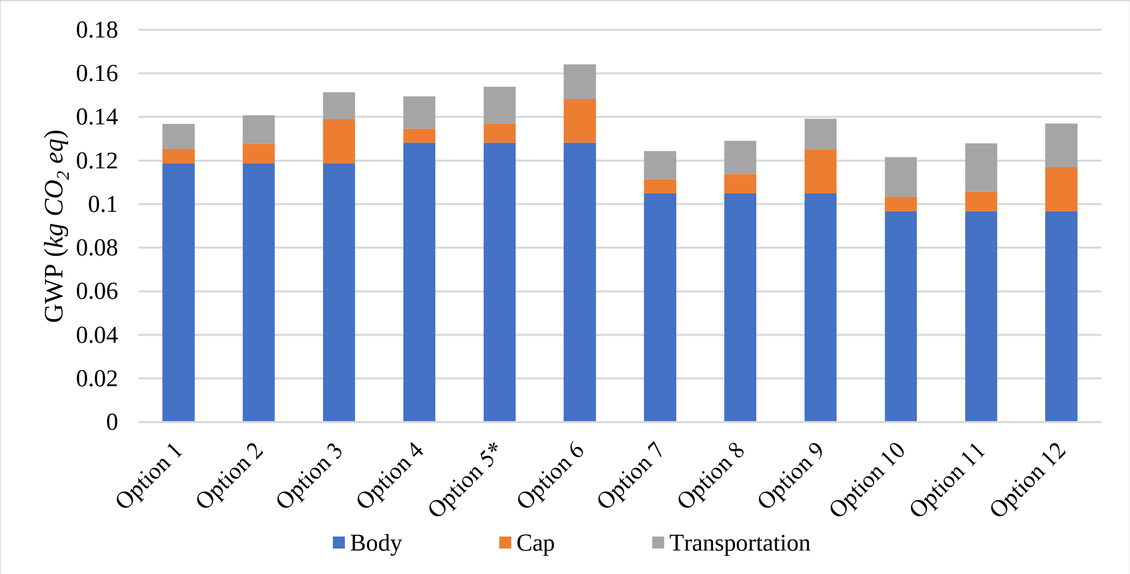


Figure 4.6: Global warming potential from ketchup bottle designs

Packaging 'Option 6' shows the highest amount of impact, followed by 'Option 5' (refer to Figure 4.7), which is readily available in the market today. This highlights a significant potential of taking action to find solutions for an eco-friendlier packaging design. The body of the containers seems to have the highest influence on GWP, followed by the cap and transportation in every packaging design.

Figure 4.7: Different Ketchup bottle designs

Besides the induced environmental impact, several design-specific characteristics could influence the EoL scenarios. In every bottle design, the body and the cap are made of two different materials which lowers the ability to recycle. The first cap design (shown in Figure 4.3) comes with a pilfer-proof ring which is undetachable from the body. This raises a limitation in separating materials during the recycling process. Nevertheless, other cap designs allow for pulling out the PP or LDPE cap completely from the bottle body, allowing easy recycling.

2. Functional satisfaction

The completed HOQ shown in Figure 4.9 was assisted in identifying the consumer preference over different packaging options. The weights that indicate the consumer preference for each design were calculated as given in HOQ. 'Option 5' seemed to have the highest consumer preference which is already available in the market. The convenience of use would have been highly influential for the result. These biases could have been eliminated by presenting the questionnaire to an audience that has not used these products previously. However, finding such an audience from a foreign country is challenging, and their usage behaviour may not be similar to the locals. Thus, the results obtained from a different community would not be applicable to the local community.

The functional satisfaction was calculated as a percentage with respect to the sum of the functional satisfaction score values (the functional satisfaction score is discussed in Section 3.7.2) in HOQ as in Figure 4.8. Results show that nearly 14% of the population prefers 'Option 5' over other options. The first six options, which have square-shaped bottle bodies, show a higher consumer preference compared to the last ones. This has been caused by the higher consumer preference values they have obtained under the ‘closing/opening lid’ and ‘handling/ holding’ functional criteria. However, these two functional attributes seem to be much related to one another since ketchup bottles are opened while holding them by hand. Additionally, the rectangular cross-sectional shape seems to be preferred by consumers.

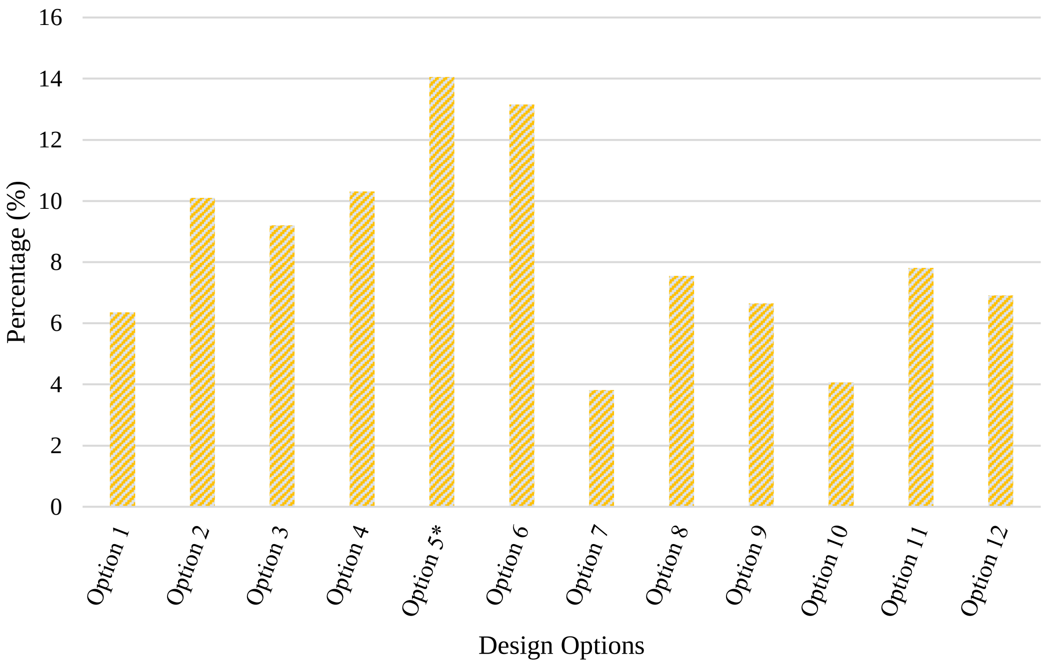
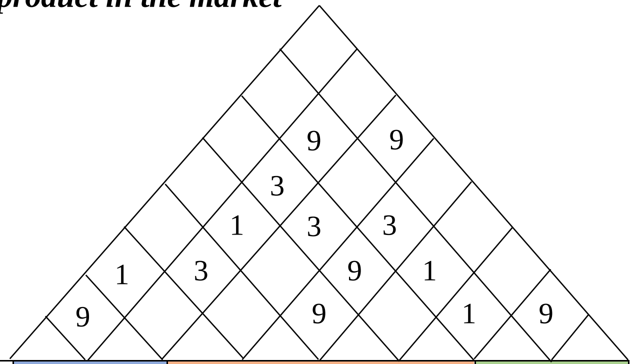


Figure 4.8: Percentage-wise functional satisfaction of different bottle designs

**Existing product in the market*



Features / Functional attributes		Lid/ cap		Body				Seal													
		Material	**Closure mechanism**	**Material**	**Shape**	**Dimensions**	**Strength/ Thickness**	**Type/ Shape**	**Material**	**Option 1**	**Option 2**	**Option 3**	**Option 4**	**Option 5***	**Option 6**	**Option 7**	**Option 8**	**Option 9**	**Option 10**	**Option 11**	**Option 12**
Taking out sauce	26	3	9	9	3	3	9			4	6	10	4	6	10	4	6	10	4	6	10
Closing/ opening lid	21			1	9	9	3			5	5	5	9	9	9	3	3	3	3	3	3
Handling/ holding	19			1	3	3				6	6	6	8	8	8	2	2	2	1	1	1
Storing	17			1	1	1		9	9												
Opening the seal	15	9	9	3	3	3	6			7	20	12	17	29	21	5	18	10	7	19	11
Weights		187	315	318	368	368	351	153	153	**24**	**37**	**34**	**38**	**52**	**49**	**14**	**28**	**25**	**15**	**29**	**26**
Importance rating		6	5	4	1	1	3	7	7												

Figure 4.9: House of Quality for ketchup bottles

3. Cost estimation

The costs incurred for each component and transportation are shown in Figure 4.10. Option 6, which has the highest environmental impact, dominates the cost criteria too. The amount of material and energy used for that packaging design would have influenced the environmental impact and cost.

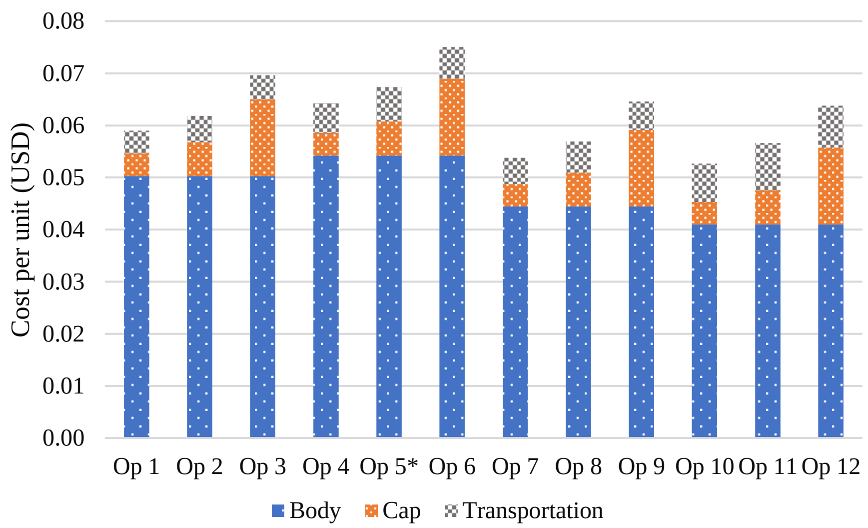


Figure 4.10: Estimated cost for ketchup bottle designs

4. Normalising the results

The calculated values for consumer preference, GWP, and cost are as in Table 4.5.

Table 4.5: Consumer preference, eco-impact, and cost incurred for ketchup bottles

	Option 1	**Option 2**	**Option 3**	**Option 4**	**Option 5***	**Option 6**	**Option 7**	**Option 8**	**Option 9**	**Option 10**	**Option 11**	**Option 12**
Functional satisfactions score	23.6	37.5	34.1	38.3	52.12	48.8	14.2	28.1	24.7	15.1	29.0	25.7
GWP per unit (*kg CO_2 eq*)	0.14	0.14	0.15	0.15	0.15	0.16	0.12	0.13	0.14	0.12	0.13	0.14
Cost per 100 units (USD)	5.68	5.93	6.73	6.14	6.40	7.20	5.13	5.39	6.19	4.90	5.20	5.98

The consumer preference values behave differently compared to the others where it should be maximized, and the other two parameters should be minimised. Therefore, these three parameters needed to be normalised to compare packaging options with one another. Equation 10 was used to normalise consumer preference. Then the eco-impact which is indicated by the GWP, and the cost per unit needed to be normalised such that the higher the better using Equation 9. The normalised results are represented graphically in Figure 4.11.

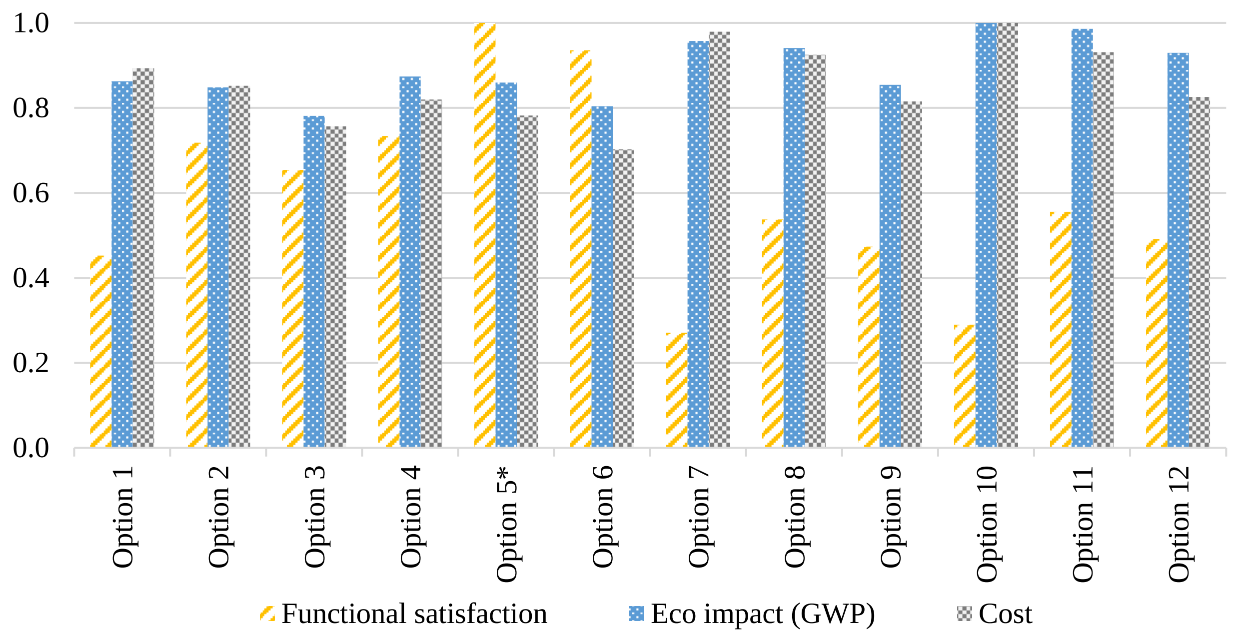


Figure 4.11: Normalised parametric values for ketchup bottle designs

The diagrams show that Options 5 and 6 have the highest consumer preference. Meantime, ‘Option 10’ shows the lowest environmental impact and cost of production. Therefore, for the considered case study, none of the packaging options perform best under all three parameters. Thus, the final decision for the most suitable packaging option should come up with compromises between these parameters. The environment or cost-biased decision will follow ‘Option 10’ and the market-oriented choice would be ‘Option 5’. In between, there could be different preferences when all three aspects are considered in aggregation.

The packaging which is available in the market (Option 5) shows the 2nd highest environmental impact. At the same time, ‘Option 5’ showed the highest consumer preference, which could have been affected by the convenience of the product to the respondents. ‘Option 10’ shows a cost reduction of 23% compared to the existing design (Option 5), which would drag the attention of packaging producers under the economic aspect. Thus, it would be noteworthy to try this new packaging on the market, which would help to identify the real consumer preference compared to the existing options. Meantime, some consumers consider the environmental aspect of the product they are purchasing [65]. Therefore, marketing 'Option 10' as an eco-friendly product would be worth when winning customers.

As per the above discussion, the selection of the packaging design may differ based on the personal perception of the evaluator. Therefore, the methodology proposed in Section 3.7.4. was followed to integrate three sustainability indicators into a single index. The fuzzy AHP method was used to aggregate results and prioritise options, as shown in Figure 4.12. According to the results, 'Option 5' showed the highest sustainability index, followed by 'Option 6'.

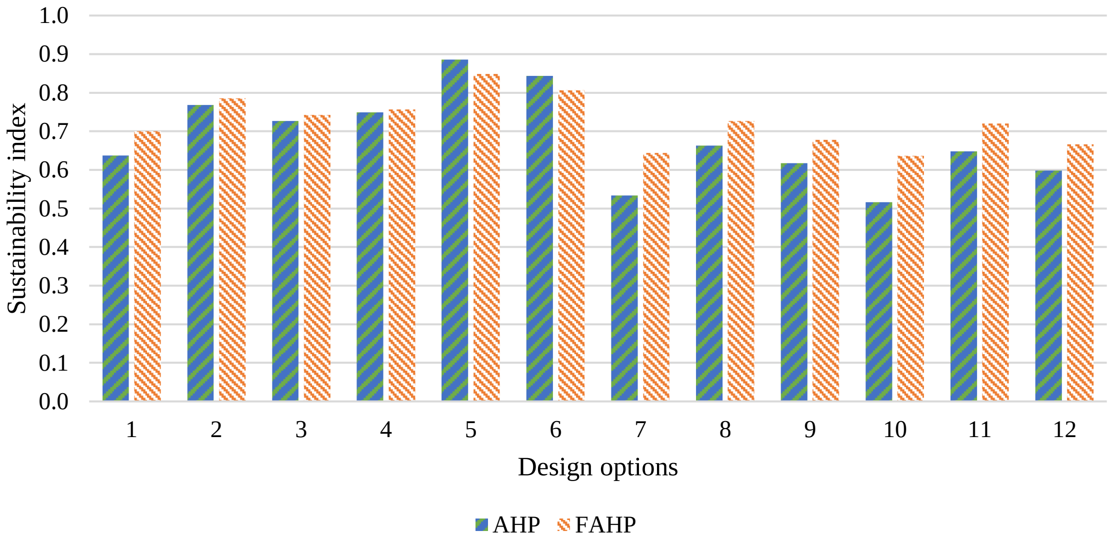


Figure 4.12: Aggregated sustainability score for the ketchup bottles

4.2. Case 2- Ice cream containers

The ice cream containers were considered as the second case study due to their high market availability, multitude of stacking concerns, and essential storage conditions. Ice cream needs to be kept frozen and any meltdown would cause an unfavourable taste or texture. Thus, maintaining the appropriate temperature is significant under food preservation. There are few leading ice cream producers in Sri Lanka and few small-scale producers. The large-scale producers have their unique packaging designs, while the majority of small-scale producers use a standard container.

There are several types of ice cream packaging available in the market. The plastic containers for multiple servings consist of a range of products varying from 500 *ml* to 4 *l*. The cuboid and cylinder are the most common shapes and there are some deviations to add uniqueness to the packaging. Poly-Propylene (PP) has been used as the packaging material and paperboard ice cream containers were introduced very recently.

4.2.1 Classifying functional requirements of ice cream containers

The functional attributes related to ice cream containers were filtered as given in Figure 4.13. The majority of the ice cream containers do not contain a seal for tamper proofing and only one producer uses a body-integrated seal only for their 1 *l* containers. Thus, tamper-proofing the product was identified as a non-mandatory functional attribute.

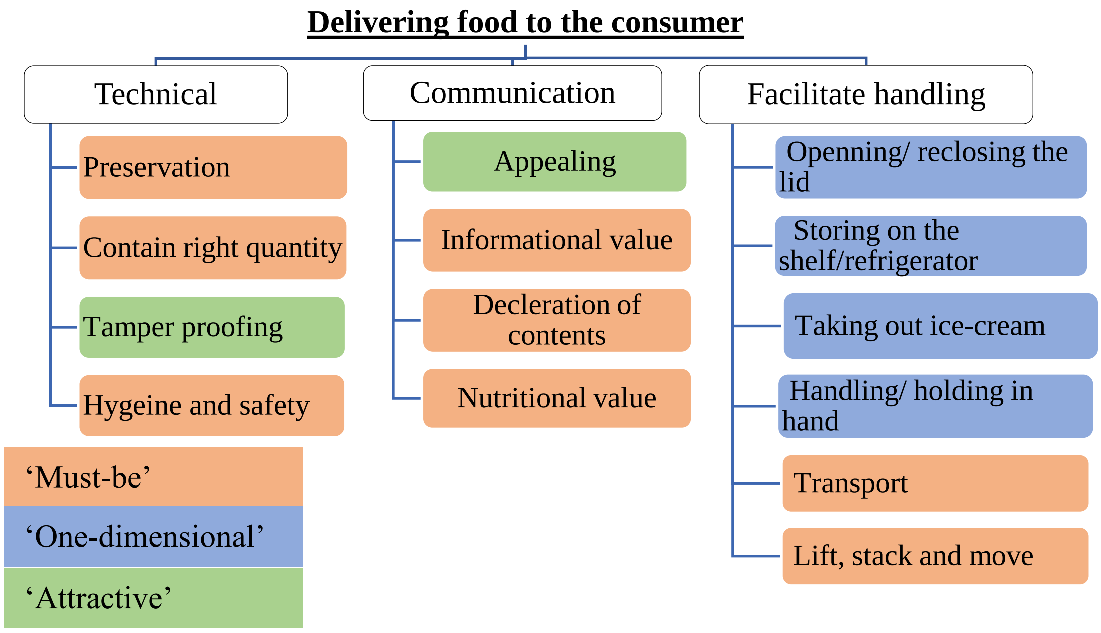


Figure 4.13: Functional attributes of ice cream containers

The next step was to prioritise and assign weights to functional attributes expected by the consumers. Similar to the previous case study, the 'one-dimensional' attributes were chosen to be considered to evaluate consumer satisfaction. An online questionnaire was used to collect consumer responses, and the results are shown in Table 4.6.

Table 4.6: Assigning weights to functional attributes for ice cream containers based on Questionnaire-A

Attribute	**Score**	**Weight (%)**
Taking out ice cream	208	28.41
Storing on the shelf (refrigerator)	188	25.68
Opening/ closing the lid	186	25.41
Holding the container	150	20.49

4.2.2 Identifying and prioritising design characteristics

The lid, body, and label are the main components identified as components of ice cream containers. The container body comes in different shapes, and the lid is designed along with the body to suit the shape. The snap-fit mechanism is used to attach the lid to the body, and there was no other mechanism to be considered for the ice cream container case study. There are two types of labels available for ice cream containers in the local market. Sticking the paper to the lid using adhesives was the most common method while in-mould labelling (IML) is another technology becoming popular. Somehow, the label was eliminated from the design phase since it does not facilitate any physical functionality. The features related to the body were identified similarly to the previous case study.

The next step was to prioritise the design features of each component based on their significance during the design phase using the HOQ. The questionnaire was prepared to conduct semi-structured interviews with the packaging designers as discussed in Section 3.7.2. It was able to contact two packaging designers who have developed ice cream containers for multiple food producers/ brands. Semi-structured interviews were conducted with the packaging designers to collect data for the HOQ. The developed HOQ is shown in Table 4.7. The dimensions of the body were identified as the prominent feature, followed by the shape and strength of the body.

Table 4.7: Prioritised design features for ice cream containers using HOQ

Features / Functional attributes	Weight for each attribute (%)	Lid	Body			
		Material	**Shape**	**Dimensions**	**Strength/ Thickness**	**Material**
Opening/ closing	28	6	1	1	3	3
Handling	26		6	9	1	1
Storing	25		9	9	3	
Taking out	21		9	6		
Weights		168	598	613	185	110
Importance rating		4	2	1	3	5

4.2.3 Designing packaging options

The body of the container was identified as the most significant component. The dimensions of the body were the features that needed higher attention in the designing phase. The container needed to be held in hand when taken out of the refrigerator. Somehow, unlike the ketchup bottle, the container is not held in hand while taking out the contents, and it was possible to use both hands in case of handling the container. Therefore, there was enough room to increase the dimensions since holding the container using a single hand while taking out the content was not a concern.

The dimensions of the ice cream container were determined in such a way as to accommodate different sizes of ice cream containers during stacking. A single producer develops ice cream containers with different sizes ranging from 500 *ml* to 4 *l*. The container dimensions were determined so that two 500 *ml* containers could be positioned in the space provided for a single 1 *l* container and so on. A schematic diagram of how to determine the dimensions of ice cream containers of all sizes is given below in Figure 4.14. This was identified as the guide for determining suitable dimensions for ice cream containers in different sizes. All the containers needed to be within the dimensions of the given cube. Therefore, the shape of each container size may not be similar.

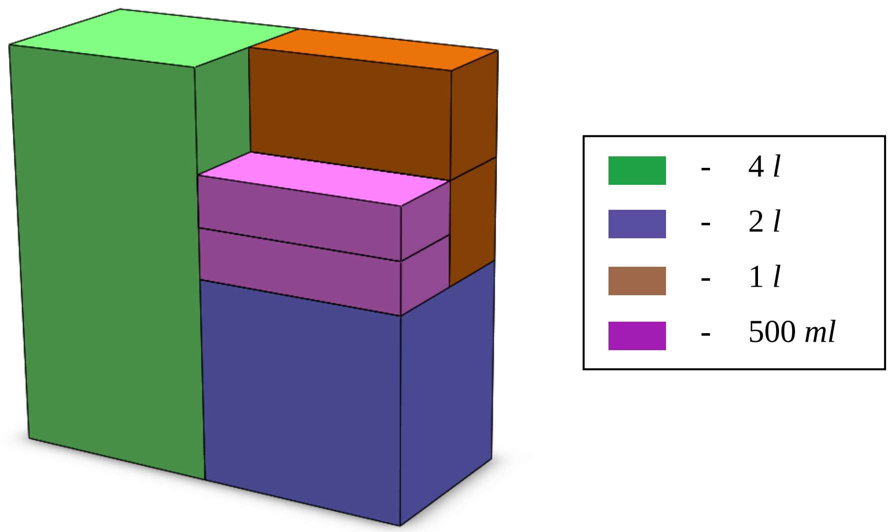


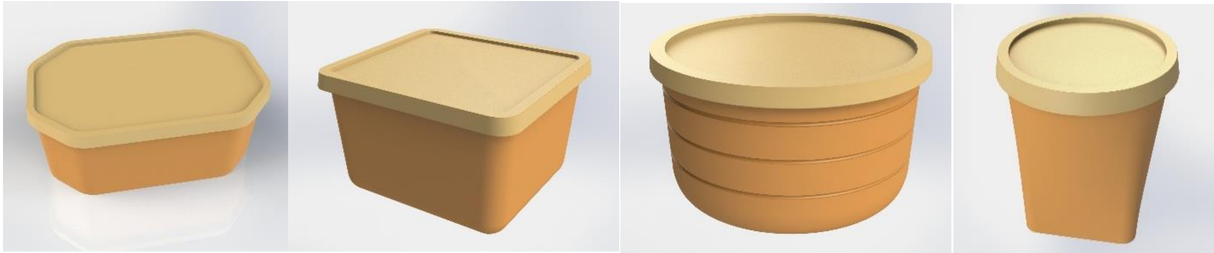
Figure 4.14: Stacking ice-cream containers in a space-saving way

Meanwhile, there was another factor which needed to be considered when deciding the suitable shape. In the local context, larger ice cream containers (4 *l*) are more tend to kept outside for a prolonged period during the use phase. This was due to the higher number of portions being served when the container was taken outside the refrigerator. When kept outside, the surface of the container absorbs heat from the atmosphere and melts the content inside. To maintain suitable temperature conditions, it was necessary to minimize the heat absorption rate. Reducing the surface area of the container was identified as a key measure for reducing the heat absorption rate when developing larger ice cream containers.

The 1 *l* container was selected for the case study since it is the most commonly available size in use. Among many other shapes available in the market, the cuboid and the cylinder were the basic shapes. Combinations or modifications of these shapes were possible to create eye-catching designs. Somehow, since ice cream is taken out using an ice cream scoop or a spoon, it was necessary to avoid small radius curvatures or ribs inside the container to easily remove the content. Special features such as ribs were added to the top edge of the container to provide sufficient rigidity to maintain the shape.

The ability to hold the content is a main concern when designing food packaging. Therefore, it was necessary to identify if the containers could withstand the forces acting on them. It was considered that the ice cream containers are stacked up to a height of 4 *m* and thus, the top load was determined flowing a similar methodology as in the ketchup case study. The top load on each design option was determined to be 600 *N*, 490 *N*, 400 *N*, and 315 *N*, respectively. The FEA was conducted using Ansys software. The simulation was carried out for the 0.4 *mm* thickness which was the least manufacturable thickness and was found to withstand the loading forces.

The lid of the container needed to be designed to fit the dimensions of the opening. A flat surface was left on the top for the label. Similar to the body, ribs and curvatures were added at the edge of the lid to offer sufficient rigidity to maintain the shape. Four different container designs were developed as shown in Figure 4.15. The container body and the lid were made with the same material (PP), and the weights of the container are given in parentheses.



Option 1 (33.9 *g*) Option 2 (34.6 *g*) Option 3 (32.6 *g*) Option 4 (32.2 *g*)

Figure 4.15: Ice-cream container designs

4.2.4 Calculating the sustainability index

The results obtained for functional satisfaction, environmental impact, and cost are discussed in this section. Finally, the calculation of a single parameter for sustainability is discussed.

1. Environmental impact

The LCI for ice cream containers is given in Table 4.8.

Table 4.8: LCI for ice-cream containers

	Material weight (g) Material (PP)	**kg.km value**
Option 1	33.9	62.3
Option 2	34.6	68.6
Option 3	32.6	78.9
Option 4	32.20	92.3

The environmental impact was calculated under 18 impact categories with ReCiPe MidPoint(H) as discussed in Section 3.7.1. ‘Option 4’ seemed to have the highest impact under all impact categories. ‘Option 1’ had the minimum impact under most of the impact categories which had the second highest material weight. This provides sufficient proof to conclude that the material weight is not the prominent factor which determines the overall environmental impact when transportation is considered.

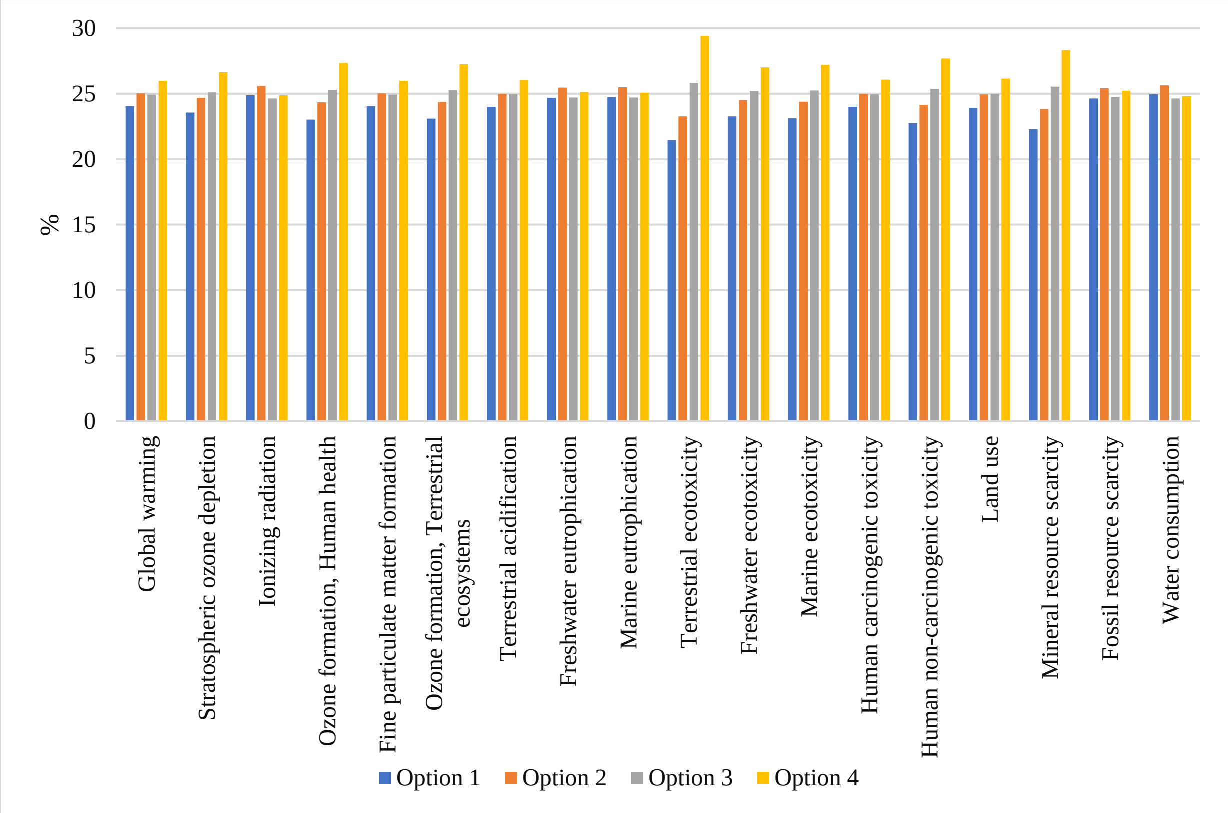


Figure 4.16: Environmental impact from ice-cream container designs

The GWP was considered as the parameter for interpreting the environmental impact. The values obtained are shown in Figure 4.17.

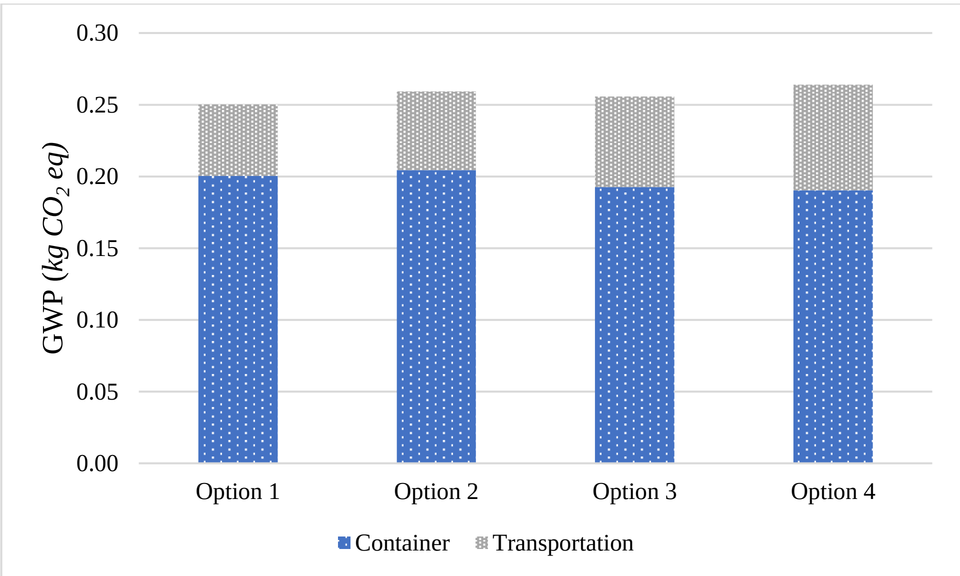


Figure 4.17: Global warming potential of ice-cream containers

The impact of transportation in the second case study seemed to be highly influential to the overall environmental impact compared to the ketchup bottle case study. Once the occupied volume is significantly higher, the number of packaging that could be transported in a lorry decreases significantly. As a result, the environmental impact caused by the un-loaded lorry is divided among the small number of units and causes to spike in the overall environmental impact per unit.

The EoL of the ice cream container designs is the next concern to be discussed. Almost all the ice cream containers used in Sri Lanka are made of PP, which is recyclable. The label of the ice cream containers are made of paper and therefore needs to be removed mechanically before recycling. In-mould labelling (IML) is a technique used to imprint images and labels with injection moulding or blow moulding. A pre-printed plastic film made of PP, HDLE, or LDPE is inserted into the mould and then plastic is injected or blown into the cavity [184]. The heat on the molten plastic will adhere the film to the product, and no adhesives would be necessary. This eliminates the removal of the label or adhesives, which is advantageous in recycling. Therefore, it could be identified as a measure that could be adopted by packaging manufacturers to improve the recyclability of food packaging.

2. Functional satisfaction

In the ice cream container case study, unlike the first case study, only a few options were designed. The four options consisted of two components that are unique for each design. As a result, consumer responses on functional satisfaction as collected using a simple questionnaire. The respondents were asked which packaging design they would prefer considering all functional requirements. The questionnaire is given in Appendix C and the results obtained are given in Table 4.9.

Table 4.9: Consumer preference over ice cream containers

Design Option	Image	No. of choices	Preference as a percentage (%)
Option 1		30	35%
Option 2		34	40%
Option 3		13	15%
Option 4		9	10%

'Option 2', which has a square cross-section, has the highest consumer preference, followed by 'Option 1'. Even in this analysis, we can see that respondents have preferred rectangular cross-sectional shapes over round designs.

3. Cost estimation

The estimated cost for each packaging unit is shown in Figure 4.18. 'Option 3' had the highest cost incurred while 'Option 1' had the minimum cost. The cost for the raw materials and production seemed to dominate the cost criteria, while transportation was a major concern contributing 13-19% to the total impact, which is much higher compared to the first case study.

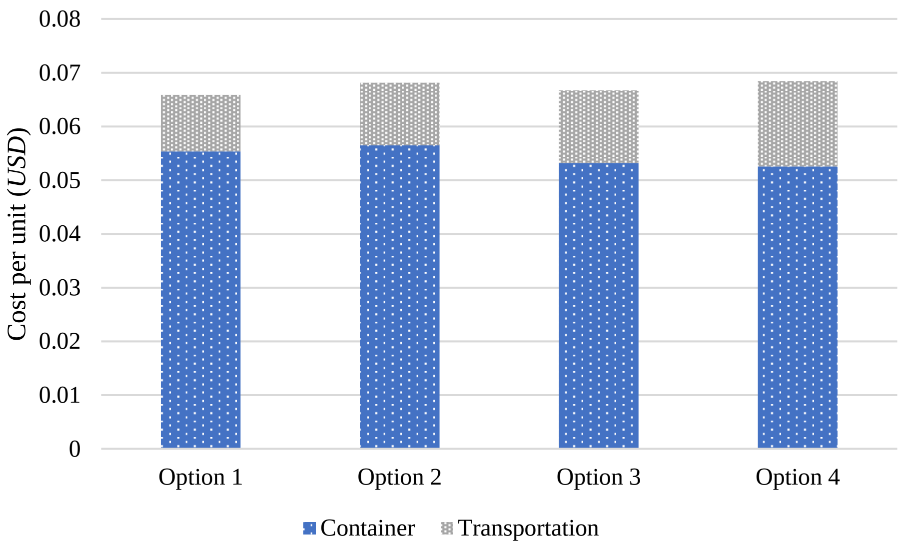


Figure 4.18: Estimated costs for ice cream containers

4. Normalizing results

The calculated values for the second case study are given in Table 4.10. Then the consumer preference results were normalized using Equation 9 and the other results using Equation 10 in Section 3.7.4. The normalised results are graphically shown in Figure 4.19.

Table 4.10: Consumer preference, eco-impact, and cost estimations for ice-cream containers

	Option 1	**Option 2**	**Option 3**	**Option 4**
Functional satisfactions score	30	34	13	9
GWP per unit (*kg* CO_2 *eq*)	0.250	0.259	0.256	0.264
Cost per 100 units (USD)	6.41	6.62	6.49	6.65

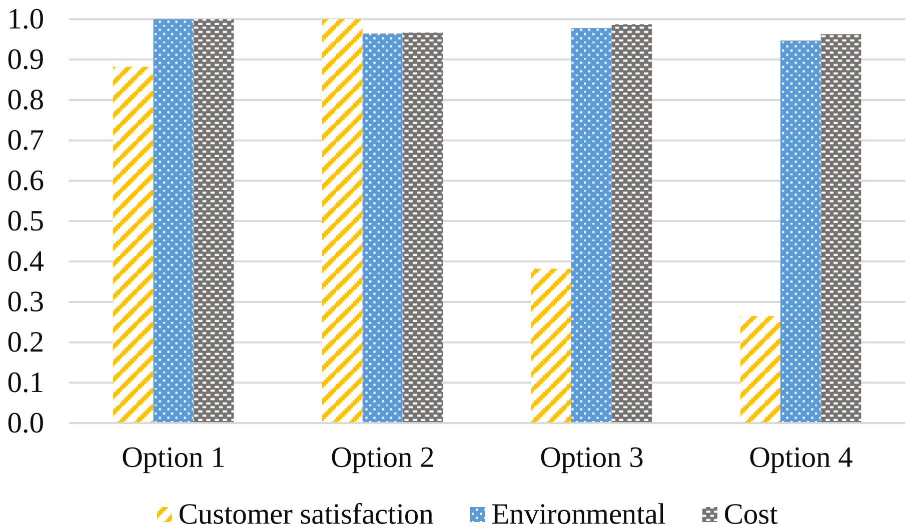


Figure 4.19: Normalised parametric values for ice cream container designs

'Option 2' (see Figure 4.15) seems to have the highest consumer preference. 'Option 1' performs best under cost and costs incurred, followed by 'Option 3 and 4'. Similar to the first case study, a single packaging option which has the best performance under all three criteria could not be found. Somehow, 'Option 1' seemed to have an acceptable level of performance with a compromise in consumer preference. To simplify the decision-making, the normalised values under three criteria were aggregated using AHP and FAHP as shown in Figure 4.20.

The aggregated results show that 'Option 2' has the highest sustainability score compared to the other three options. The highest consumer preference would have been a reason for the increased aggregated score.

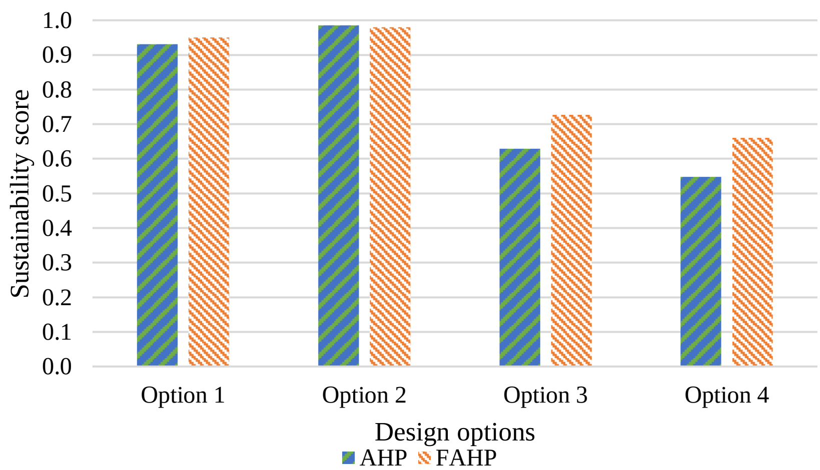


Figure 4.20: Aggregated sustainability index for ice cream containers

4.3. Insights from the case studies in developing the policy framework

The case studies revealed the influence of different design parameters on three performance criteria: functional, environmental, and cost. Literature has discussed the impact of different packaging types in detail. However, this study reveals that the impact may differ a lot even within the same packaging type and material; rigid packaging for bottles and ice cream containers. The influence of the environmental impact from the material type and quantity is apparent as per the literature as discussed in the first few paragraphs. Beyond that, the occupied volume was identified as a parameter that influences the environmental impact during the transportation phase of this study, as discussed in Sectio 4.3.1.

The **wall-thickness** is a design characteristic that depends on the strength of the packaging and the manufacturability, which are both mandatory to be satisfied. In the meantime, the wall thickness is a main determinant of the material quantity, which highly influences the cost and environmental impact.

The **shape** of the container influences both the material quantity and occupied volume, which are key areas in determining the environmental impact and cost. The shape is governed by functional satisfaction, strength, and content volume. When considering the basic geometric shapes, the sphere can contain a unit volume of content with a minimum surface area proportionate to the material quantity. The cuboid is suitable for eliminating void spaces. However, due to impracticality, both spherical and cuboid shapes are not preferred. Therefore, it is necessary to design a unique shape with less material utilization and lower occupied volume.

The results from the case studies show that the overall environmental impact had a significant correlation with the **material quantity** used. The burden carried by the material quantity throughout the production, usage, and EoL has caused this significant correlation coefficient. Beyond that, the material quantity has influenced the cost of the packaging significantly. Therefore, reducing the material quantity using appropriate shapes should be a concern in developing food packaging.

Material type is based on functional satisfaction, rules and regulations with concerns about cost. However, the regulations prevailing for selecting the material type are also crucial. Meanwhile, the type of material highly influences the environmental impact. Figure 4.21. illustrates the identified relationship between the performance indicators and design characteristics through case studies. The arrow points towards the element that is influenced by the element at the root of the arrow.

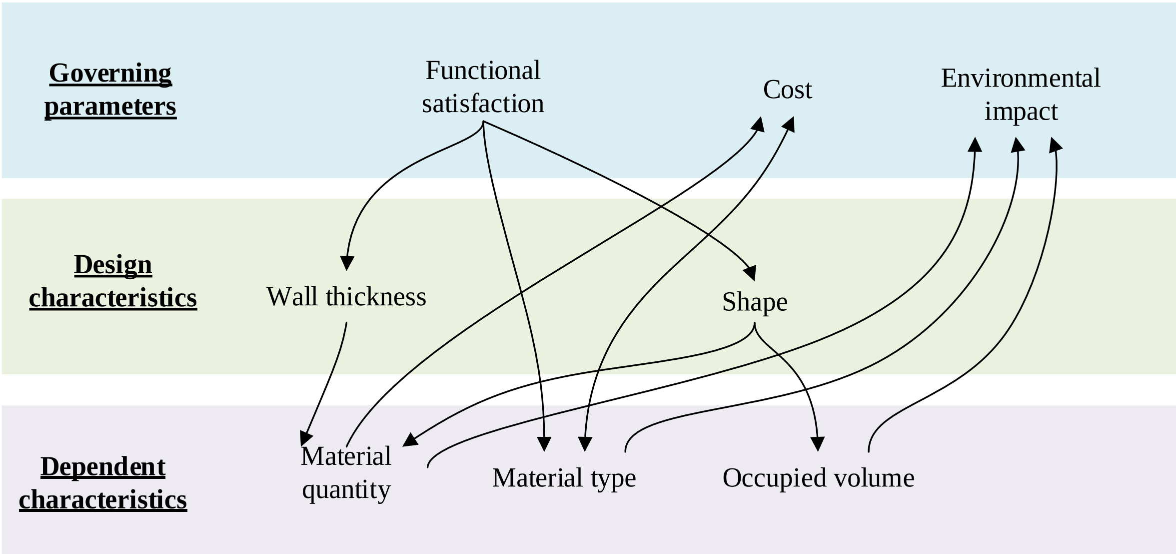


Figure 4.21: Relationship between design characteristics and performance indicators

4.3.1 The influence of occupied volume

The influence of the occupied volume was undiscussed in the food packaging industry. Thus, as discussed under topic 5 in Section 3.7.1, a mathematical model was proposed. Then, the influence of occupied volume on the impact of transportation was estimated using case studies as below.

The influence of the occupied volume on the overall environmental impact and cost was apparent for both case studies. For further analysis, a graph was plotted to identify the relationship between the environmental impact of transportation and the occupied volume for the two case studies as shown in Figure 4.22. and Figure 4.23. Graphs show a high positive correlation (for ketchup bottles 0.998, for ice cream containers 0.999) between the occupied volume and the impact from transportation. The weight of the packaging is the other packaging-related factor influencing the impact of transportation. However, the weight has become a negligible factor compared to the occupied volume. Therefore, the reduction of occupied volume can be identified as a measure for reducing the environmental impact of transportation.

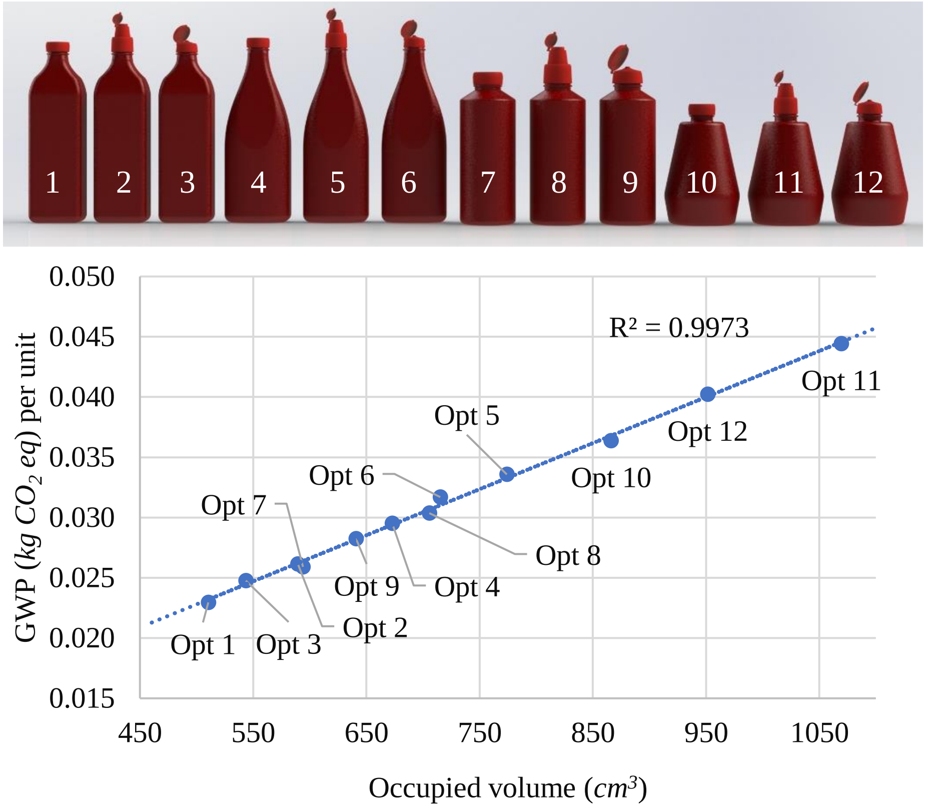


Figure 4.22: GWP vs occupied volume of transportation for ketchup bottles

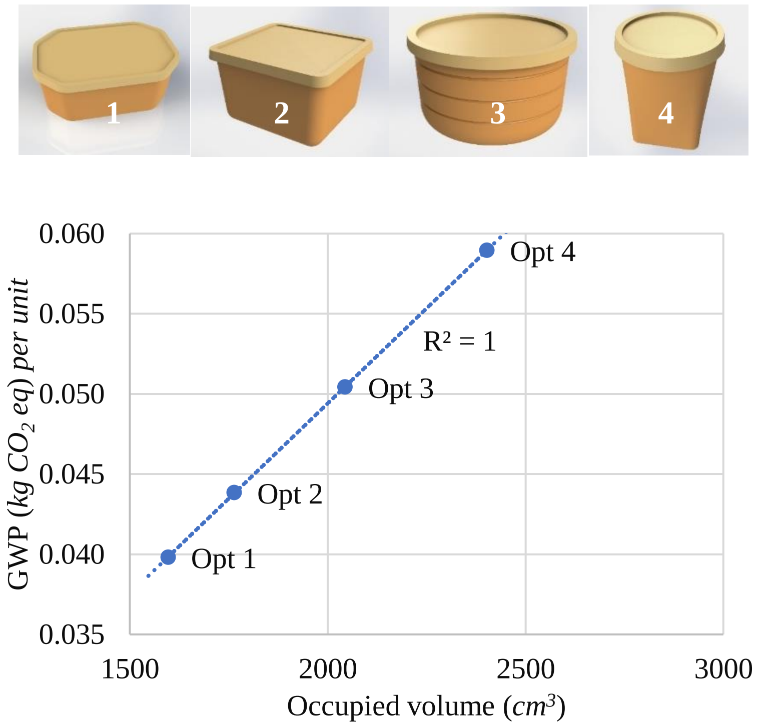


Figure 4.23: GWP vs occupied volume of transportation for ice cream containers

Reduction of occupied volume may result in some adverse consequences when considering the total environmental impact of packaging. The material quantity is influenced by the shape and the occupied volume. Thus, the reduction of occupied volume may result in increasing material utilization. For the considered case studies, the impact of the material contributes to a significant portion. Therefore, material utilization should be given priority to gain a benefit from the total environmental impact. However, this scenario would be different for cases where the transportation distances are higher, and the portion of environmental impact from transportation is significant. For these cases where the environmental impact from transportation is significant, reducing occupied volume using a higher amount of material could be beneficial. Therefore, travel distance plays a key role in determining the suitable strategy for reducing the overall environmental impact of packaging.

Comparison between the proposed transportation model and the existing transportation model

Environmental impact from transportation was calculated using the existing model without considering the occupied volume and the proposed model considering the occupied volume. The comparison of the two models for the ketchup bottle and ice cream container case studies are given in Figure 4.24 and Figure 4.25 respectively. The existing model showed minor variations due to the weight difference between the packaging options. Compared to that, the suggested model showed a higher level of impact since it accounts for the impact caused by the lorry itself apart from the weight of the packaging.

For the ketchup bottle case study, ‘Option 6’ showed the highest GWP for transportation when the ordinary model was used and ‘Option 11’ when the occupied volume was also considered.

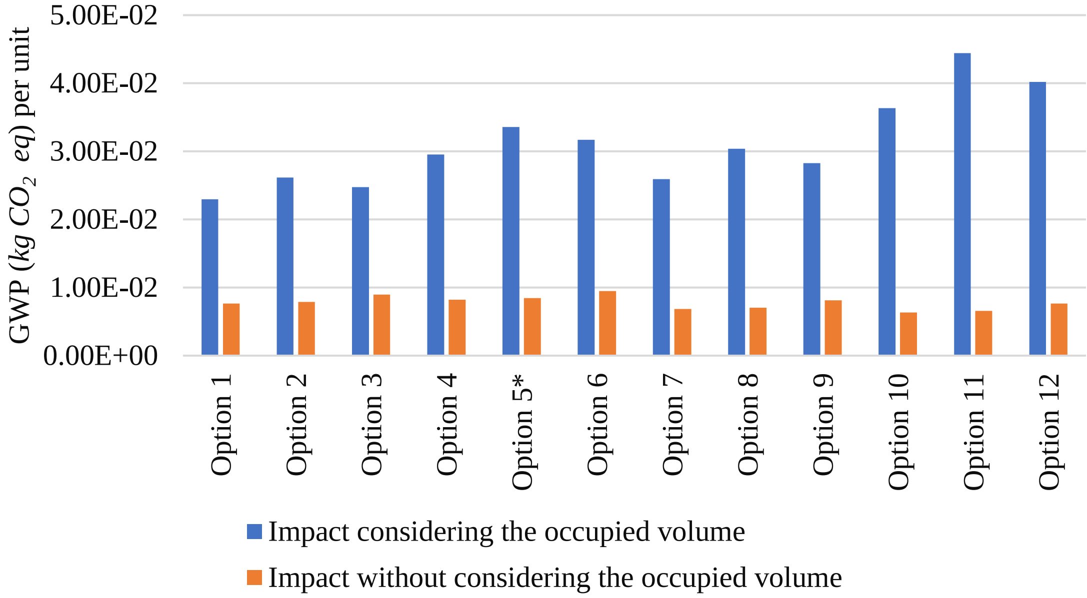


Figure 4.24: Comparison between two transportation models- ketchup bottles

For the ice cream container case study, 'Option 4' showed the highest impact for the proposed model and 'Option 2' showed the highest value for the existing model.

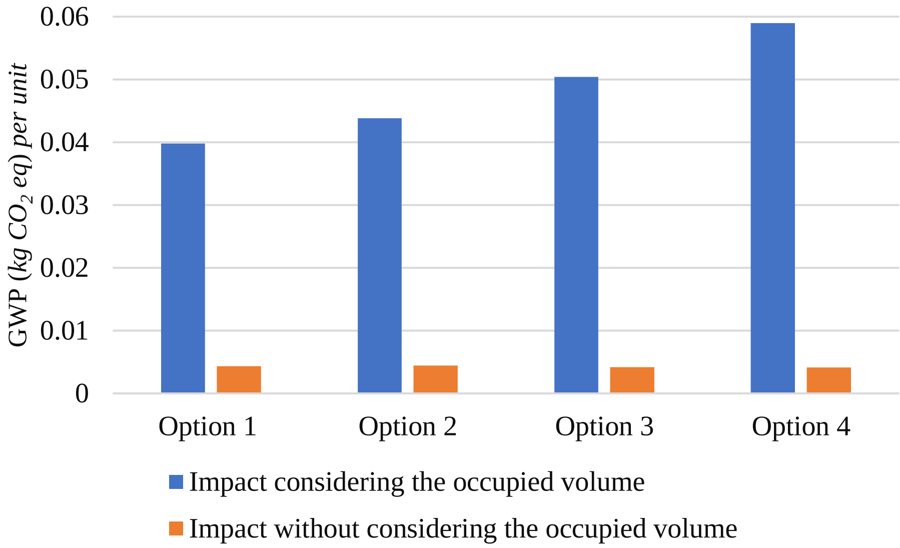


Figure 4.25: Comparison of two transportation models- ice cream containers

4.3.2 Sustainability index

As per the previous discussions, the determination of the most sustainable design would be influenced by the personal perspective of the evaluator. A single sustainability indicator was introduced to avoid this phenomenon by aggregating multiple aspects together. For this particular study, only three performance indicators were considered.

The performance indicators for assessing sustainability have different units. Furthermore, some performance indicators are preferred to be higher, while some are preferred to be lower. As a result, it is impossible to compare multiple performance indicators on a single platform. However, the purpose of introducing a sustainability index was to compare different packaging designs. Interpreting the sustainability relative to one another was sufficient instead of calculating an absolute value. Initially, the values were normalized such that all impact indicators were expected to be higher. Then, the performance indicator values of different components were normalized concerning the highest value under each indicator. The next step was to aggregate the values of weights and aggregate multiple performance indicators together.

In this study, only three performance indicators were used to assess sustainability. However, there is room for considering several other performance indicators whenever necessary. The assignment of weights for different indicators needs to be done with care in such incidents since the use of multiple indicators may hinder the importance of the environmental factor. The index encounters continuous or discrete values and cannot integrate one-zero performance indicators.

The sustainability index was used for assigning a numerical value for the two case studies, as discussed in Section 4.1.4 and Section 4.2.4.

5. DEVELOPMENT OF THE FRAMEWORK

This chapter discusses the development of the policy framework for sustainable food packaging based on the results of the study and literature. The purpose of the policy framework is to provide a structure for authorities to develop policies to regulate the design and manufacture of food packaging. The methodology in Section 3.8 and 3.9 was followed to develop and validate the framework.

5.1. Proposed framework

There were two main areas to be considered in the framework development phase as discussed in Section 3.8. The environment related to the framework, including people, organization, and technologies, was identified through a literature review and discussion with industry experts. Meanwhile, the essential knowledge base for the framework development was identified through a literature review, interviews, and case study outcomes were discussed in Section 4.3.

Food packaging designers, food producers, regulatory bodies, and organizations related to the food supply chain were identified as stakeholders through discussions with industrial experts and illustrated in Figure 5.1. Besides stakeholders, the influences from regulatory authorities were identified under the packaging-related environment.

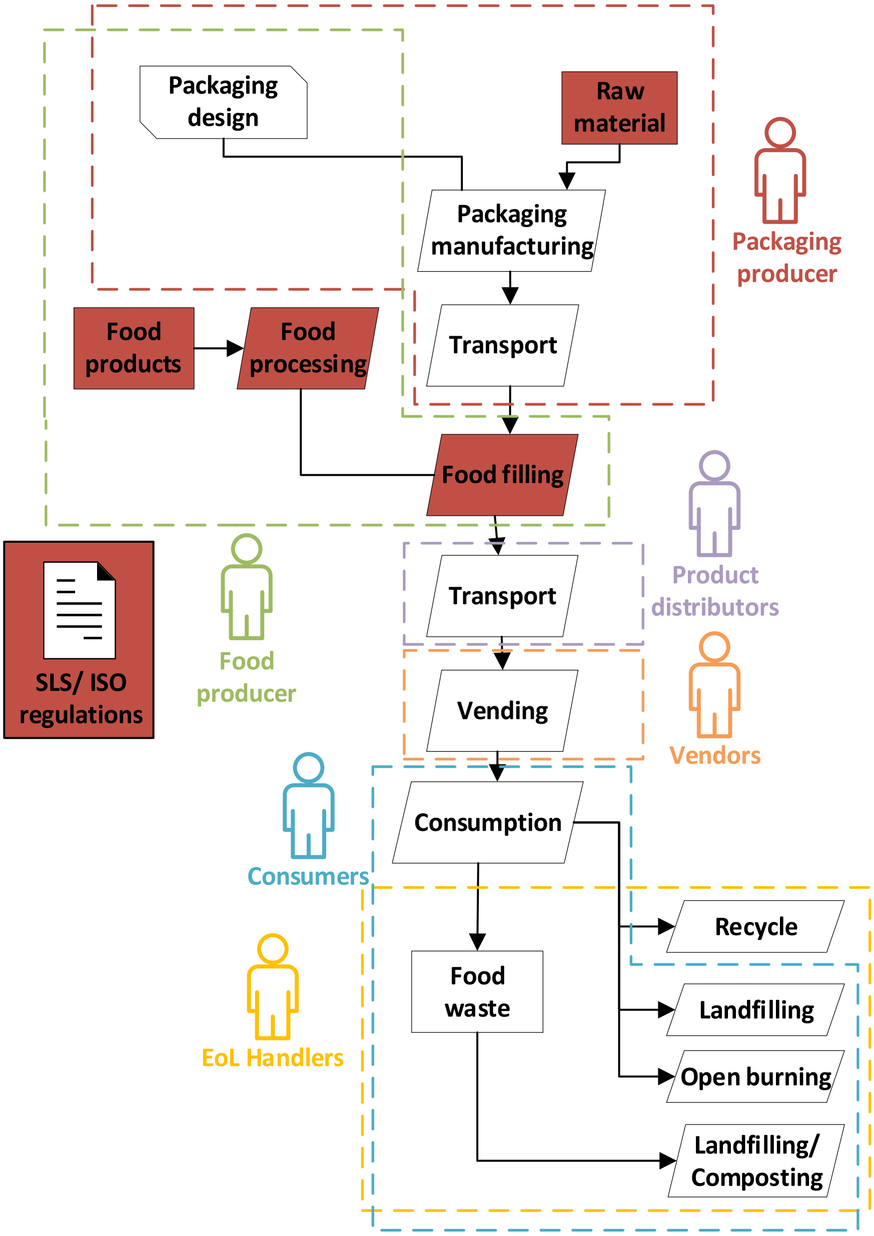


Figure 5.1: Stakeholders and their involvement in the food supply chain

The knowledge base, the second area of consideration in DSR, consisted of two main categories: the existing body of knowledge and the findings from the case study. Under the existing body of knowledge, the waste hierarchy discussed in Section 2.5, was assisted in minimising the environmental impact. The evaluation methods were extracted from the literature and were organized to develop a single parameter for assessing sustainability, as discussed in Section 3.7. The features influencing the sustainability of food packaging were identified, and the way these features could be manipulated to improve the sustainability aspect of food packaging was discussed in Section 4.3.

The framework was developed after determining the system constraints and boundary conditions. The framework was under four phases considering the ease of guiding the flow and ease of modifying. The first two phases, type selection and design, are focused on the design process. The first phase determines the feasible types and materials that can be used based on the characteristics of the food product. In the second phase, the packaging is designed following the standards and guidelines. Meanwhile, suggestions for improving the sustainability of food packaging are included. Next, the designs are scrutinized based on environmental, regulatory, and functional aspects and finally assessed under three performance criteria. The proposed framework is given in Figure 5.2. The content of the framework is discussed in the following sections.

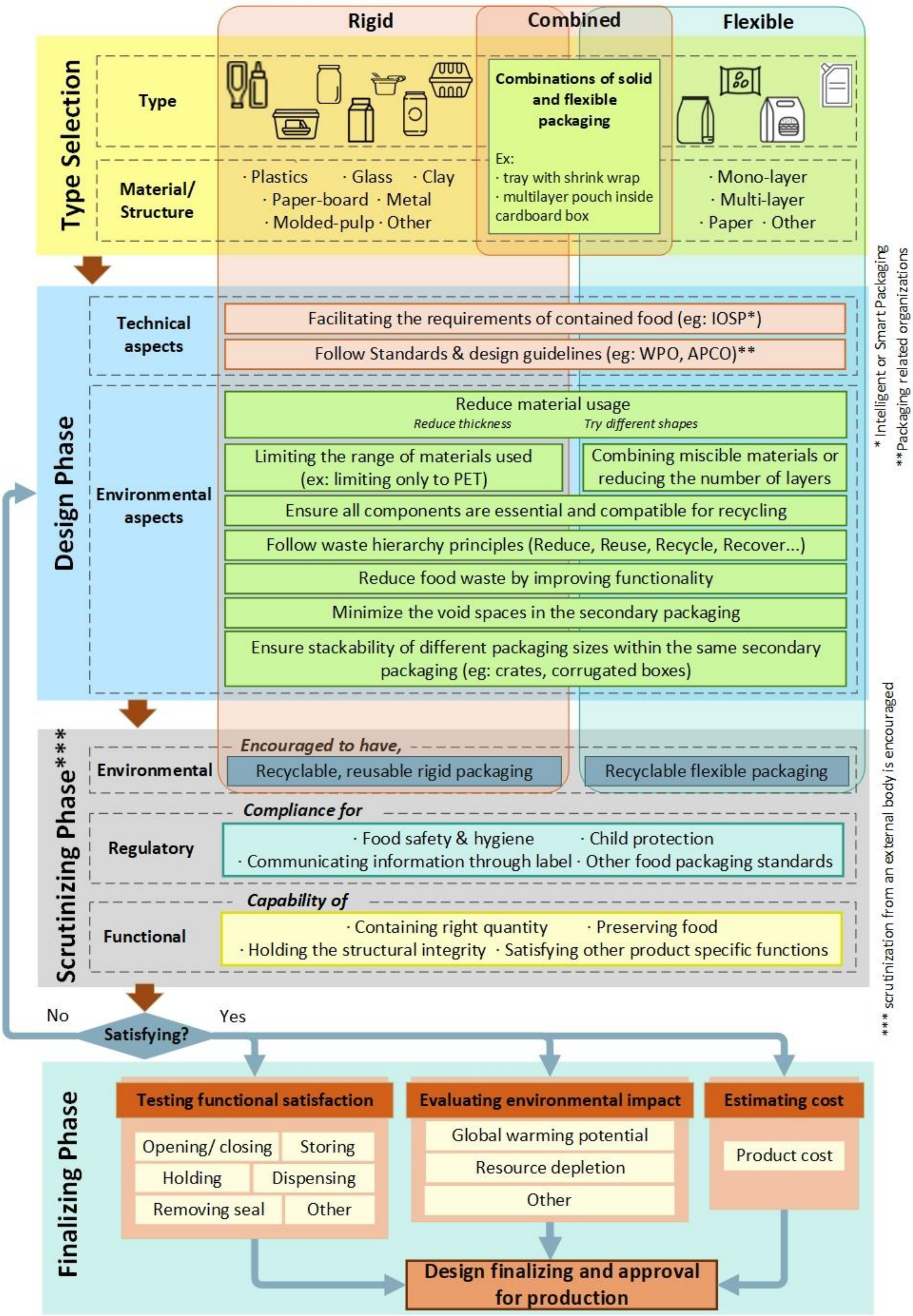


Figure 5.2: Proposed Framework V 1.0

5.1.1 Type selection

There are two basic types of packaging defined by ISO: rigid packaging and flexible packaging. For a considered product, the type of packaging is determined based on the characteristics of the food product. Since the type of packaging has been established for years, the use of novel types of packaging for a given food item is challenging. Therefore, instead of a detailed description of the type selection, this section illustrates the different types of packaging that could be used for a considered food item.

Rigid packaging is a commonly used type of food packaging, including bottles, jars, cups, clamshells, pouches, tetra-packs, cans, etc. Different materials and material combinations could be used for rigid food packaging, such as plastics, glass, and clay. Under material selection, the reusability of the packaging also needs to be considered. For example, replacing the plastic bottle with a glass bottle would have environmental and economic benefits after several cycles of reuse with increased concerns on logistics. However, at this stage, it is possible to select multiple technically feasible options to contain the considered food item since the designs would be reviewed several times to determine the best among them.

Flexible packaging is the other type with several functional limitations compared to rigid packaging. On the other hand, it has multiple advantages in facilitating appropriate environmental conditions for food items. While the low cost is economically advantageous, the difficulty of recycling is undesirable. In the following sections, suggestions are included for improving the environmental sustainability of flexible packaging. Monolayer flexible packaging is preferred for environmental sustainability due to the ease of recycling. However, multilayer packaging are more common due to its favourable characteristics as FP. Therefore, considering single-layer packaging is highly recommended if it appears to be a technically feasible solution.

A combination of flexible and rigid packaging is commonly used in biscuit packaging. A tray is used to stack the biscuits in rows, while flexible packaging is used for wrapping them around. In chocolates and cookies, flexible packaging is used to wrap the food, while rigid packaging is used externally. The use of the two types of packaging causes excessive material usage and higher costs compared to single packaging. However, it would provide additional functionality to attract consumers. Therefore, this increased environmental impact needs to be justified along with the functional aspect as described later in this framework.

In general, it is recommended to try different types of packaging for the same food product since the consumers and packaging designers have only experienced the existing products in the market. For example, within the local context, only rigid plastic bottles could be seen for ketchup packaging, and no one has yet experienced flexible ketchup pouches. Thus, there is a gap in trying a new type of packaging and evaluating it under functional, economic, and environmental aspects.

5.1.2 Design phase

Next is the design phase, where the virtual designs are developed. After identifying suitable packaging types, the designs are rendered using 3D modelling software. In the design phase, the technical aspects are mandatory to be satisfied. The facts considered under the environmental aspect focus on improving the environmental sustainability of the packaging. Additionally, the basic functional requirements of packaging such as; food preservation and containing food, also need to be considered.

1. **Technical aspect**

The main focus of the technical aspect in the design phase is to ensure the utility of the FP. There are several guidelines provided by organizations such as WPO, APCO, SPA, etc., that could be assisted. Additionally, novel technologies such as Active Packaging, Intelligent packaging, or Smart Packaging (IOSP) could be used to extend the shelf life of the packaging while monitoring the food condition.

ISO has introduced standards for ensuring the health and safety concerns of food packaging. Feasible materials that can be used for food contact surfaces are directly regulated by standards. Additionally, there are regulations for packaging dimensions and testing guidelines. Authorities such as; the Federal Food and Drug Administration (FDA), EU Regulations for Food Packaging (CEPE), and EU Chemical Agency (ECHA) are some of the international agencies for introducing food packaging-related regulations. In the local context, Sri Lanka Food, Cosmetics and Drug Authority and SLSI are responsible for regulating food packaging.

Tamper proofing is a product and producer-specific concern and has not been considered in many cases. Even with the same food producer, there are packaging options with tamper-proofing, while some are not tamper-evident. This may depend on the food producer’s preference and the cost of the content. There are several considerations when tamper-proofing a product [85]. They are to avoid,

- Removing the original content and substituting it with an inferior product
- Product sampling from customers
- The risk of theft
- Adding harmful substances to damage the reputation

2. **Environmental aspect**

Suggestions have been mentioned under the environmental aspect focusing on reducing the environmental impact by promoting circular economy principles and waste hierarchy. Food packaging designers are encouraged to follow these guidelines for rendering a range of packaging designs.

Two different approaches have been suggested for reducing material usage. Reducing the thickness of the packaging without functional requirements is the most common and easy way of decreasing material usage. The finite element analysis (FEA) is capable of justifying the allowable thickness reduction for a given packaging design. Moreover, topology optimization is another technique that could be used to provide additional strength to the packaging while reducing the thickness. The manufacturability is a constraint which limits the inability to reduce the thickness. Under existing manufacturing technologies, a minimal thickness is recommended to prevent warping and other manufacturing defects. The shape of the packaging is a highly influential factor in determining the material quantity. In general, the cuboid requires a higher amount of material compared to the cylindrical shape. However, selecting the suitable width: length: height ratio is crucial in minimizing the material quantity. Additionally, the shape determines the occupied volume of the container, which also is influential for the environmental impact.

Limiting the number of materials used for rigid food packaging is another approach that could ease the material sorting process in recycling. Even within the same packaging, different materials have been used, which causes difficulties in recycling. Paper is used as the label material, which causes difficulties in sorting materials and removing the adhesives in recycling. These limitations could be eliminated by replacing paper labels with polyethene films, heat shrink sleeves, or in-mould labelling (IML). Using a similar material for the label as used in the body would eliminate many of the recycling limitations of paper labels and would simplify the manufacturing process. Beyond that, using one material type as much as possible for food packaging applications is another approach to ease the sorting process in recycling. In flexible packaging, the use of a single material is highly preferred for ease of recycling. However, in cases where multiple materials are needed to be used, it is highly recommended to use miscible materials that can be recycled together with minimum degradation. The miscibility of different materials is given in Table 5.1.

Table 5.1: Miscibility of Materials [25]

		Polymer matrix					
		PE	PP	PET	PA	PS	PVC
Additive material	PE	1	3-4	4	2-4	4	4
	PP	2-4	1	4	2-4	4	4
	PET	4	4	1	3-4	4	4
	PA	4	4	3	1	3-4	4
	PS	4	4	3	3-4	1	4
	PVC	4	4	4	4	2-4	1

1: good miscibility, 2: miscible up to approximately 20%, 3: miscible up to approximately 5%, 4: immiscible

The use of multiple levels of packaging is common in food packaging. For example, chocolate slabs are wrapped in flexible packaging and then inserted into a paperboard box. However, there are similar chocolate products that have used only flexible packaging. Thus, it is necessary to revise the necessity of several levels of packaging and reduce them if it is not mandatory. In some cases, the second level of packaging requires protecting the primary packaging. Therefore, it is necessary to find novel methods to integrate the functionality of the secondary level of packaging into the primary packaging. Additionally, reusable secondary packaging should be considered in designing the packaging.

The main concern is adapting waste hierarchy into food packaging to reduce the environmental burden. The author does not intend to mention the measure to be taken under the waste hierarchy since it has already been discussed in Section 2.5.1.

The void spaces between the packaging affect the number of units that could be loaded into a single truck. If there is a higher portion of void spaces, then only a few items could be loaded into a truck and vice versa. The lower number of packaging transported in a lorry may increase the environmental impact per unit. Therefore, a minimum amount of void spaces is preferred within the secondary packaging. The shape of a cuboid is preferred to minimize the void spaces. However, it may result in higher material utilization for packaging. Thus, finding the optimum shape that results in minimal environmental impact with lower material utilization and void spaces is necessary.

In general, a truck transports different products at the same time. Even with the same product, different sizes are loaded. Therefore, it is necessary to ensure that different product sizes can be stacked in a given space with minimum space wastage. This phenomenon is described in detail in Section 4.2.3.

5.1.3 Scrutinizing phase

This phase's objective is to ensure that eco-friendly and technically viable products are present in the market. Three aspects have been considered in the scrutinizing phase: environmental, regulatory, and functional.

1. **Scrutinizing based on environmental concerns**

There are several criteria suggested for improving the environmental sustainability of food packaging. Using biodegradable materials is a novel approach to eliminating the waste stream caused by packaging materials. Currently, the cost of biodegradable materials is high, which restricts their utilization to limited applications. However, national-level policy implications could be insisted on promoting biodegradable materials. Simultaneously, the induced environmental impact from biodegradable packaging should be encountered at the finalizing phase. Similarly, encouraging recyclable and reusable packaging should be enforced through policy implementation.

Reuse - The reuse of food packaging is influenced by several factors. The ability to clean the containers is significant, while reverse logistics is another concern. However, it is essential to consider the entire food supply chain before implementing new food packaging [24]. In flexible packaging, reusable packaging has not been included due to hygiene issues associated with challenges in cleaning the product. Even though the primary packaging cannot be reused in most cases, secondary packaging needs to be designed as reusable.

Recycling - There are certain aspects to be considered when packaging is designed for recycling. The packaging should be designed to minimize the challenges faced during plastic materials' collection, sorting, and reprocessing phases [117]. The ability to separate materials is a main concern in recycling different materials used in a single packaging [27]. The complete separation is difficult, it is suggested to have a low degree of contamination of other materials [185].

2. **Scrutinizing based on regulatory concerns**

The regulatory measures are mandatory to be satisfied by the packaging designers. Ensuring safety and hygiene, and child protection are the main regulatory requirements. Moreover, it is essential to communicate information related to the food product and needs to be guided through standards. The nutritional content, usage instructions, and other health concerns should be mentioned on the label. The content on the label needs to be regulated by the authorities to protect the consumers. Additionally, disposal methods of the packaging also should be included. Meanwhile, the regulatory bodies must examine whether all relevant packaging-related standards have been followed.

3. **Scrutinizing based on functional concerns**

Different types of functional requirements for food packaging are discussed in Section 3.4. Among them, 'Must-be' attributes are mandatory to be satisfied. In the scrutinising phase, attention should be paid to evaluating whether these functional requirements have been satisfied. The 'must-be' attributes may vary depending on the food and packaging type. However, food preservation, containing the correct quantity, and health and safety are mandatory for every food packaging.

Food preservation is a huge discussion area due to different expectations of food content to ensure edibility. Most of the food items prefer hermetic seals, which are commonly known as airtight, while some others prefer protection against insects. In addition, there are specific atmospheric conditions required to preserve food items [23].

5.1.4 Finalizing phase

The finalizing phase is the last phase which determines the optimum packaging design to be introduced into the market. The packaging design in accordance with the scrutinizing criteria, is eligible for evaluation over the three sustainability criteria. Under policy developers' perspective, the cost is not a mandatory criterion to be considered, while the other two, functional satisfaction and environmental impact, must be considered. Therefore, the cost criterion is given a light colour background in the framework (refer to Figure 5.2). The methodology suggested in Section 3.7 is a rational way of determining the optimum packaging design considering all three facts.

Functional performance and cost are the two main concerns in designing food packaging in the conventional approach. Among them, functional performance is deemed the independent parameter determining the packaging features, while the cost and environmental impact depend on the features. Therefore, the functional aspect was given priority in the design phase with concerns about environmental impact. This allows packaging designers to focus more on the functional aspect, reducing the complications in the design phase. Meanwhile, the cost, the dependent variable on packaging features, was integrated into the evaluation phase. The same scenario has been applied to the other dependent variable's environmental impact. In addition, functional parameters directly influencing consumer satisfaction were included in the evaluation phase. However, having a sufficient number of designs with a range of variations is essential for ensuring the optimum design is included in the set of evaluated alternatives. Otherwise, design guidelines should be provided for diversifying the packaging designs.

The environmental impact is estimated through LCA, and the product cost using analytical costing methods. Moreover, the proposed mathematical model for estimating transportation-related environmental impacts and costs would provide more precise estimations. After calculating the values, the results need to be aggregated to identify the most suitable design option using the fuzzy AHP method.

1. **Testing functional satisfaction**

In addition to the 'Must-be' functional constraints, there are 'One-dimensional' functional attributes which will increase consumer satisfaction, as discussed in Section 3.4.3.4. Consumer preference needs to be assessed through surveys or experimental setups. Questionnaires and conjoint analysis could be used in assessing consumer preference by combining multiple aspects, as discussed in Section 3.7.2. Additionally, the direct estimation method is also could be used as follows in the second case study in this research.

2. **Evaluating environmental impact**

The environmental impact is estimated through LCA, as discussed in Section 3.7.1. Moreover, the proposed mathematical model for estimating transportation-related environmental impacts and costs would provide more precise estimations. Different parameters could be used to estimate the environmental burden as described in the proposed framework. Additionally, there are several other criteria available in life cycle assessment tools.

3. **Estimating cost**

The cost mainly depends on the features of the packaging. Packaging developers commonly use the analytical cost estimation model, which is a well-established method in cost estimation (see Section 3.7.3). The mathematical model proposing a novel approach for estimating the cost of transportation can provide more accurate results than the conventional cost estimation model.

The financial considerations in the evaluation phase could be accompanied in two different ways. Either costs could be estimated from numerical values or designs below the threshold cost limit could be considered for evaluation. Both these methods could be followed in the evaluation phase from the packaging designer's perspective.

Design finalizing and approval for production

The next step is to determine the optimum packaging design based on the three evaluation parameters. The Fuzzy AHP method suggested in Section 3.7.4 is a feasible way of aggregating the three performance criteria into a single parameter. After determining the optimum design, it could be sent for approval/ certification and then to production. Even after introducing the new packaging to the market, it is possible to reevaluate the functional performance through consumer feedback and make finer adjustments if necessary.

5.2. Framework validation

The methodology described in Section 3.9 was followed to validate the proposed framework using three criteria for each phase and four criteria for the overall framework, as described in Table 3.13. The responses were collected in a 5-point Likert scale and the average value obtained under each criterion is also given in the table. The average value obtained for the validity criteria for each phase is shown in the following Table 5.2. On average, most of the responses agreed that the framework had met the expected validity criteria. Some respondents mentioned that certain areas have not been covered in the framework. However, the unaddressed areas were included in the framework after their feedback and suggestions.

Table 5.2: Experts' perception of the validity of each phase under different criteria

Phase	Criteria	Likert scale score (5-highly agree, 1-highly disagree)	The level of acceptance
Type selection	Covers all aspects	3.4	Neither agree or disagree
	Proposed stages are logical	3.8	Agree
	Proposed stages are practical	4.0	Agree
Design Phase	Covers all aspects	3.4	Neither agree or disagree
	Proposed stages are logical	4.2	Agree
	Proposed stages are practical	4.2	Agree
Scrutinizing Phase	Covers all aspects	3.8	Agree
	Proposed stages are logical	4.2	Agree
	Proposed stages are practical	4.2	Agree
Finalizing Phase	Covers all aspects	3.8	Agree
	Proposed stages are logical	4.2	Agree
	Proposed stages are practical	4.2	Agree

The experts' perception of the overall validity of the framework is mentioned in the following Table 5.3. On average, respondents have agreed with the first three statements and agreed upon the validity of the framework. However, experts have neither agreed or disagreed with C4 criteria (that framework would provide a sufficient guide for packaging designers and policy developers). The improvements suggested by the experts were executed to resolve this issue and improve the validity through the fourth criterion. The same action was taken to improve the validity of C4; the sufficiency of the guidance provided to policy developers and packaging designers.

Table 5.3: Experts' perception of the validity of the overall framework under different criteria

Criteria	The level of acceptance
C1. The stages of the framework are in order and would systematically guide the user	Agree
C2. The framework sufficiently addresses the areas to improve the environmental sustainability of food packaging	Agree
C3. Framework sufficiently addresses the areas to improve the sustainability of food packaging	Agree
C4. The framework would provide a sufficient guide for packaging designers and policy developers	Neither agree or disagree.

Additionally, there were a few academics who replied through email instead of filling out the GoogleForm survey. Two key responses that were mentioned in their emails related to the validity of the proposed framework are given below.

1. "Thank you for your email and sending through your work which is an interesting review."
2. "This is a good entry-level graphic for designers to print out and refer to."

Thus, the proposed framework was modified through several iterations with feedback from experts in the food packaging industry.

During the final evaluation phase, a packaging expert from the local industry had a different perspective on the proposed framework. The reduction of food waste, material usage, and recycling were highlighted as the focus of the proposed framework. The significance of comparing the environmental impact of novel food delivery methods such as packaging-less systems, was also highlighted. Even though the author agrees with the statement, the prime focus of this research was to reduce the environmental impact of the packaging system currently in use. The novel and broad approach suggested needs further time and research, which is an approach for a revised version of the proposed framework in future research.

6. DISCUSSION AND CONCLUSIONS

6.1. Research summary

The study aimed to develop a policy framework to improve the sustainability of food packaging. Initially, five objectives were set, and case studies were used to achieve the objectives. Measures for improving sustainability were identified through case studies and literature review, and they were assisted in developing the policy framework.

Objective 1: To establish the current knowledge of food packaging technologies, policies, and practices.

Literature review and interviews were used to achieve the first objective. Functional satisfaction, environmental impact, and financial costs were identified as the performance indicators to evaluate the sustainability of food packaging. Furthermore, the functional requirements and other design considerations in developing food packaging were identified through interviews with industry experts. Moreover, policies and technologies in the food packaging manufacturing industry were identified. Suitable tools and methods for food packaging design were identified through a literature survey.

Objective 2: To identify the design considerations of mostly used food packaging.

Ketchup bottles and ice cream containers were selected as the two case studies for data collection and analysis based on higher market share and convenience for the public. A public questionnaire was used to incorporate consumer perception into the food packaging design. Semi-structured interviews with industrial experts were used to identify the significance of each design feature to satisfy the functional attributes. Then, several design options were developed to assess them under three performance indicators.

Objective 3: To conduct an environmental performance analysis of selected categories of food packaging.

The assessment of the life cycle impact of rigid food packaging was the main area considered under the third objective. Life cycle assessment (LCA) was used to estimate the environmental impact of the developed packaging designs. Furthermore, functional satisfaction was assessed using a public questionnaire and The cost incurred for each design was estimated using an analytical method. Finally, the results were aggregated to combine all three criteria for easy comparison. The influence of design parameters on sustainability was qualitatively analysed as the final step.

Objective 4: To develop a policy framework for food packaging to yield improved environmental performance while adhering to other relevant design and manufacturing considerations.

Design Science Research (DSR) was used to develop the policy framework. The influence of design characteristics on sustainability parameters was considered in developing the policy framework. The packaging's material quantity and occupied volume were the key characteristics that governed the environmental impact and cost. Meanwhile, the shape was identified as a key factor which influences the functional satisfaction of food packaging. The actions that could be taken to improve multiple aspects of sustainability were discussed.

Objective 5: To validate the policy framework for intended environmental and other benefits

The Delphi method validated the developed policy framework with insights from the packaging experts. Multiple specialists were consulted from both industry and academia. The validity was assessed in two phases; the validity of each phase using three criteria and the validity of the overall framework using four criteria. The outcome of the validation process showed successful results, and thus, the framework could be used in a more generalized context.

6.2. Limitations

The major limitation was finding packaging design specialists in the country. In most food products, the food packaging was designed years ago; therefore, even the company was unaware of the packaging designer. Therefore, contacting the packaging designers was difficult, making the data collection challenging. However, some academics had experience in packaging design and assisted in collecting data.

The other limitations associated with the data collection phase were unavailability of data, confidentiality issues, and ineffective data collection methods.

- **The unavailability of the data** was a limitation found in the analysis. Companies have not analysed the logistics plan for food distribution. Hence, packaging travel distances were not available with the logistic facilitators. Therefore, assumptions had to be made about the distance travelled.

- **Even though the in-person meetings were very effective, collecting data remotely were inefficient. Due to the pandemic that prevailed during the data collection phase in the country, there were restrictions on visiting the factories and meeting physically.** In-person meetings were arranged in possible situations for efficient and effective data collection.

6.3. Contribution to knowledge

New policy framework for the design of sustainable food packaging: The absence of a framework to gather multi-stakeholder insights in policy developments for sustainable FP was the first research gap identified. Initially, the basic parameters that influence the sustainability of FP were identified through a literature review as discussed in Section 2. Case studies were accomplished to identify the factors influencing these parameters which eventually led to the development of the framework. Similar approaches can be seen in literature, where the development of a policy framework for material resource efficiency through a study of circular economy and the development of a policy framework for the management of distributed systems [127], [186].

The proposed framework was a multifaceted approach considering different aspects of the sustainability of food packaging. The framework comprises four phases; type selection, design, scrutinize, and finalize. Measures for improving sustainability are mentioned in the relevant phases. The first two phases were focused on designing food packaging, while the initial phase was to determine the type of packaging considering the requirements of the food. The second phase considers the environmental aspects of FP while adhering to technical constraints. The scrutinizing phase examines the eligibility of the designed packaging under environmental, regulatory, and functional criteria. Finally, the scrutinized designs were assessed based on functional, environmental, and cost criteria for calculating the sustainability index.

New transport model considering occupied volume: The influence of the environmental impact from the degree of filling and the number of units transported by a lorry has been discussed in [39], [61]. However, the environmental impact from individual unit-level transportation has not been modelled for numerical analysis. Therefore, the environmental impact of road transportation was integrated with the number of units loaded to the lorry to obtain the per unit environmental impact.

The existing model for estimating the environmental impact of transportation considers weight as the only packaging-related parameter. This study elaborated on the unseen impact of the occupied packaging volume. Furthermore, the influence of the occupied volume was mathematically modelled. A novel mathematical model was introduced to estimate the environmental impact of transportation instead of only focusing on the weight of the packaging.

Methodology to reduce the environmental impact of food packaging: This study suggests a methodology which could reduce the environmental impact of the packaging without altering the packaging type. Even though the study considers the rigid plastic food packaging context, the methodology suggested in the study could be extended further to other packaging applications.

Representing the sustainability of FP using a single index: The sustainability of FP has been rarely assessed in the literature under TBL. The past FP research has considered TBL however these have considered multiple sustainability indicators and no single index can be seen [27], [39]. In this study, numerical values for different sustainability parameters were assessed following well-established methods as discussed in Section 3.7. Then, FAHP was used to determine weights for each sustainability parameter with insights from experts. FAHP has been widely used in similar applications where mismatching parameters were aggregated under multi-criteria decision-making [164], [165]. The proposed methodology presents a single index to represent the sustainability considering TBL (Section 4). The index can be used for comparing any other FP options for sustainability.

6.4. Further research

At the initial stage of the study, the case studies were limited to rigid packaging due to the higher functional demand and the significance of the packaging type. Furthermore, only the rigid packaging designs were rendered for the case studies. Therefore, further analysis could be focused on the **assessment of flexible packaging designs along with rigid packaging designs** to identify new dimensions of sustainable food packaging.

The proposed framework was validated through the insights from the experts due to the absence of a suitable method to validate a conceptual framework in the practical world. However, triangulation methods could be more reliable in validating **the framework after executing it in**

the real world. The sustainability of food packaging developed with the framework needs to be evaluated after introducing it to the market. This approach would be a long-term validation process which needs the cooperation of authorities and organizations.

The proposed framework could also be revised to **implement novel packaging innovations such as packaging-less systems**. Future research should be conducted to identify how and where these novel approaches could be adapted to the packaging industry. The proposed framework has provisions for such implementations.

The assessment of packaging-related food waste and losses is a highly controversial area. Determination of system boundaries and the separation of packaging-related food waste are the main limitations in this area. Therefore, introducing **a systematic approach for determining packaging-related food waste** would be beneficial in assessing the actual environmental impacts.

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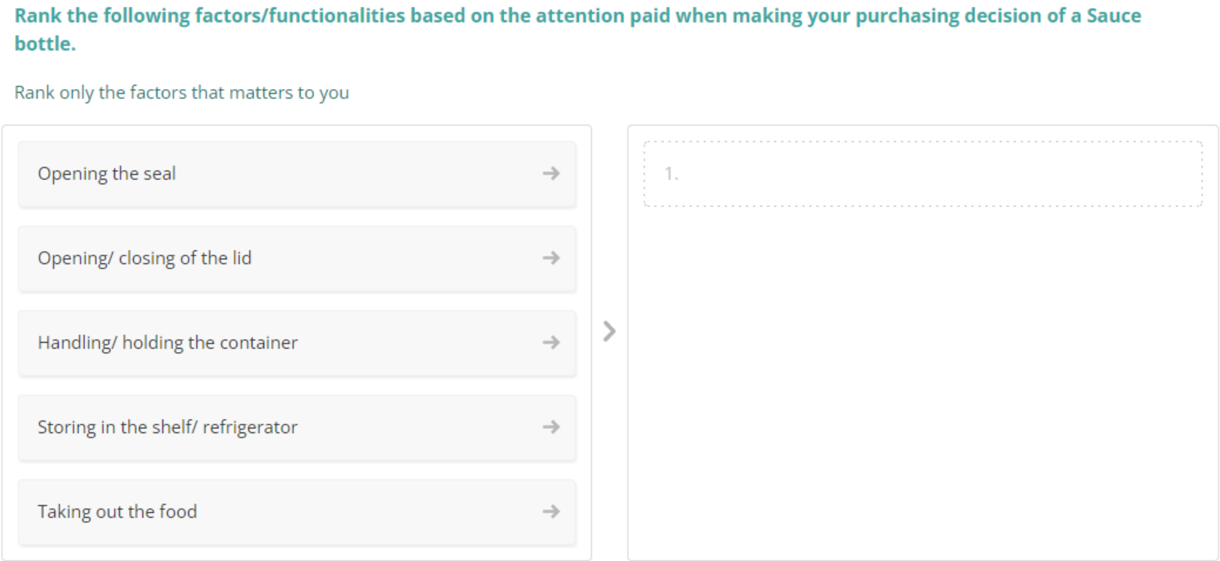
APPENDICES

APPENDIX A. QUESTIONNAIRE 'A' (ASSIGNING WEIGHTS ON FUNCTIONAL REQUIREMENTS)


Rank the following factors/functionalities based on the attention paid when making your purchasing decision of a Sauce bottle.

Rank only the factors that matters to you

- Opening the seal
- Opening/ closing of the lid
- Handling/ holding the container
- Storing in the shelf/ refrigerator
- Taking out the food

1.

APPENDIX B. (SEMI-STRUCTURED INTERVIEWS WITH PACKAGING DESIGNERS)

https://forms.gle/yzz2aqcgsesmbnyb8

Food packaging- Designers' perspective

sathindujagoda@gmail.com (not shared) Switch accounts

Basic Design Considerations

Rate the following factors based on their significance on ease of opening and closing of the packaging (0 - not relevant , 1- very low significance, 2- somewhat significant, 3- highly significant, and 4- extremely significant)

	0	1	3	9
Material used for the cap	○	○	○	○
Closure mechanism (snap fit/ thread)	○	○	○	○
Shape/ dimensions of the body	○	○	○	○
Material used for the body	○	○	○	○
Strength of the body (e.g. rigidity, flexibility)	○	○	○	○

Rate the following factors based on their significance on ease of holding/ handling the container. (0- not relevant , 1- very low significance, 2- somewhat significant, 3- significant and 4- highly significant)

	0	1	3	9
Shape/ dimensions of the body	○	○	○	○
Material used for the body	○	○	○	○
Strength of the body (e.g. rigidity, flexibility)	○	○	○	○

Rate the following factors based on their significance on ease of storing. (0- not relevant , 1- very low significance, 2- somewhat significant, 3- significant and 4- highly significant)

	0	1	3	9
Shape/ dimensions of the body	○	○	○	○
Material used for the body	○	○	○	○
Strength of the body (e.g. rigidity, flexibility)	○	○	○	○

Rate the following factors based on their significance on ease of opening the seal. (0- not relevant , 1- very low significance, 2- somewhat significant, 3- significant and 4- highly significant)

	0	1	3	9
Shape/ dimensions of the body	○	○	○	○
Material used for the body	○	○	○	○
Strength of the body (e.g. rigidity, flexibility)	○	○	○	○
Material used for the seal	○	○	○	○
Seal type/ shape	○	○	○	○

Rate the following factors based on their significance on ease of taking out the product. (0- not relevant , 1- very low significance, 2- somewhat significant, 3- significant and 4- highly significant)

	0	1	3	9
Material used for the cap	○	○	○	○
Closure mechanism (snap fit/ thread)	○	○	○	○
Shape/ dimensions of the body	○	○	○	○
Material used for the body	○	○	○	○
Strength of the body (e.g. rigidity, flexibility)	○	○	○	○
Material used for the seal	○	○	○	○
Seal type/ shape	○	○	○	○
Shape of the opening/ dimensions	○	○	○	○

Back Next Clear form

APPENDIX C. QUESTIONNAIRE 'B' (EVALUATING FUNCTIONAL SATISFACTION)

Evaluating Customer Considerations on Selecting Food Packaging
(4 min questionaire)

I'm a MPhil research scholar from University of Moratuwa working on developing a framework to increase the sustainability of the food packaging in Sri Lanka. The purpose of this survey is to analyse the consumer preference among the packaging options found in day to day life. The survey will take you nearly 4 minutes to complete and wish you may provide me your fullest support in this survey for identifying the qualities which are highly concerned by the consumers. The answers will only be used on academic purposes and the identity of the participant will be confidential.

Note :

1. ***Please consider that all the packaging options (bottles, cups, containers) are only made of plastics unless specified otherwise***
2. ***All the containers in each question, contains the same amount of food***

What is/are the type of Sauce bottle shown below that you would prefer only considering the *ease of opening/ closing/ quality of sealing?* (considering only the lid/ cap) *

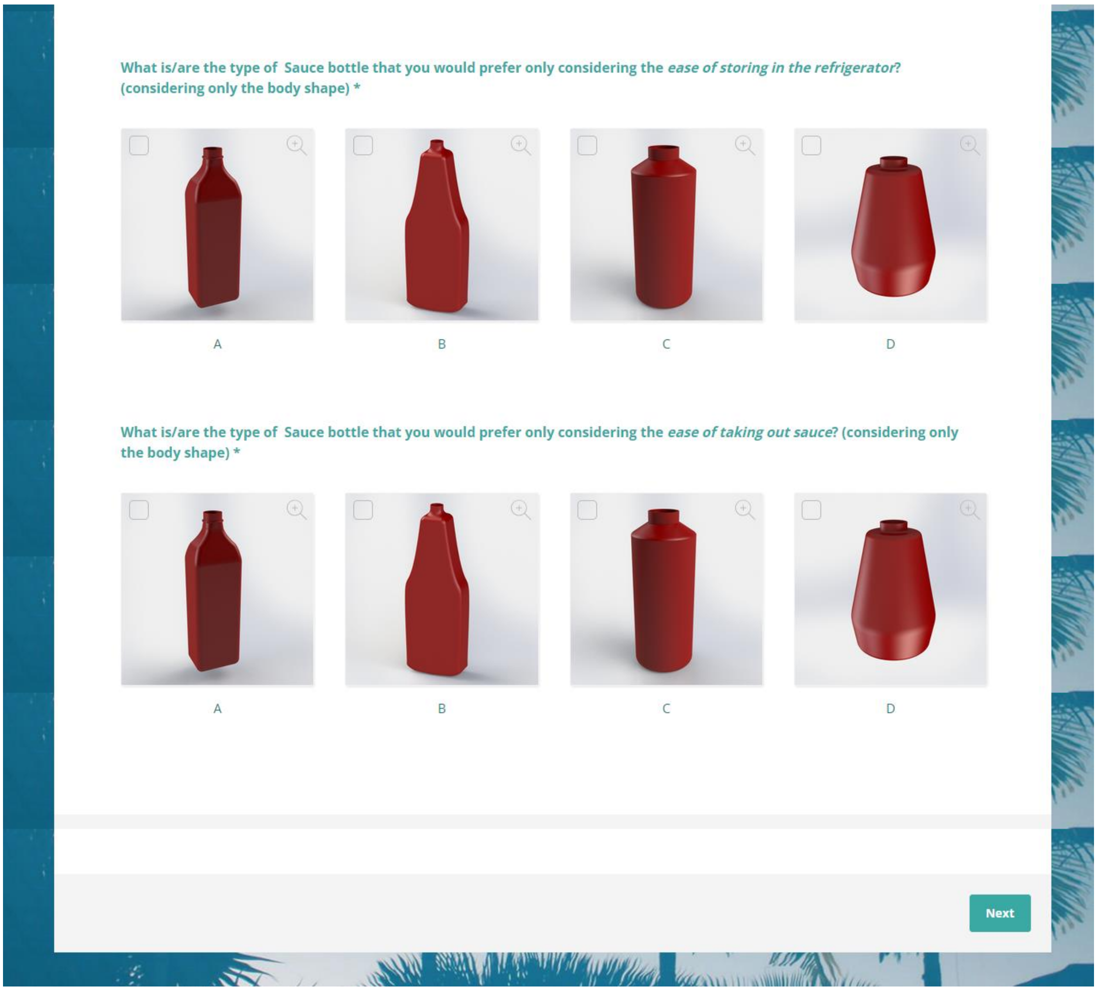
A B C

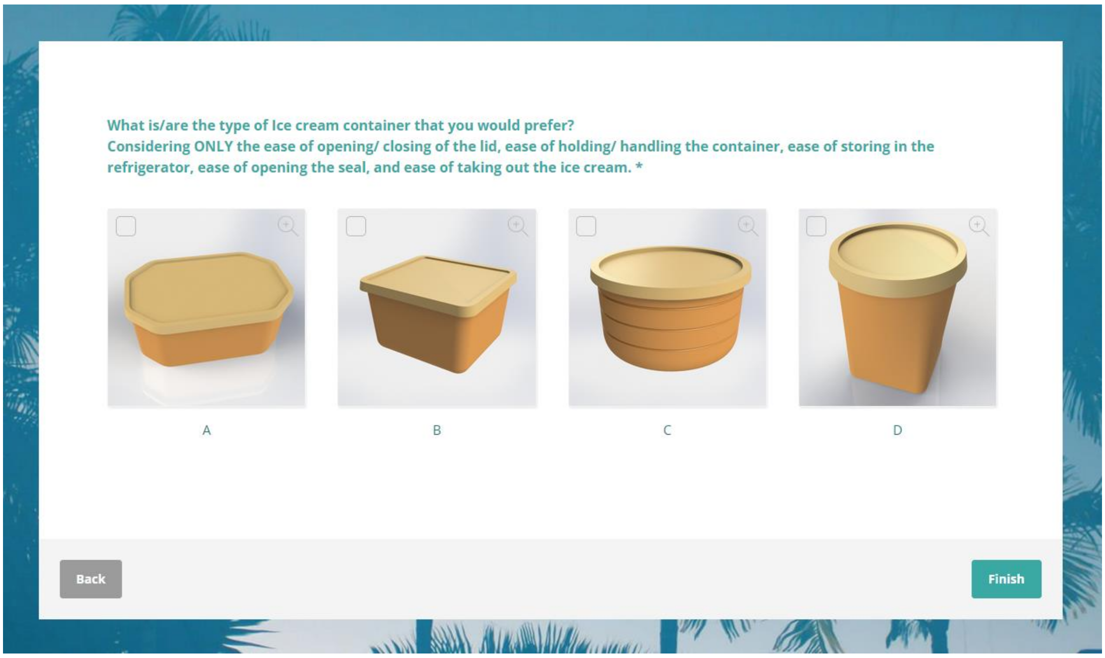
What is/are the type of Sauce bottle shown below that you would prefer only considering the *ease of taking out the product?* (considering only the lid/ cap) *

A B C

What is/are the type of Sauce bottle that you would prefer only considering the *ease of handling/ holding?* (considering only the body shape) *

A B C D


What is/are the type of Sauce bottle that you would prefer only considering the *ease of storing in the refrigerator*? (considering only the body shape) *
A
B
C
D
What is/are the type of Sauce bottle that you would prefer only considering the *ease of taking out sauce*? (considering only the body shape) *
A
B
C
D
Next


What is/are the type of Ice cream container that you would prefer?
Considering ONLY the ease of opening/ closing of the lid, ease of holding/ handling the container, ease of storing in the refrigerator, ease of opening the seal, and ease of taking out the ice cream. *
A
B
C
D
Back
Finish

APPENDIX D. QUESTIONNAIRE FOR VALIDATING THE FRAMEWORK

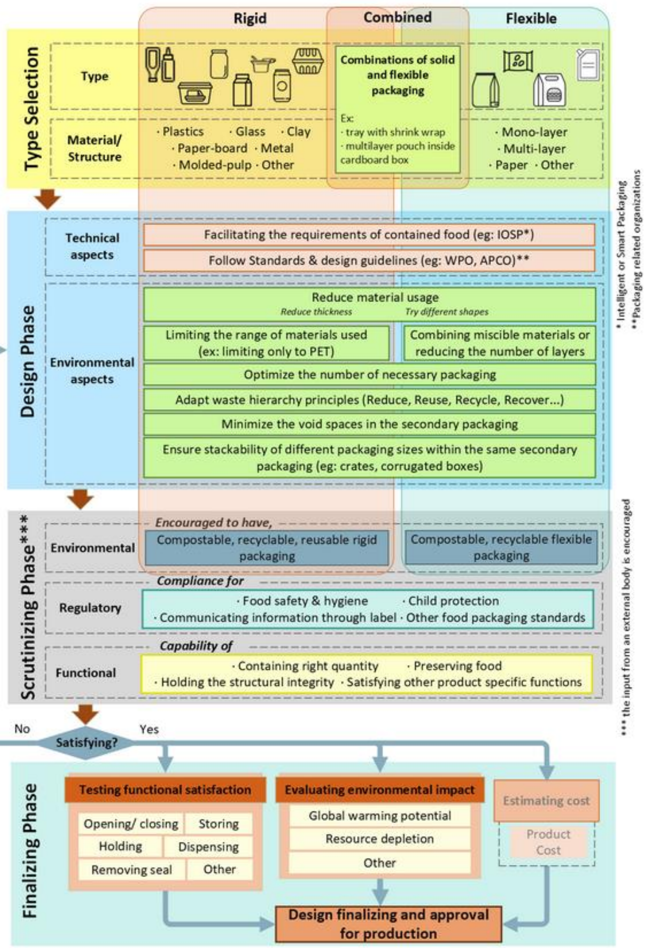
Feedback on policy framework for food packaging design

As a part of my MPhil research at University of Moratuwa, I developed a framework for the design and manufacture of sustainable food packaging. The intention of this questionnaire is to externally evaluate the developed framework for finer improvements and validation. **The framework is supposed to provide guidance for both policy developers and food packaging designers to improve the sustainability of food packaging.** The answers would be kept confidential and used only for academic purposes.
Thank you very much for time and support.
The developed policy framework is attached below.

sathindujagoda@gmail.com (not shared) Switch accounts

*Required

Proposed Policy Framework



How would you agree with the following statements when considering '**Type Selection**' phase? (Please refer to the framework diagram on the top) *

	Highly disagree	Disagree	Neither agree or disagree	Agree	Highly agree
Covers relevant aspects to be considered					
Proposed stages are logical					
Proposed stages are practical					

If you have any specific suggestions to improve **type selection**, please mention.

Your answer

How would you agree with the following statements when considering '**Design Phase**'? (Please refer to the framework diagram on the top) *

	Highly disagree	Disagree	Neither agree or disagree	Agree	Highly agree
Covers all the aspects to be considered					
Proposed stages are logical					
Proposed stages are practical					

If you have any specific suggestions to improve the **design phase**, please mention.

Your answer

How would you agree with the following statements when considering '**Scrutinizing Phase**'? (Please refer to the framework diagram on the top) *

	Highly disagree	Disagree	Neither agree or disagree	Agree	Highly agree
Covers all the aspects to be considered					
Proposed stages are logical					
Proposed stages are practical					

If you have any specific suggestions to improve the **scrutinizing phase**, please mention.

Your answer

How would you agree with the following statements when considering '**Finalizing Phase**'? (Please refer to the framework diagram on the top) *

	Highly disagree	Disagree	Neither agree or disagree	Agree	Highly agree
Covers all the aspects to be considered	○	○	○	○	○
Proposed stages are practical	○	○	○	○	○

If you have any specific suggestions to improve the **finalizing phase**, please mention.

Your answer

To what extent do you agree that '**the stages of the framework are in order and would systematically guide the user**'? (Please refer to the framework diagram on the top) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

If you have suggestions for improving the order and guidance for the user, please mention.

Your answer

To what extent do you agree that the '**framework sufficiently addresses the areas to improve the environmental sustainability of food packaging**' ? (Please refer to the framework diagram on the top) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

If you have suggestions for including/ excluding/ amending areas for improving environmental sustainability, please mention.

Your answer

To what extent do you agree that the '**framework sufficiently addresses the areas to improve the sustainability of food packaging**'? (Please refer to the framework diagram on the top) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

If you have additional suggestions for improving the framework, please mention.

Your answer

To what extent do you agree that '**the framework would provide sufficient guide for packaging designers and policy developers**'? (Please refer to the framework diagram on the top) *

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

If you have additional suggestions for improving the framework, please mention.

Your answer

Submit Clear form

APPENDIX E. THE CONFERENCE ARTICLE PUBLISHED ON MERCON 2021

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A Comparative Analysis of the Environmental and Structural Performance of PET Bottle Designs in Sri Lanka

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***Abstract*—Polyethylene Terephthalate (PET) has become the most commonly used material in the global beverage bottling industry. PET bottle production has increased by over seven times within the last three decades. However, the use of PET has a considerably detrimental effect on the environment, and many studies have been carried out on curbing this damage. Reducing the amount of material used, design for recycling, repurposing, and reusing are possible approaches for mitigating the negative environmental impacts of the PET bottle industry. The local PET bottle market has a range of products to cater the various customer requirements. To obtain a holistic vision of the actual impacts of this industry, life cycle thinking becomes necessary. The objective of this study is to present a methodological framework for comparing the environmental performance and structural performance of PET bottle designs, using case studies from the Sri Lankan market. A life cycle assessment and a finite element analysis were carried out to evaluate the overall environmental impacts of the PET supply chain and the structural performance of PET bottles. The outcomes of the study are used to provide recommendations on the short and long-term strategies to increase the eco-friendliness of the PET bottle industry.**

***Keywords*—PET bottle design, Life cycle analysis, Environmental impact, Methodological Framework**

I. INTRODUCTION

Plastics used for food packaging accounts for approximately 42% (approx. 141 million tons) of global plastic production [1]. This industry accounts for various environmental damages due to production and the generated waste. Marine pollution caused by inappropriate plastics disposal has been identified as one of the major environmental issues around the world. Global statistics show that 8 million metric tons of plastic disposed into the sea every year and 150 million tons of plastics are accumulated in the ocean [2]. With the current trends, the United Nations predicts that the plastic content will outweigh the fish in the ocean by 2050 [3].

PET bottles are a key contributor to worldwide plastic pollution. By 2018, global PET production had increased by over seven times compared to 1990 levels, and the global PET production was estimated to be 23.5 million tons in 2016 [7][8]. PET bottles account for over 92% of water bottles produced globally and have shown a 4.9% annual growth rate in the past few years [9].

Sri Lanka has been identified as the 5th largest sea polluter [4]. According to the report from the Marine Conservation Institute, 25,555 PET bottles and 15,057 bottle caps have been collected along a coastal length of 88 *km* during the annual beach cleaning program in 2019 [5]. In fact, there is a growing trend observed and highlighted by many studies worldwide, where plastics including PET bottles are washing up on beaches [6]. PET-related pollution is a direct result of littering and poor disposal practices [6]. The high amount of irresponsibly disposed PET bottles and caps in many countries highlights the importance of taking immediate action to minimize the impact of PET bottles. Interest in reducing material usage has also emerged among PET bottle manufacturers, since the amount of material used accounts for a significant portion of costs incurred by them in production.

The purpose of this paper is to present a methodological framework to evaluate PET water bottles in terms of environmental and structural parameters, and to compare their performance based on life cycle thinking. In the discussion, an analytical approach to minimize the environmental impact caused by PET water bottles is suggested.

With the above aim, the structural performance of existing PET bottles was simulated. The environmental impacts of the PET life cycle were evaluated on a cradle-to-gate basis under 18 environmental impact categories and were then further aggregated under three major classifications. The findings of this study will be of use not only to the PET bottle manufacturing industry in developing more eco-friendly and cost-effective pathways, but also to policy developers and researchers interested in enhancing the sustainability of this industry.

II. LITERATURE REVIEW

The background research was conducted based on publications including journal papers, theses, conference papers, and books published after 2005, to ensure up-to-date information. Recent documents and articles from high-impact journals were prioritised to ensure the validity and timeliness of the findings. Various scholarly article repositories including ScienceDirect and reports published by reputed bodies were made use of in the literature review.

A. Environmental Impact from PET Bottles

Several studies have been carried out from a global context to analyse the impact and sustainability of the PET bottle industry. In these, various environmental parameters have been used as evaluation criteria.

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PET has been identified to have worse environmental performance compared to high-density polyethylene (HDPE) and multilayer carton packs through a previous study, in which the functional unit was defined as the packaging required to contain 1 *l* of extended shelf-life (ESL) milk [10]. The other components of the packaging such as lid, labels and secondary packaging throughout the entire life cycle from raw material extraction to end of life (EoL) have been taken into account in this assessment. Even with modifications, PET was found to be the most poorly performing packaging material compared to other improved designs [10].

The life cycle of PET bottles from manufacture to disposal has been analysed considering the functional unit as 9000 *l* of water including the secondary packaging. The cap weighed around 5% of the bottle weight and the label about 1%. It was determined that the highest environmental impact occurs during the assembly and the disposal phases. Preparing the preform and blowing was found to be a highly energy-intensive process [11].

B. Structural Capability

PET bottles are expected to fulfil a list of functionalities including containment, protection, communication, and convenience to users [12]. Structural rigidity is a major consideration when it comes to evaluating the performance of food packaging. Computational analysis has helped to design PET bottles with a minimum quantity of material while eliminating costly prototyping. The structural strength has been analysed based on top load and drop tests.

The behaviour of PET bottles has been analysed using ANSYS workbench v.18.1 while comparing the results with practical test results. For ease of modelling and analysis, complex geometries such as chamfers, notches of the bottle were neglected. The thickness of the bottle wall was considered to be equal to 0.3 *mm* throughout the bottle. It was observed that the experimental and simulated results do not show much deviation from each other [13].

Solidworks and 'ABAQUS' have been used as software platforms to generate 3D models and simulate the structural performance of PET bottles in research, analysing dynamic and static loading conditions and buckling analysis. In one study, deflections up to 59.2 *mm* showed a maximum stress of 119 *MPa,* which is within the safe zone. The optimization results for the analysis showed that the thickness of the bottle could be reduced by 0.26 *mm* (approx. 20%) [14].

Another experimental and numerical analysis has been conducted to evaluate the compression behaviour of thin-walled plastic bottles filled with fluids [15]. A 750 *ml* bottle was taken into consideration. Three simulations were carried out by partially filling the bottle (at 90%, 75%, and 0%) with water. The numerical results have given promising results compared with the experimental results [15].

Another researcher has conducted a structural analysis using computational modelling [16]. Eight different PET bottle designs existing in the market were tested in this study. A standard 'INSTRON' setup was used to conduct the top-loading test until the bottle was completely deformed. 'MagnaMike' was used to measure the thickness of the bottle over the height of the bottle. 'ABAQUS' was used to mesh and run the simulations for bending and top-loading conditions [16].

An Australian study has specifically analysed the performance of 1.5*l* PET bottles under various weight categories. Simulations have been carried out by reducing the weight at 0.5 *g* intervals, from the initial weight (40 *g*) up to 37 *g*. The top load on a bottle was expected to be 196 *N*, which is equal to 15 piled up bottles. The simulated top-load strength for 40 *g* bottles was 307 *N* while the 37 *g* bottle was strong enough to withstand the 196 *N* top load. The 3 *g* weight reduction was estimated to save over 16,500 *MWh* of electricity consumption in the Australian market [7].

C. Policies and Practices

Sustainable production practices have become a major topic of discussion among global communities, and actions have been taken to develop policies and guidelines to regulate this area. For example, the waste framework directive by the European Union in 2008 is considered to be a protocol to follow in minimizing the negative impacts of waste and enhancing sustainable practices [18].

Waste prevention is a foremost concern in sustainable production, since it focuses on cutting off the source by avoiding the generation of waste in the first place. Package producers, food producers, retailers, and consumers are the directly involved stakeholders in waste prevention [19]. Several countries have introduced tax and deposit refund schemes, which have shown promising results in reducing and regulating plastic packaging. There are similar actions taken by some European countries, which have led to high recycling rates [2].

Reducing the amount of waste generated by reducing the quantity of material used is the next major action to be adopted. In doing this, the thickness of the bottle can be reduced while introducing ribs to reinforce the strength as needed. This approach is quite popular in the bottle production industry from a cost perspective, since materials account for 70-75% of the total production costs [20]. The fact that the weights of PET bottles have reduced by over 50% during the past 20 years is seen as a positive trend in the industry [21].

Introducing new methods for reusing the containers and/or their materials too will divert a significant fraction of the food packaging waste. This initiative has been adopted by several retailers joining hands with food and package producers, as a part of extended producer responsibility [22]. Using reusable glass bottles instead of single-use PET bottles is seen as another initiative with a positive environmental impact [23].

D. Sri Lankan Context

Sri Lankan PET water bottling industry has only a few large-scale producers, while the market majority is dominated by small scale water bottling companies. Hence, the degree of environmental impact caused by each bottle design and its life cycle varies greatly due to the nonconformity among the different producers.

The monthly PET consumption solely accounted by water bottles (without considering carbonated drinks) within Sri Lanka exceeded 1000 metric tons per month as per a survey conducted by one of the industry resource persons in 2018 contacted in this study. Out of this, a considerable amount of waste produced by PET water bottles is ultimately disposed without following proper EoL guidelines. The Audit Office report in 2019 shows only 30% of plastic is being recycled in Sri Lanka while the remaining 70% is dumped into the environment, causing numerous environmental issues [24].

Even though pollution is highlighted by many organizations and authorities, it is evident that there is a lack of research carried out on this subject within the local context. For example, there have been no studies on the structural rigidity of PET bottles and the longitudinal forces acting on the top of the bottle considering the loading practices in Sri Lanka. Moreover, no life cycle impact assessments have been carried out in this sector focusing the Sri Lankan market.

III. Methodology

A. Functional Analysis

The literature survey for 'PET bottle design' mainly focused on patented designs in the market. Novel designs and features have been used in a number of products for various design objectives, including structural performance, cost reduction, and aesthetics. To identify the expected performance characteristics, necessary design features, and available alternatives in the market, a functional analysis was conducted based on literature and manufacturer websites.

The basic requirements of food packaging are to contain food, protect and maintain taste and food safety, facilitate storage and distribution of the product, communicate information, and attract customers [25], [26]. Several other functions can be categorized under these sections as seen in Table 1.

B. Market Survey

A leading PET water bottle producer who holds a high share in the Sri Lankan market was interviewed and required data for the life cycle inventory was gathered via datasheets.

As a result of the high number of bottle producers, a vast range of designs are available in the market to contain the same water quantity. Table II shows the variety of products manufactured by one of the PET bottle manufacturers in Sri Lanka. The actual variation in the market would be even higher compared to the information found in the table, due to the presence of numerous producers. In this study, three major products were analysed based on structural and environmental performance. These three products were chosen as they possess the largest single-use market share. The collected data regarding the three major items are as shown in Table III.

TABLE I. The Functionality of Each Component of a PET Bottle

Feature	Requirement	Function
Body	Contain food	Contain water
Cap	Protect and maintain the taste	Reopening and reclosing
Thread		Holding the cap
Pilfer proof cap		Sealing to avoid pilfering
Wall thickness	Stack and distribute the product	Strengthen the product for transporting and stacking
Ribs		
Secondary package		
Label	Communicate	Convey information to the user

TABLE II. Existing Product Alternatives within the Market[30]

Product Code	Volume (ml)	Bottle weight (g)	Height (mm)	Diameter (mm)
500V1	500	13	206	64
500V2	500	15	200	60
1000V1	1000	22	258	75
1000V2	1000	24	256	80
1500V1	1500	28	292	84
1500V2	1500	32	292	84
1500V3	1500	28	300	90
1500V4	1500	32	300	90
1500V5	1500	29	290	94
5000V1	5000	90	321	160
5000V2	5000	90	342	157
7000V1	7000	110	373.6	168
7000V2	7000	100	365.9	184
10000V1	10000	330	402	218
19000V1	19000	750	490	269
19000V2	19000	750	490	269

TABLE III. Bottle Specifications Considered in the Analysis

Bottle volume (*ml*)	Weight of the bottle (g)	Weight of the PP cap (g)	Number of bottles per box
500	13	2.1	24
1000	22	2.1	12
1500	27	2.1	12

C. Environmental Impact Comparison

The life cycle impacts were analysed with SimaPro LCA software using the Ecoinvent database. The ReCiPe Endpoint (H) LCIA method was used to identify the bottle design with the highest environmental impacts [27]. The endpoint method was used for the assessment, as endpoint results can be presented in a more relatable and less complicated form for public communication of product designs [28], [29].

Necessary product information and specifications were collected from the water bottle production and bottling company. The life cycle of the three main components of the water bottle, i.e. PET bottle, cap, and the label, were considered while also including the corrugated cardboard box(which is the secondary packaging). The functional unit was defined as "the production of bottles and packages to deliver 1 litre of water", within a boundary defined to encompass a scope from raw material production to the end of bottle production. Fig. 1 provides an overview of the life cycle system boundary considered for this analysis. A cradle-to-gate boundary condition was considered for the inventory development and impact assessment. To align the purchased water volume with the functional unit, the possible combinations of bottle volumes were analysed and the reference flows were defined accordingly. For example, in the case of purchasing 1 litre of water, the possible container size combinations would be, either two 500 *ml* bottles or one 1-litre bottle. Then, the same analysis was repeated for purchasing 1.5 litres using three 500 *ml* bottles, one 1-litre bottle with one 500 *ml* bottle, or a single 1.5-litre bottle.

D. Structural Strength for Stacking

The ability to stack the bottles or the stackability was analyzed using the simulation results. SolidWorks 2017 was used to develop the 3D model of the exact bottle. The dimensions of the bottles (with water to avoid distortion during measurements) were measured using a vernier calliper. It was

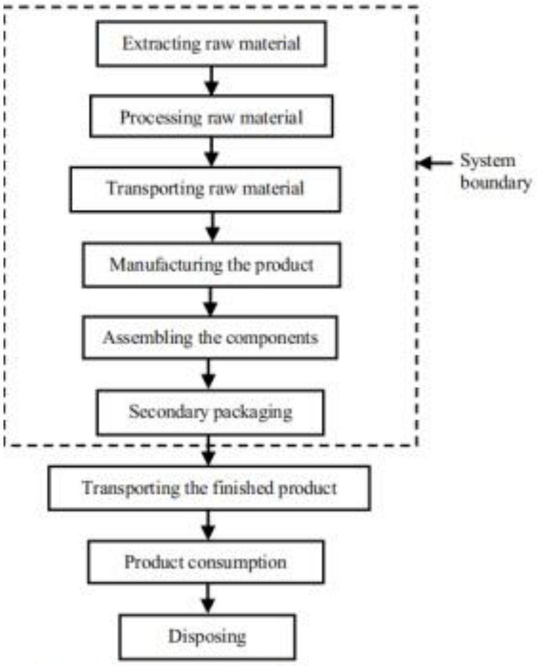

Fig. 1. Considered system boundary for this analysis

assumed that the thickness is even throughout the wall, equivalent to an average of 0.3 *mm*. This value was obtained by measuring the thickness at several points using a dial indicator thickness gauge.

"Ansys" was used for computational finite element analysis. The loading conditions of the bottle was modelled by combining both transient structural and fluid fluent analysis systems via system coupling. The deformation of the bottle caused by the force applied on the top surface was considered in the fluid system and the pressure exerted by the fluid was considered for the next iteration in structural analysis. It was assumed that the entire bottle was filled with water, and no void was allocated for the air gap.

The bottles are expected to stack up to 4 *m* and the forces acting on the bottom-most bottle was considered for analysis as this is the maximum possible loading condition. A column of 21 bottles was considered for 500 *ml* bottle and 16 for 1 *l* and 14 for 1.5 *l* bottles based on the market survey data. Therefore, the forces acting on the top surface of the bottles were calculated as 100 *N*, 150 *N*, and 195 *N* for 500 *ml*, 1,000 *ml*, and 1,500 *ml* bottles respectively. The force was applied on the top surface of the bottle keeping the bottom fixed for the finite element analysis.

IV. Analysis & Results

The flow chart shown in Fig. 2 is a representation of the suggested framework in this study.

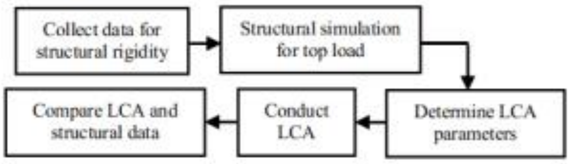

Fig. 2. Suggested framework for PET bottle analysis

A. Comparison of the Environmental Performance

Table 4 presents the endpoint impact data for the different bottle types analysed in the study. A "division by sum of values" approach was taken to normalise the results, where the individual impacts under a particular bottle type were compared to the total of the impacts of all types, under each impact category for the considered scenarios. The normalised results obtained from the life cycle impact analysis for the delivery of 1 *l* of water are shown in Table IV.

In Fig. 3, the possible delivery scenarios of two 500 *ml* bottles and a single 1-litre bottle are compared. Fig. 4 shows the normalised environmental impacts from conveying 1.5 litres of water using three 500 *ml* bottles, 1-litre bottle with 500 *ml* bottle, or one 1.5 litre bottle.

TABLE IV. Environmental Impacts Caused by Each Bottle

Impact category	Unit	500ml bottle	1 l of bottle	1.5 l bottle
Global warming, Human health	DALY	1.99E-07	1.62E-07	1.99E-07
Global warming, Terrestrial ecosystems	species.yr	6.00E-10	4.89E-10	5.99E-10
Global warming, Freshwater ecosystems	species.yr	1.64E-14	1.34E-14	1.64E-14
Stratospheric ozone depletion	DALY	3.64E-11	2.99E-11	3.70E-11
Ionizing radiation	DALY	1.01E-10	8.41E-11	1.03E-10
Ozone formation, Human health	DALY	4.12E-10	3.35E-10	4.12E-10
Fine particulate matter formation	DALY	2.37E-07	1.94E-07	2.39E-07
Ozone formation, Terrestrial ecosystems	species.yr	6.03E-11	4.90E-11	6.03E-11
Terrestrial acidification	species.yr	1.55E-10	1.27E-10	1.56E-10
Freshwater eutrophication	species.yr	4.78E-11	3.95E-11	4.87E-11
Marine eutrophication	species.yr	1.18E-14	9.71E-15	1.19E-14
Terrestrial ecotoxicity	species.yr	4.53E-12	3.79E-12	4.67E-12
Freshwater ecotoxicity	species.yr	3.08E-12	2.55E-12	3.15E-12
Marine ecotoxicity	species.yr	6.57E-13	5.45E-13	6.72E-13
Human carcinogenic toxicity	DALY	2.54E-08	2.09E-08	2.58E-08
Human non-carcinogenic toxicity	DALY	2.81E-08	2.34E-08	2.88E-08
Land use	species.yr	1.47E-10	1.19E-10	1.54E-10
Mineral resource scarcity	USD2013	8.14E-05	6.77E-05	8.37E-05
Fossil resource scarcity	USD2013	0.025588	0.020467	0.024846
Water consumption, Human health	DALY	4.50E-09	3.68E-09	4.57E-09
Water consumption, Terrestrial ecosystem	species.yr	2.74E-11	2.24E-11	2.78E-11
Water consumption, Aquatic ecosystems	species.yr	1.22E-15	1.00E-15	1.24E-15

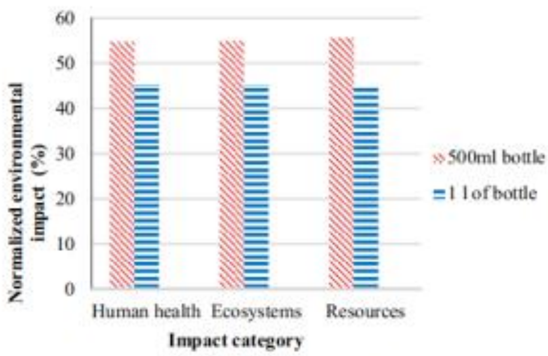

Fig. 3. Case study of delivering 1 litre of water

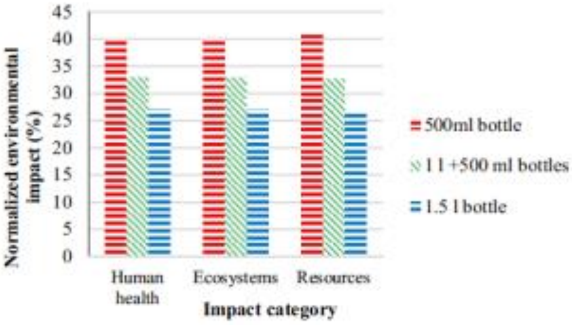

Fig. 4. Case study of delivering 1.5 litres of water

B. Strength Simulations

The deformation and the induced stress under the calculated forces acting on the bottle are shown in Fig. 5 and Fig. 6 respectively. The highest principle stresses induced and the maximum displacement in each bottle was obtained as in Table V.

V. Discussion

The literature survey has highlighted some significant aspects that should be attended to during the design stage to reduce the overall environmental impacts throughout the entire life cycle of PET bottles. A vast variety of PET bottle designs with varying characteristics can be seen in the local market. The aesthetic designs mainly focus on the marketing aspect, and this approach can result in adversely affecting the environmental sustainability of this industry.

It is obvious that proper administrative guidance and a cooperative approach among the stakeholders to share the environmental responsibility can lead to the development of better packaging products with minimized impacts. Inadequate supply of local PET recycling plants and the leakage from closed-loop product life cycle should be addressed by strengthening local infrastructure for the reverse supply chain. Promoting and raising public awareness of proper disposal methods should be highlighted in a long-term strategic plan.

The case study considered has shown that 500 *ml* PET bottle has the highest and 1500 *ml* bottle has the lowest negative impacts on the environment from a life cycle perspective. This statement is only valid when the environmental impacts are normalized for a specific volume of the product. The environmental performance of each bottle category may differ based on the volume required by the consumer and the application. For example; a 1-litre bottle would have a better eco-performance compared to two 500 *ml* bottles. However, it is better to supply a single 500 *ml* bottle for a consumer application where only a small volume of water is required, rather than replacing it with a 1-litre bottle leading to an overall waste.

The results show a linear correlation between the environmental impacts and the amount of PET material used. Therefore, the effect of reducing the amount of material used per bottle is significant irrespective of the volume consumed by the end-user. The simulation results imply that a failure due to stacking is not likely for the selected bottle designs under the possible loading conditions. The stress level of each bottle was far below the yield stress of PET, which implies that material reduction is still possible. The principal stress distribution over the bottle height shows a stress concentration near the neck of the bottle. This is caused by the lower cross-sectional area available to transfer the longitudinal force across the wall. Thus, the safety factor for that specific region seems to be lower compared to the other regions. Therefore, extra attention should be paid to the neck of the bottle when further design modifications are being done. Similarly, rib features can be used in the design to reinforce and further reduce overall material use.

The structural rigidity should be further analysed with modified simulations considering the air gap which has not been incorporated in this study. Moreover, the accuracy of the simulation results needs to be validated. This can be done via an experimental approach using existing bottles where the results are compared with the simulation outcomes. Then, more accurate results could be obtained for the novel design suggestion and the results will be a closer approximation of the real-world scenario.

This analysis shows the potential of improving the eco-performance of the PET water bottles used in Sri Lanka. Even a minor reduction would be remarkable compared to the national level where the monthly demand is over 1000 tonnes.

Table V. Maximum Stresses and Deformations under Calculated Force

Volume of the bottle (*ml*)	Maximum stress (*MPa*)	Maximum displacement (*mm*)
500	10.1	0.54
1,000	10.2	0.98
1,500	23.1	0.32

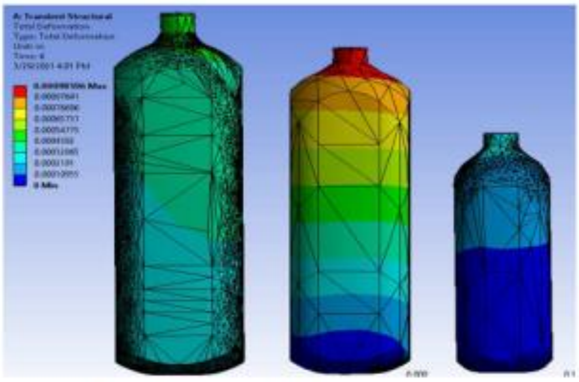

Fig. 5. Deformation under calculated force

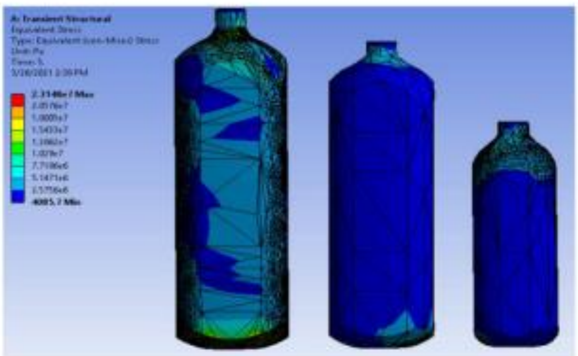

Fig. 6. Stress distribution under applied load

These aspects need to be stringently studied and incorporated to design guidelines and policies that streamline the PET bottle production in the Sri Lankan market.

VI. Conclusion and Recommendations

The study reveals an unexplored area of PET bottle designing within the local context, which should be examined more intensively. The methodological framework proposed herein can be customized and extended to other packaging products. However, the impact of non-quantifiable parameters such as aesthetics that could affect the functionality of PET bottles should be evaluated with detailed stakeholder inputs under the design phase when implementing modifications. It is evident that taking a life cycle perspective to product design is of utmost importance when attempting to enhance sustainability. In future studies, the potential for utilising reusable secondary packaging needs to be analysed. It is also beneficial to engineer the reverse supply chain of used PET bottles so that the bottles could be collected more effectively and efficiently.

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APPENDIX F. THE JOURNAL ARTICLE PUBLISHED IN THE JOURNAL OF CLEANER PRODUCTION

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Environmentally sustainable plastic food packaging: A holistic life cycle thinking approach for design decisions

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A B S T R A C T

Enhancing the sustainability of food packaging (FP) is challenging due to the conflicting environmental and functional requirements, even though it leads to many negative environmental impacts over different life cycle phases. Sustainable FP aims to strike a balance in fulfilling protection, facilitation of handling, and communication functions while minimizing the environmental impacts and economic costs. Yet, there is a lack of holistic frameworks that support sustainable FP design decision-making processes based on life cycle thinking. Thus, the objective of this study is to develop a generalizable framework combining life cycle thinking with functional analysis for systematically and holistically comparing sustainable packaging design options, considering environmental, economic, and consumer preference dimensions. The proposed approach was applied to a rigid plastic packaging case study involving ketchup bottles. Kano's theory and Quality Function Deployment (QFD) were used to identify the user requirements, applicable design features, and prioritisation. Then, conjoint analysis, life cycle analysis (LCA), and analytical cost estimation were used to estimate the functional satisfaction, environmental impact, and costs incurred respectively. Finally, the values obtained for three criteria were aggregated using Fuzzy Analytical Hierarchy Process (AHP) and the overall sustainability of the design options was compared. The results show that both material quantity, type, and shape majorly influence the functional, environmental, and economic impacts. There is a disparity between the options with the highest functional satisfaction and the lowest environmental impacts respectively. The aggregated score indicates that an option currently available in the market has the highest performance, and yet there are other options with better environmental performance. However, even after the scores are aggregated, the inputs of packaging experts maybe necessary to successfully balance the sustainability requirements with the user expectations. The findings of this research, which proposes a systematic and holistic design process, can support packaging designers, industry decision-makers, and policy planners in enhancing the sustainability of FP.

1. Introduction

Plastic pollution is a major problem in today's world, leading to a multitude of negative impacts (Kan and Miller, 2022; Springle et al., 2022). The widespread use, long half-life, and single-use nature are the key factors that increase the impact of plastics (Ayrilmis et al., 2008). An exponential growth in pollution is expected in the coming decades, with the low degradation rate and the high production rate of plastics (Sharma et al., 2014; Song et al., 2018; Watkins et al., 2019). Plastic waste ends up in landfills and ultimately contaminates land, waterways, and oceans, causing much damage to plant and animal life (Mendes and Pedersen, 2021). Not only the end-of-life impact but also the production phase contributes significantly to the total impact.

Over 42% of the plastics produced globally are utilised in food packaging (FP), which accounts for nearly 141 million tons per year (Nemat et al., 2020). In most cases, petroleum-based polymer materials are used in developing plastic packaging, making this industry complicit in fossil fuel-related greenhouse gas (GHG) emissions (Mendes and Pedersen, 2021). The environmental impacts created during the life-cycle of FP can be attributed to multiple factors. The eco-impact caused during the production phase has been estimated to be 50%–70% of the overall impact for different FP options (Kakadellis and Harris, 2020; Yokokawa et al., 2019). In addition, a significant fraction of the plastics-related impacts can be attributed to vehicular emissions during transportation and the infrastructure development for production (O'Mahony et al., 2000). While the common perception of FP only

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focuses on primary packaging, the often-forgotten presence of secondary and tertiary packaging further increases the actual environmental footprint of a product. Primary packaging is the main container holding the food product, secondary packaging combines several primary units as one set to facilitate stock keeping or handling. Tertiary packaging combines several secondary packages and facilitates storage and transport (Alamri et al., 2021). The indirect impacts arising from food losses and waste (FLW) caused by packaging is also a key topic researched in designing sustainable FP (Brennan et al., 2021). Around 5–16% of the food delivered to the consumer is wasted due to packaging-related reasons (Williams et al., 2012). The ergonomic concerns in packaging design (such as ease of handling, reclosing, emptying, or food dispensing) have been identified as the reasons for packaging-related food waste (Wikström et al., 2019; Williams et al., 2008).

It is evident that there is a critical need for reducing the environmental impacts of FP. Replacing plastics with alternative biodegradable materials has now become a trend (Mendes and Pedersen, 2021). However, completely eliminating the use of plastics in the packaging industry is not currently feasible. Further, with the above information, it can be seen that a life cycle perspective should be applied when assessing the impacts of FP since it is not limited to simply the disposal phase of plastics. Reducing the impacts associated with transportation, production, and energy usage, along with those associated with plastic waste requires holistic thinking. Pursuing sustainability through enhanced packaging designs is one option for reducing the life cycle impacts of FP (Yokokawa et al., 2021).

However, the development of sustainable packaging is a challenging and complex task, as both functional benefits to the users and environmental impact reduction have to be considered simultaneously, and it can be difficult to achieve a balance that satisfies both these ends (Yokokawa et al., 2021). FP is expected to accomplish multiple functions, including the protection of the product from environmental stresses, protection of the user, extending the shelf life, facilitating handling, storing, transportation, and minimizing waste generation (Accorsi, 2019). Conventionally, the goal of packaging designers was to enhance packaging functionality, so that the stakeholder needs across the different life cycle phases are met. The trend towards integrating environmental concerns while also meeting functional requirements in the design process is more recent, and it requires multidisciplinary thinking in a complex ecosystem [19]. Furthermore, the development of sustainable packaging requires trade-offs to be made between different functional and environmental dimensions, such as the shelf-life vs utility of the design (Yokokawa et al., 2021). Thus, "optimizing" the designs for sustainability in terms of resource and energy use while delivering the intended benefits to stakeholders is not a simple task.

In order to make sustainable packaging widely adopted in the market, the industry needs to be provided with the right tools and support to make the transition. Packaging design needs to incorporate functional requirements, life cycle environmental impacts, and economic costs and benefits. A review of the literature reveals that while studies have been carried out on designing sustainable packaging for specific applications, and understanding the environmental impacts, (Boesen et al., 2019; Del Borghi et al., 2018), very few studies have focused on the development of a generalizable and holistic framework that supports sustainable packaging design decision-making process. While methods such as quality function deployment (QFD) have been used to translate user needs to the designers' perspective, they do not incorporate environmental aspects in a meaningful way, and quantitative relationships have not been established between design decisions and environmental implications (Yokokawa et al., 2021). Thus, individual designers and industries struggle in integrating sustainability into their designs, due to the lack of sufficient knowledge, expertise, and decision-making capacity to balance the conflicting functional and environmental needs.

The objective of the present study is to develop a generalizable framework combining life cycle thinking with functional analysis for holistically comparing sustainable packaging design options. Ketchup containers were selected as a case study to demonstrate the proposed methodological framework. Functional requirements were analyzed from a user-centric perspective by eliciting consumer preferences, which was then extended to a QFD approach. The developed design alternatives were compared under the lens of functional satisfaction, life cycle environmental impacts, and cost criteria with the developed framework. The proposed approach has been demonstrated through a case study, and the data relevant to the Sri Lankan context has been used in this. This framework allows designers in taking a multistage decision-making approach to make sustainable packaging choices that reflect the practical realities in this industrial sector. The findings will assist the packaging industry in determining the most suitable sustainable packaging alternatives and policymakers in developing standards and environmental regulations for this industry.

Table 1
Functional requirements/attributes.

Functional requirements	Sub-functional attributes	References
Protection	Preservations	(B. H. Lindh et al., 2016)
	Conservation	(H. Lindh et al., 2016)
	Tamper evident	Yokokawa et al. (2020)
	Hygiene and safety	
Facilitation of handling	Transport	(H. Lindh et al., 2016)
	Open/reclose	(B. H. Lindh et al., 2016)
	Storage	Yokokawa et al. (2020)
	Taking out	
	Distribution	
	Apportioning	
Communication	Marketing	(H. Lindh et al., 2016)
	Promoting	Allione et al. (2011)
	Appealing	Harahap et al. (2020)
	Informational value	
	Nutritional value	
	Preservation methods	

2. Literature review

A detailed literature review was carried out on FP sustainability using 'food packaging', 'sustainability', 'consumer preference', 'functional satisfaction', 'environmental impact', 'LCA', 'cost estimation' etc. as keywords, in Scopus and other databases.

The parameters considered in the design for sustainability decision-making have evolved during the past few decades based on market needs and socio-technical dynamics (Ceschin and Gaziulusoy, 2016; Kannan et al., 2013). Even though the cost and functional criteria were dominant in design decisions a few decades ago, environmental sustainability has become a major consideration with the increasing awareness about environmental consequences. However, the concern about the functional and financial aspects is significant from the stakeholder perspectives. Therefore, sustainability is discussed under three main aspects in life cycle sustainability assessment (LCSA) (Alejandrino et al., 2021). Therefore, a balance between these three aspects should be maintained via scientific and evidence-based decision making.

Past literature presents a multitude of relevant parameters that can be related to sustainability. These parameters can be classified into three main dimensions as given below.

1. Functional satisfaction
2. Environmental sustainability
3. Costs incurred

While some studies have been conducted on the life cycle impacts of specific FP types and their functional attributes, very few studies have incorporated the economic aspects into this problem. The functional attributes of FP have been identified and analyzed in multiple research projects in conjunction with other parameters. The following sections discuss the identified parameters for assessing the sustainability of FP.

2.1. Parameter 1: functional satisfaction of food packaging

Under this, protecting, communicating, and facilitating handling are the main functional attributes whereas several other sub-functional attributes could be listed as shown in Table 1.

There are several studies focused on identifying and evaluating the functional requirements of FP. Functional attributes have been evaluated for different food products such as coffee, cocoa, and cinnamon via a survey (Brozovic et al., 2021). The significance of the shape and the colour on consumer preference over milk dessert cups have been highlighted using survey and conjoint analysis (Ares and Deliza, 2010). In most research, the level of functional satisfaction has been analyzed in combination with the environmental impacts as discussed in Section 2.4.

2.2. Parameter 2: life cycle impacts (LCI) of food packaging

A number of research articles available on LCA of FP highlight the significance of focusing on minimizing the impact caused during all life cycle phases. Improving the eco-friendliness of the packaging and reducing food waste and losses are the two different approaches proposed minimizing the overall environmental impact of FP in existing studies. However, a majority of studies have discussed the potential to minimize the environmental burden solely from the packaging. Therefore, studies have highlighted the importance of using low-impact materials and incorporating the circular economy into packaging design (Schmidt Rivera et al., 2019). Meanwhile, food waste and loss reduction is another concern in reducing the overall environmental impact of FP (Wikström and Williams, 2010). The life cycle phases that cause the highest accumulated environmental impact have been identified in the studies, and the methods and tools that can be used for life cycle analysis have been discussed (Zampori and Dotelli, 2014).

In the hierarchy of waste management, reducing usage has been given priority over reuse, recycling, recovery, and landfilling by European Union ("Directive 2008/122/EC of the European Parliament and of the Council," 2008), and some other researchers (Zhu et al., 2022). However, cleaning and ensuring hygiene is challenging when reusing FP due to contamination issues (Kakadellis and Harris, 2020; Vignali and Vitale, 2017). The most preferred methods for handling FP waste have been identified as recycling and energy recovery (Kalliopi, 2020; Mooren, 2015). Thus, the packaging designs were developed without hampering recycling or any other end-of-life (EoL) handling methods.

Transportation has a significant impact depending on the mode and the distance travelled (K. Verghese et al., 2012; Zhu et al., 2022). Some studies indicate that the impact from transportation is relatively small (Qin and Horvath, 2022; K. L. Verghese et al., 2010), while in some studies it can be as high as 46% (Choi et al., 2018). Amidst the conventional parameters for regulating the impact of transportation such as the distance travelled, loaded weight, and the mode of transportation, there are new approaches for reducing the impact of transportation. Enhanced volumetric capacity utilization of the freight truck is among the suggestions for improving the sustainability of packaging (Svanes et al., 2010). These concepts indicate more opportunities for improving the sustainability of transportation via packaging design enhancement.

2.3. Parameter 3: cost estimation of food packaging

In practical reality, when it comes to packaging design, the cost is perhaps the most important parameter that determines the market feasibility of a sustainable packaging option. However, the relationship between packaging designs and the overall economic burden associated with them is complicated. For example, the direct cost of producing the packaging is only a part of the actual economic impact of the packaging. The packaging design affects supply chain costs related to storage and warehousing, transportation, inventory carrying and lot sizing, and order processing and inventory (Meherishi et al., 2019). Depending on the type of material and design, the disposal costs may vary. Food wastage in the filling and the use phase and issues with shelf-life can create additional costs for the producers and users (Chan, 2022). A seemingly low-cost design option can lead to significant indirect costs to stakeholders across the supply chain.

A method has been suggested for cost estimation of the FP industry considering multiple case studies (Dahlström and Peterson, 2013). The cost for FP components has been estimated considering three cases with the data collected from companies. The cost of producing 1000 units has been estimated and the significant cost components of three case studies have been identified (Dahlström and Peterson, 2013). Material alternations and reduction in energy utilization have been suggested as cost-reducing techniques (Sun and Wang, 2010). The cost of different packaging materials for the fresh vegetable supply chain has been analyzed and contrasted (J. Wang et al., 2019). Some studies have discussed the significance of considering the cost aspect for raw materials, production, and transportation when designing a sustainable FP (Marsh and Bugusu, 2007; Pauer et al., 2019).

2.4. Evidence of collective assessment of the above parameters

Some studies have evaluated functional satisfaction along with the environmental impact. The functional satisfaction of four different FP options for potato salad products has been evaluated over greenhouse gas emissions using conjoint analysis (Yokokawa et al., 2021). In a similar study, consumer preference has been analyzed over the environmental impact of milk and cabbage (Yokokawa et al., 2019). Analyzing the intended functions of each feature is significant in FP design since the functional requirements dominate over the environmental performance (Yokokawa et al., 2020). Functional attributes such as the ability to reseal, stacking capacity, and reusability have been used as parameters to rate the chocolate packaging along with environmental criteria (Allione et al., 2011). Another research has suggested a framework to evaluate the environmental sustainability of FP considering three main aspects; the impact of packaging, food losses and waste, and the circularity of the packaging system (Pauer et al., 2019).

Apart from the studies, several organizations are regulating the design of FP with the motive of sustainability. Sustainable Packaging Coalition (SPC) is a USA-based organization focused on making packaging that is compatible with the circular economy model while ensuring health and safety. In addition to the environmental aspect, market performance and cost have also been mentioned as significant factors in sustainability (Sustainable Packaging Coalition, 2011). Australian Packaging Covenant Organization (APCO) has issued guidelines for incorporating environmental concerns associated with the stakeholders' viewpoints. There are several examples from industrial applications provided on how these measures could be implemented in developing sustainable packaging (APCO, 2019). Another such entity is the Sustainable Packaging Alliance (SPA) which is an Australian organization that has proposed a framework for FP considering the triple bottom line. Further, SPA is the distributor of the Packaging Impact Quick Evaluation Tool (PIQET), an online tool focused on streamlined life cycle assessment evaluating the environmental and economic aspects of packaging (K. Verghese et al., 2012; K. L. Verghese et al., 2010). Consumer perception has hardly been taken into account as much effort has been put into evaluating the environmental and economic aspects of FP.

The house of quality (HOQ) is a tool utilised for analysing the relationship between consumer needs and product features, so that designers can get a better idea about which aspects should be of more concern in the product development phase (Ginting et al., 2020; Ocampo et al., 2020; Otani and Yamada, 2011). The colour and the material of the packaging have been identified as highly significant attributes in take-out food packaging, based on a case study analysis conducted in Indonesia (Widaningrum, 2014). Additionally, HOQ has been used as a design support tool in several other studies focused on the development of products considering consumer satisfaction (Ginting

Table 2
Summary of the literature review.

Article	Consumer satisfaction	Environmental impacts	Cost	Sustainability	Parametric evaluation/analysis
(B. H. Lindh et al., 2016)	✓	✓			
Yokokawa et al. (2020)	✓	✓			
Allione et al. (2011)	✓	✓			
Harahap et al. (2020)	✓	✓			✓
Brozovic et al. (2021)	✓				✓
Schmidt Rivera et al. (2019)	✓	✓			
Cappiello et al. (2021)		✓			✓
Simon et al. (2016)		✓			✓
Zampori and Dotelli (2014)		✓		✓	✓
(K. Verghese et al., 2012)	✓	✓		✓	
Qin and Horvath (2022)		✓			✓
Svanes et al. (2010)	✓	✓	✓		
Choi et al. (2018)		✓			✓
Vignali (2016)		✓			
Yokokawa et al. (2021)	✓	✓			✓
Yokokawa et al. (2019)	✓	✓			✓
Sustainable Packaging Coalition (2011)	✓	✓	✓	✓	
Pauer et al. (2019)		✓			
Chan (2022)			✓		
Dahlström and Peterson (2013)			✓		✓
Marsh and Bugusu (2007)	✓	✓	✓	✓	

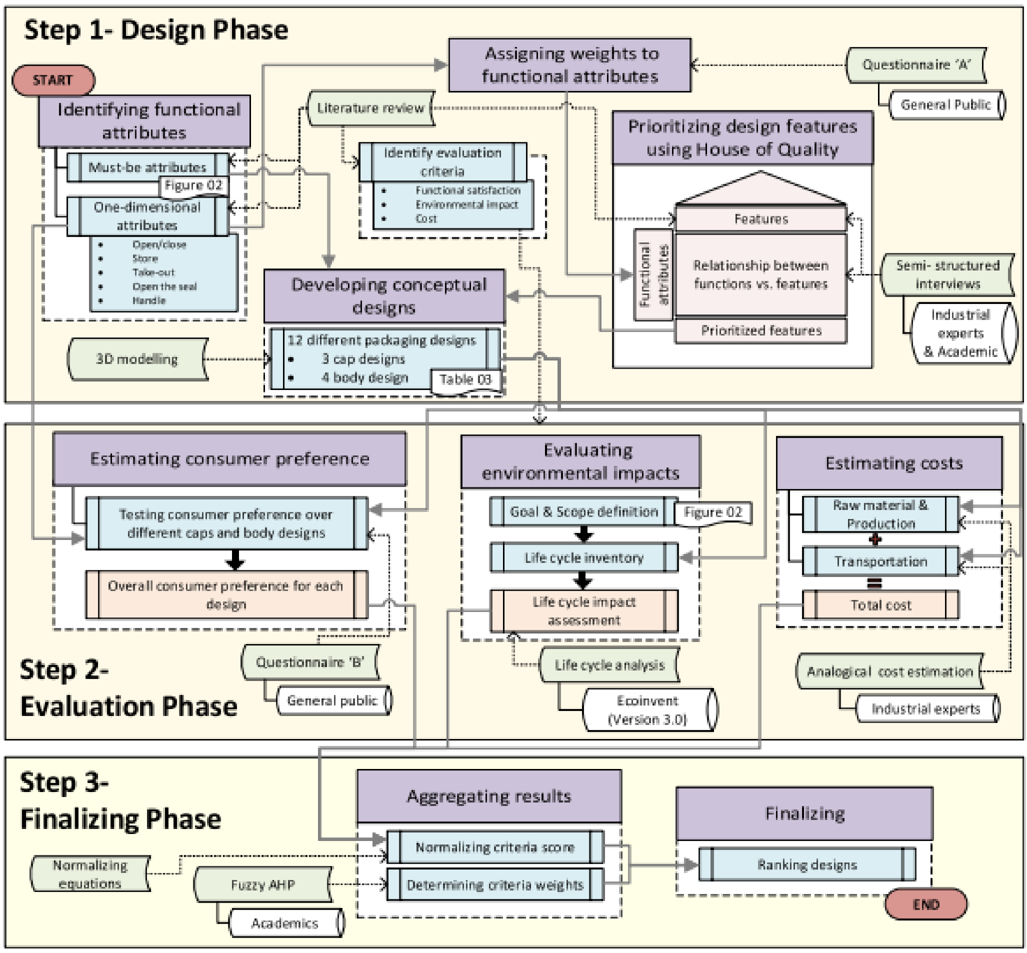


Fig. 1. Overview of the research approach.

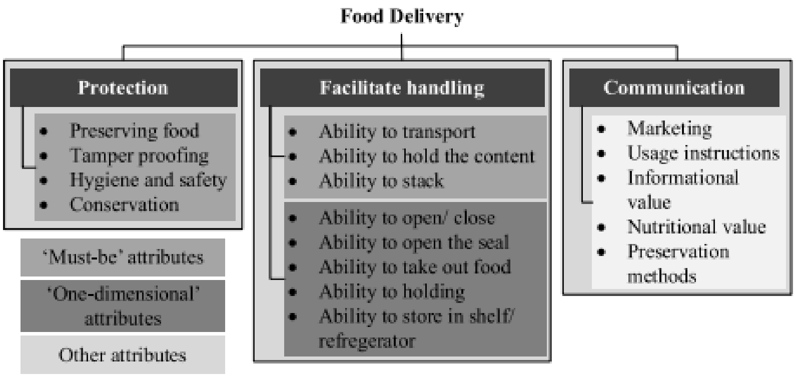


Fig. 2. Functional attribute classification.

et al., 2020; Marjudi et al., 2012; Moynihan and Garrett, 2010).

While not many studies have focused on combining the consumer satisfaction dimension with the TBL sustainability specifically for the packaging industry, some researchers have used methods such as quality function deployment (QFD) (Vinodh and Rathod, 2010) and analytical network process (ANP) together with LCA for sustainable product design problems (Menon and Ravi, 2021). A comprehensive review published on sustainable product design and development indicates that qualitative methods are often used in eco-design. However, these methods are often lacking in the integration of the economic dimension and consistency.

Surveys and questionnaires have been widely used to estimate the consumer viewpoint regarding a product in many studies (Aguilar and Cai, 2010; Ares and Deliza, 2010; Q. J. Wang et al., 2022). Consumer preference for different design features has been analyzed on metal tins and PET bottles (Anh, 2015). Additionally, some studies have evaluated consumer choices over different packaging designs and eco-friendliness. Most of these studies have considered simple case scenarios. For complex cases, data analysis tools, such as conjoint analysis have been used when multiple combinations of design options are considered (Aguilar and Cai, 2010).

For a better understanding, the publications most relevant to this have been summarized in Table 2 under five main themes; consumer/functional satisfaction, environmental impacts, cost, sustainability, and parametric analysis of packaging. Some of the publications have simply focused on qualitatively reviewing and presenting the above aspects related to packaging. In the last column in the table, the publications that have numerically evaluated or analyzed aforementioned parameters are identified. The table highlights the gap in research regarding a framework for assessing the sustainability of FP with a holistic perspective, to develop a single index for estimating the sustainability of FP.

As per the above review, it seems that evaluating the sustainability of FP is a widely discussed topic under three main criteria. However, functional satisfaction and cost have not been examined together, thus only highlighting the significance of environmental sustainability in the design of FP, which is the case in most of the above studies. Further, there are studies conducted to evaluate the environmental impacts, cost, and consumer preference or functional satisfaction in isolation. However, there is no evidence that all three parameters, environmental impact, functional satisfaction, and economical aspect, have been considered collectively in holistic decision-support frameworks for FP. This would support making more comprehensive decisions on sustainable packaging designs.

Normally, secondary packaging consists of several primary packaging. The geometry of the container makes it impossible to fill the secondary packaging without voids. Thus, a void space is left within the secondary packaging, which depends on the shape of the primary packaging limiting the number of packaging that fits in the secondary packaging. This shape factor which affects the impact of transportation has also not been accounted for when assessing the life cycle impact.

3. Methodology

This study attempts to address the above gaps via a methodological approach to support decision-making, based on functional, environmental, and economic parameters to select FP options with a fair compromise between environmental and economic concerns without sacrificing the functional requirements. The first objective is to generate design options for FP following standard product design tools. Then, the product designs are validated for environmental impact, costs incurred, and functional attributes. Finally, a method is suggested to aggregate the performance under the differing criteria and compare them on a common platform for design selection. At the initial stage, the necessity of conducting the research on a selected case study was eminent to void complexities with the vast product variation.

Packaging categorization introduced by ISO was followed for selecting a suitable product as the case study (International Standards Organization ISO, 2015). The packaging that does not deform or change its shape when food is added or taken out is known as rigid packaging while the rest are known as flexible packaging. The functional requirements of rigid packaging are much more versatile compared to flexible packaging since most rigid plastic food packaging (RPFP) is used in containing multi-serving food where functional requirements are high. In addition, approximately 15% of FP used in Asia Pacific region are RPFP which signifies the necessity to regulate them (Rexam PLC, 2012). Under RPFP, ketchup bottles were chosen as the specific case study considering the convenience of the product to the public, diversity of packaging, higher market share, and the ability to extend to other FP products. After determining the case study, the research was carried out in three phases aligned with the three objectives. The methodology followed is shown in Fig. 1.

3.1. Design phase

The purpose of the design phase was to develop different packaging designs to be used in the following evaluation phases. The methodology described in the following sections was followed to ensure that the existing industry demands were met while adhering to the standards.

3.1.1. Identifying and classifying the functional requirements of food packaging

Initially, the basic functional attributes that are expected to be satisfied by FP were identified through a literature review. There were

Table 3
Prioritising and assigning weights to functional attributes.

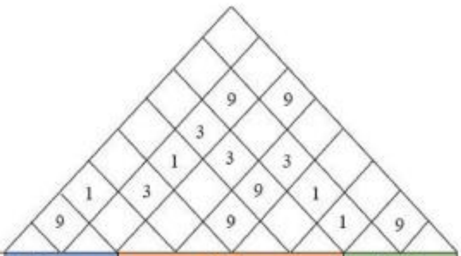
Attribute	Weight (%)
Taking out sauce	26.3
Closing/opening the lid	21.7
Handling/holding	19.4
Storing	17.0
Opening the seal	15.6

several articles published on different functional requirements attributed to protection, facilitate handling, and communication (H. Lindh et al., 2016). However, the expected level of stakeholder satisfaction differs for each functional attribute based on stakeholders' perspectives. As a result, it was necessary to distinguish the significance of each functional attribute and how it influences stakeholders' satisfaction. Accordingly, Kano's theory was followed in classifying the functional attributes based on the stakeholders' perspective on each functional attribute. According to Kano's theory, two types of attributes were filtered; 'Must-be' and 'One-dimensional', to be considered for this study. 'Must-be' attributes are mandatory to be satisfied and the inability to fulfil them will cause total consumer dissatisfaction (Brozovic et al., 2021; Löfgren and Witell, 2005; Williams et al., 2008). 'One-dimensional' attributes cause consumer satisfaction if fulfilled and vice versa. Therefore, 'One-dimensional' attributes could be utilised in evaluating consumer preference since the level of functional satisfaction is proportionate to consumer satisfaction (Dash, 2021). The functional attributes of the case study were identified as shown in Fig. 2, through literature review and brainstorming sessions.

3.1.2. Prioritising the design features using house of quality

The next step was to identify the features that need to be focused on during the design phase for improving consumer satisfaction. Initially, it was essential to identify and assign weights for the functional attributes. 'One-dimensional' attributes were considered for the HOQ since they are proportional to consumer satisfaction as described in Section 3.1.1 (Dash, 2021). Questionnaires have been used to collect data on functional attributes by several other researchers and thus, a similar approach was taken in this study also (Brozovic et al., 2021; H. Lindh et al., 2016). Respondents were asked to rank the functional attributes in 'Questionnaire-A', based on the attention paid when selecting the most convenient packaging ('Questionnaire-A' is given in Annex-1). The questionnaire was prepared using an online platform, 'SurveyHero', and was distributed among the public through social media platforms from September to October 2021. Respondents participating in this survey were not classified since responses from an equally distributed sample were required for the study. Responses from 102 individuals were collected for the analysis. The results obtained from the questionnaire are summarized in Table 3.

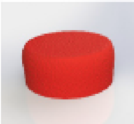
Then, the packaging features that could satisfy functional requirements were identified through a literature review (B. H. Lindh et al., 2016; Vasantha et al., 2011). Semi-structured interviews were conducted with industrial experts to establish and validate the identified interrelationships between the functional attributes and features. The existing design guidelines for streamlining the design phase and other necessary information for completing the HOQ were also discussed with the resource persons. In addition, one packaging designer from a well-known local company who has experience for more than 10 years and one academic were interviewed through online communication



Functional attributes \ Features	Consumer importance rating (%)	Lid/ cap: Material	Lid/ cap: Closure mechanism	Body: Material	Body: Shape	Body: Dimensions	Body: Strength/ Thickness	Seal: Type/ Shape	Seal: Material
Opening/ Closing	26	3	9	9	3	3	9		
Holding	21			1	9	9	3		
Storing	19			1	3	3			
Opening the seal	17			1	1	1		9	9
Emptying container	15	9	9	3	3	3	6		
Weights		187	315	318	368	368	351	153	153
Importance rating		6	5	4	1	1	3	7	7

Fig. 3. House of Quality for prioritising design features.

Table 4
Component combinations for packaging options.

			Body			
			$Op_{Body,1}$ PET (33.5 g)	$Op_{Body,2}$ PET (36.2 g)	$Op_{Body,3}$ PET (29.6 g)	$Op_{Body,4}$ PET (27.3 g)
						
Cap	$Op_{Cap,1}$ PP (3.0 g)		Option 1	Option 4	Option 7	Option 10
	$Op_{Cap,2}$ HDPE (4.1 g)		Option 2	Option 5[a]	Option 8	Option 11
	$Op_{Cap,3}$ HDPE (9.2 g)		Option 3	Option 6	Option 9	Option 12

[a] *'Option 5' is available in the market which was used to benchmark other packaging options.*

platforms to discuss the design considerations. The rating scale for the significance of the relationship consisted of four levels, where 0 stands for not related, 1 for weakly related, 3 for related, and 9 for strongly related (Otani and Yamada, 2011; Widaningrum, 2014). The developed HOQ for prioritising the packaging features is shown in Fig. 3.

3.1.3. Developing design options

After prioritising the features and identifying functional requirements, packaging designs were developed considering the industrial experts' perspective and the facts identified through the literature review.

The consumer perspective is one of the main aspects when developing FP (Wikström et al., 2014). Even though consumer expectations may differ based on ethnicity, age, and food type, 'must-be' attributes are mandatory and 'one-dimensional' attributes are encouraged to be satisfied. Considering all of these functional requirements is essential since it would directly affect the consumer preference influencing the purchase decision (B. H. Lindh et al., 2016). Meanwhile, the thickness was reduced up to the minimum value possible without demarcating the functional expectation, as per the recommendations by the packaging designers.

SolidWorks 2016 was used as the software tool to model the design options for the FP components. 'Must-be' attributes such as food preservation, leakage and pilfer proofing were considered at the design phase. New designs for the components were inspired by the existing products in the local and international markets while ensuring manufacturability with the existing facilities in the country.

The cap and the body were selected as relevant and significant components in developing design options. The guidelines followed by the packaging designers were considered when developing options. The cap is made of high-density polyethylene (HDPE) which shows favourable surface properties allowing ketchup to come out easily without sticking. However, if the packaging design is not forcing the content (ketchup) to flow through the cap (Refer $Op_{Cap,1}$ in Table 3), then PP would also be an alternative material for the cap even though it may cause more sticking than HDPE. The neck of the bottle was designed to avoid any disturbances such as horizontal ribs and suitable angles to create a continuous flow over the body wall for easy dispensing. In addition, the diameter of the opening should be large enough for the ketchup to squeeze out easily and small enough to prevent the ketchup from flowing out suddenly in the upside-down position.

Three different cap designs and four designs for bottle bodies were developed resulting in 12 packaging options. The developed packaging designs and the specifications of the components are as follows in Table 4.

3.2. Evaluation phase

The developed packaging designs were assessed based on the three main performance criteria identified through the literature review.

3.2.1. Questionnaire for calculating the functional satisfaction score

'Questionnaire-B' was prepared to identify the level of satisfaction with components (lid and body) over the functional attributes of the developed designs ('Questionnaire-B' is given in Annex 2). The survey was conducted again using 'SurveyHero', an online platform, and was distributed among the public via online platforms. Ninety-six (96) responses were received from December 2021 to January 2022. The respondents were asked which design option they would prefer considering each 'One-dimensional' functional attribute. For example, the respondents were asked which cap/lid they would prefer considering the ease of opening and closing. The number preference for each component (l) under each attribute (r) was determined through the questionnaire ($N_{r,l}$).

After identifying the consumer preference for components, conjoint analysis was used to combine them and estimate the level of functional satisfaction for the packaging design (Ares and Deliza, 2010; Silayoi and Speece, 2007; Widaningrum, 2014). The functional satisfaction on the k^{th} packaging option was calculated based on the results from the survey using the following equation and the weight for each rth attribute (W_r)

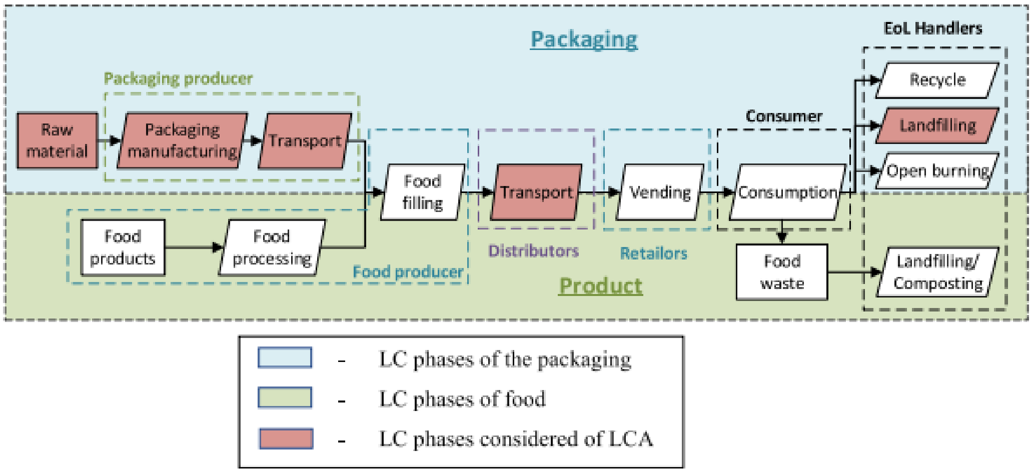


Fig. 4. System boundary of the study (the elements considered for the LCA system boundary is highlighted in maroon colour). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

was calculated using the responses from 'Questionnaire-A'.

$$\text{Functional satisfaction score for } k^{th} \text{packaging option } (P_k) = \sum_{r=1}^{\#\text{ of attributes}} N_{r,l} \times W_r$$

$N_{r,l}$ = Number of preferences for l^{th} component design option under r^{th} attribute

W_r = Weight for the r^{th} attribute

3.2.2. Life Cycle Analysis (LCA) for estimating the environmental impact

Life cycle analysis (LCA) has been utilised for comparing the environmental impact of different FP designs and different supply chains (Cappiello et al., 2021; Kan and Miller, 2022; Kang et al., 2013). A similar approach was taken in this study since the goal of the study was to compare the environmental impact of different FP designs instead of acquiring an absolute value for them. The standard procedure consists of four phases; goal and scope definition, life cycle inventory, life cycle assessment, and life cycle interpretation was followed in the study as described below (Cappiello et al., 2021; Kang et al., 2013).

The 'cradle-to-grave' approach was followed to define the system boundary, where the environmental impact is considered from raw material production to End-of-Life (EoL) as shown in Fig. 4. The life cycle phases considered in this study are highlighted in maroon colour. The life cycle phases of the packaging included within the box with the blue background while the life cycle phases of the food are included within the green background. Only the landfilling was considered as the EoL due to the large portion of plastic being sent to landfilling and the unavailability of data for the remaining EoL options. Delivering a single unit of FP was considered the functional unit since all the packaging options contained the same quantity of food. The ReCiPe Midpoint (H) method was used for impact assessment using Ecoinvent (Version 3.0) database with the SimaPro software. The midpoint method is better for design-level decision-making due to the higher accuracy and lower uncertainty (Muthukumarana et al., 2018). The data relevant to the global was considered from the Ecoinvent database. The Cut-off concept was followed in modelling the environmental impact since recycling was not considered. This method has been used to effectively represent the impact categories relevant to FP (Konstantas, 2019; Sangwan et al., 2021).

It was deemed important that the indirect environmental impacts of packaging, including that of food waste, are significant enough to be in the LCA. Considering only the direct impact of the packaging itself may lead to sub-optimal recommendations that actually increase the overall impact of the food-packaging combination (Mendes and Pedersen, 2021). Allocating the same amount of food losses for every packaging option is not effective since it may not contrast packaging-induced environmental impact. For accurate results, food losses and waste (FLW) have been estimated experimentally when conducting LCA (Williams et al., 2014). However, considering FLW for food products with low environmental impact is not necessary, since the avoided environmental burden from reducing FLW becomes non-significant (Williams and Wikström, 2011). Meanwhile, only 5–16% of food delivered to the consumer is wasted due to packaging-specific reasons while the balance is caused by behavioural factors such as excessive purchasing, over-preparation of food etc. (Williams et al., 2012). Thus, FLW was excluded from the study due to the negligible amount of FLW and the low environmental impact caused by ketchup.

The life cycle inventory (LCI) was developed for the packaging using the weights of the components calculated using the 3D model as given in Table 3. (A detailed LCI is given in Annex 3) The body is manufactured using injection blow moulding and the cap using injection moulding. A similar label and seal were designed for every packaging when estimating the environmental impact. Therefore, it was not necessary to consider them for comparing multiple options since the impact from the excluded components may not distinguish the environmental impact of packaging.

3.2.2.1. Calculating LCI from transportation. The transportation inventory was calculated using the suggested mathematical model considering the mostly used type of freight truck by the companies, taking the average data from the consulted industrial organizations. The empty FP needed to be transported for 50 km from the packaging manufacturer to the food producer. In addition, it was considered that the packaging is transported 150 km from the filling point to the retail shops. Therefore, it was estimated that single packaging would travel 200 km in total. This was an indicative value agreed upon by the packaging manufacturer for the specific study located in Sri Lanka (where the maximum length of the country is approximately 430 km and the maximum breadth is 224 km) and the production facility is located in the most populated area of the country. These values are subjected to change if a different case study was considered. According to the packaging producers, the freight truck that transports the empty bottles to the food producer is returned empty. The same scenario was approximated for the transportation from food producer to retailer. However, the return freight truck may carry some other goods on their return trip (which are not related to the product under study, i.e., ketchup). Additionally, it was assumed that the freight truck is completely occupied on its forward trip to the retailer for the simplicity of the analysis. The load space of the freight truck was approx. 17.5 m^3 and the gross vehicle weight (GVW) was 4.9 tons. The emission data for Euro-3 graded trucks were considered for the analysis.

A mathematical model was developed for estimating the environmental impacts considering the number of packaged items loaded onto a freight truck, which is a parameter that influences the effective environmental impact. An imaginary volume, which includes the product volume and the void volume, was defined as the occupied volume. The concept behind the occupied volume is illustrated in Fig. 5.

Based on the results from previous studies, it has been estimated that an empty freight truck would account for 61% of the environmental impact caused by a fully loaded freight truck, which is mathematically presented in Equation (1). The remaining 39% would linearly accumulate based on the load (Bertolini et al., 2016).

$$\text{Environmental impact from a partially filled freight truck} = 0.61 \bullet IFLL + 0.39 \bullet LF \bullet IFLL \quad (1)$$

$$= IFLL \bullet (0.61 + 0.39 \bullet LF)$$

LF = Load Factor

IFLL – Impact from Fully Loaded Freight truck

N – total number of items to be transported

V – volumetric capacity of the freight truck (load space)

v – occupied volume of the packaging

$n\ (= V / v)$ – nu. of items that could be transported by a single freight truck

m – the weight of the packaging (without the product)

M – load capacity of the freight truck

$$\text{Load factor } (LF) = \frac{\text{Weight of the shipment}}{\text{Max. load capacity}}$$

$$= m \times n / M \text{ (Since only the packaging is considered, the weight of the content was neglected)}$$

$$\text{Number of turns for transporting } N \text{ number of items} = N/n$$

$$\text{Total environmental impact} = \text{Nu. of turns} \times \text{Impact from a single turn}$$

$$= \frac{N}{n} \times \left(0.61 \bullet \text{IFLL} + 0.39 \bullet \text{LF} \bullet \text{IFLL}\right) \text{ (Assuming all the freight trucks are not overloaded)}$$

$$\text{Resulting environmental impact from single packaging} = \text{Total environmental impact}/N$$

$$= \frac{IFLL}{n} \bullet \left(0.61 + 0.39 \bullet \frac{m \bullet n}{M}\right)$$

$$= IFLL \bullet (0.61 \bullet v / V + 0.39 \bullet m / M) \quad (2)$$

3.2.3. Analytical approach for estimating financial impacts

Techniques for estimating costs based on previous data are a well-established body of knowledge. Qualitative cost estimation is done by intuitive or analogical techniques while the qualitative approach focuses on parametric and analytical techniques (Niazi et al., 2006). In this study, a quantitative approach was followed for obtaining a numerical value for decision-making. The system boundary considered for the cost estimation is shown below in Fig. 6. A quantitative analogical approach was followed identifying the material and process costs incurred using the data collected from industrial personnel. The equation used for estimating the cost is as follows.

$$\text{Cost}_{\text{Total}} = \text{Cost}_{\text{material}} + \text{Cost}_{\text{labour}} + \text{Cost}_{\text{transport}} \quad (3)$$

The cost of material was calculated based on the amount of material used for a single unit of product. The unit material cost was obtained from the interviewee from the packaging manufacturing company. The weight of the material was multiplied by the cost of the unit weight. The labour cost is a highly vague parameter and therefore, sufficient data for estimating the labour costs were not available with the resource person. In addition, the labour cost for each packaging design was considered the same which eliminates the necessity to consider it within the cost model. The figures for each cost component collected from the industrial personnel (from the financial managers of the packaging manufacturing companies) are as in Table 5.

Transportation cost has been calculated based on the cost per-kilometre. Therefore, the unit cost for transportation could be calculated as below.

$$\text{Cost}_{\text{Transport}} = \frac{\text{Nu. of kilometers} \times \text{Cost per km for the freight truck}}{\text{Nu of units in the freight truck}}$$

$$\text{Cost}_{\text{Transport}} = \frac{\text{Nu. of kilometers} \times \text{Cost per km for the freight truck}}{V} \times v \quad (4)$$

3.3. Single-score sustainability index development

The next phase was to determine the optimal packaging design by

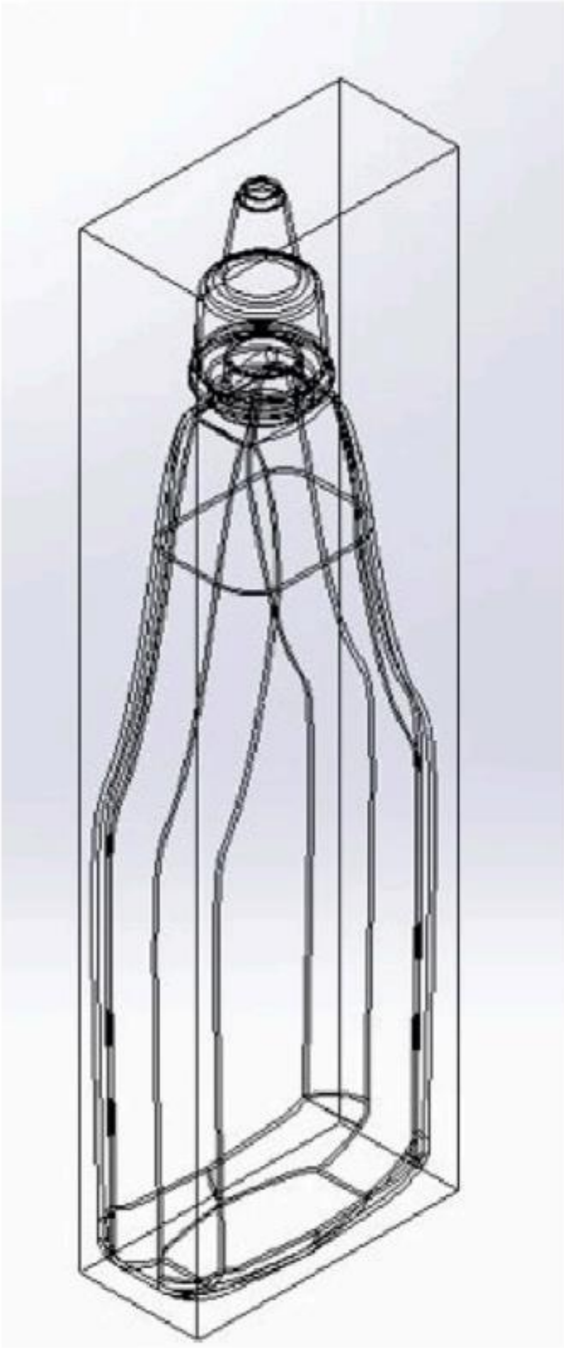


Fig. 5. The occupied volume (shown in the cuboid).

aggregating the results obtained.

3.3.1. Normalizing results

Environmental impact and monetary cost are cost attributes, where a lower score is more desirable, and functional satisfaction is a benefit attribute, where a higher score is the expectation. Therefore, the results were normalized using equation (5) for benefit attributes and equation (6) for cost attributes (Alamerew et al., 2020).

$$N_i^g = \frac{X_i}{X_{max}^g} \tag{5}$$

$$N_i^g = \frac{X_{min}^g}{X_i^g} \tag{6}$$

N_i^g – normalised value for the i^{th} option under g^{th} *criteria*

X_i^g – value of the i^{th} option under g^{th} *criteria*

X_{min}^g, X_{max}^g – minimum and maximum value in the data set under g^{th} criteria

The normalized values given in Section 4.4. were used as parametric values for aggregating in the next step.

3.3.2. Aggregating results using fuzzy AHP

The final step was to aggregate results and determine the optimum packaging design for manufacturing. There are several multicriteria decision making (MCDM) methods used for aggregating such as Analytical Hierarchy Process (AHP), ELECTRE, TOPSIS, VIKOR etc. (Kumar et al., 2017). Among these, AHP facilitates comparing alternatives without complex calculations using pairwise comparison based on experts' perspectives (Kasie, 2013; Kumar et al., 2017). First, two criteria were selected, and the respondent was asked which criteria they consider to be most important. Then, the relative preference for the attribute considered to be more important was indicated using numerical values ranging from 1 to 9 where 1 stands for equally preferred and 9 for extremely preferred. Similarly, the questionnaire was extended to determine the level of significance between all the criteria combinations. A simple fuzzy approach was assisted to compensate for data uncertainty. The fuzzy triangular method was used for this study due to its straightforwardness and reliability (Liu et al., 2020). After collecting responses, a pairwise comparison matrix was developed with fuzzy sets for each response. Then, the obtained responses were normalized using equation (7) (Kannan et al., 2013).

$d_{i,j}^k$ – fuzzy set of the k^{th} respondent's preference of i^{th} criterion over j^{th}criterion

a^k, b^k, c^k – lower, middle, and upper fuzzy numbers for the k^{th} response

f – the total number of responses received

$$d_{i,j} = (a_{i,j}, b_{i,j}, c_{i,j}) \quad where\ a_{i,j} = (a^1 \times a^2 \times \ldots \times a^f)^{1/f}, b_{i,j} = (b^1 \times b^2 \times \ldots \times b^f)^{1/f}, c_{i,j} = (c^1 \times c^2 \times \ldots \times c^f)^{1/f} \tag{7}$$

The developed pair-wise comparison matrix is shown in equation (8).

$$Pair-wise\ comparison\ matrix = \left[\begin{bmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{bmatrix}\right] \tag{8}$$

Then, the methodology suggested by Ayhan M.B. was followed to calculate the weights for each criterion as given below (Ayhan, 2013).

1. First, the geometric mean of fuzzy values was calculated as shown in Equation (8).

$$r_i = \left(\prod_{j=1}^{n} d_{ij}\right)^{1/n} i = 1, 2, \ldots, n \tag{9}$$

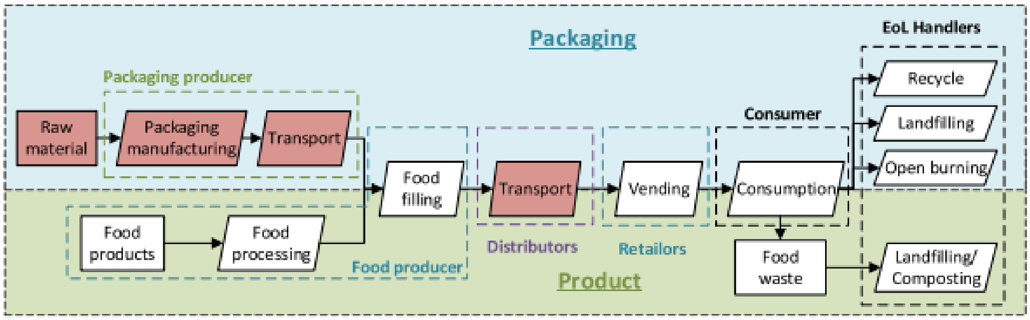


Fig. 6. System boundary for cost estimation (the elements considered for the cost estimation is highlighted in maroon colour). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Cost of items.

Cost item	Cost
PET material	1400 (USD/ton)
HDPE material	1600 (USD/ton)
PP material	1450 (USD/ton)
Transportation	0.6 (USD/km.freight truck)

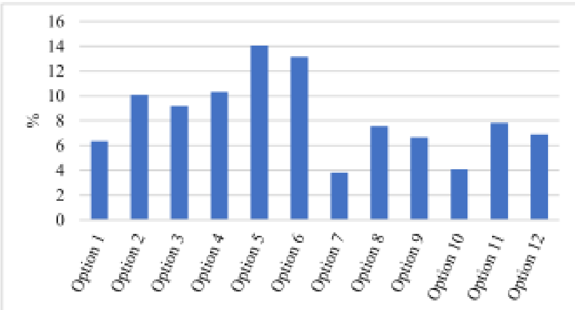


Fig. 7. Consumer preference over packaging options.

2. The summation of r_i was calculated and the reciprocal was obtained. Then they were reordered in ascending order. Finally, the fuzzy weights of criterion i (w_i) was calculated using Equation (10).

$$w_i = r_i \times (r_1, r_2, \ldots r_n)^{-1} = (lw_i, mw_i, uw_i) \quad (10)$$

3. The fuzzy triangular numbers were de-fuzzified using Equation (11).

$$M_i = \frac{lw_i + mw_i + uw_i}{3} \quad (11)$$

4. The weights were normalized to obtain criteria weight (CW) by applying Equation (12).

$$CW_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \quad (12)$$

5. The sustainability index value was obtained using the following equation.

$$\textit{Sustainability index value for } y^{th} \textit{design option} = \sum_{1}^{3} CW_i \times N_y^i$$

4. Results

This section discusses the results obtained onwards the design phase. The results from the design phase were analyzed in Section 3 for ease of understanding.

4.1. Consumer preference based on functional satisfaction

The values obtained with regard to consumer preference for the packaging options (summarized in Table 4) are shown in Fig. 7. 'Option 5' possesses the highest consumer preference which is already available in the market followed by 'Option 6'. However, a bias towards an already available product is inevitable due to convenience and familiarity. It could be identified as a drawback when conducting the survey via visual interference instead of hands-on experimental setups.

4.2. Life cycle impact assessment

The environmental impacts calculated under the 18 categories are listed in Table 6. The maroon-coloured cells show the highest impact options in each row while the green for the lowest impact under each evaluation criterion. The results are graphically represented in Fig. 9.

It was approximated that the bottles are transported in freight trucks that are fully occupied. With the suggested transportation model, the per unit impact from a packaging unit would be increased if the number of items transported is reduced when the freight truck is partially filled. However, the fully occupied scenario with the minimum impact per unit was considered in this study due to the difficulties in determining the occupied volume fraction.

'Option 6' has the highest impact under almost all impact categories and 'Options 7 and 10' have the minimum impact under most impact categories. For ease of analysis, the GWP was considered as the parameter for comparing the design options. A significant number of studies have considered GWP as the parameter for comparing the environmental impact of different options in sustainability-related assessments. There are six main criteria for selecting a suitable eco-impact indicator discussed in previous literature as (Persson, 2001),

1. Being a representative of the environmental conditions
2. Simplicity
3. Responsivity to environmental and human-related activities
4. Ability to refer to a value to get an idea of the impact being done
5. Technical viability
6. Grounding in international standards

Table 6
Environmental impact results.

Impact category	Unit	Option 1	Option 2	Option 3	Option 4	Option 5*	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11	Option 12
Global warming	*kg CO_2 eq*	0.253433	0.257732	0.279788	0.250355	0.254434	0.272127	0.22842	0.232397	0.256038	0.218716	0.221782	0.235252
Stratospheric ozone depletion	*kg CFC11 eq*	7.05E-08	7.1E-08	7.48E-08	6.98E-08	7.02E-08	7.26E-08	6.35E-08	6.39E-08	6.82E-08	6.1E-08	6.11E-08	6.22E-08
Ionizing radiation	*kBq Co-60 eq*	0.013464	0.013571	0.014144	0.013173	0.013277	0.013769	0.011991	0.012093	0.012694	0.011214	0.011299	0.011715
Ozone formation, Human health	*kg NO_x eq*	0.000538	0.000546	0.000597	0.000545	0.000551	0.000576	0.000497	0.000502	0.000563	0.000502	0.000502	0.000503
Fine particulate matter formation	*kg PM2.5 eq*	0.000435	0.000441	0.000472	0.000429	0.000435	0.000458	0.000391	0.000397	0.000429	0.000372	0.000377	0.000394
Ozone formation, Terrestrial ecosystems	*kg NO_x eq*	0.000556	0.000564	0.000619	0.000562	0.000569	0.000598	0.000513	0.00052	0.000584	0.000518	0.000519	0.000522
Terrestrial acidification	*kg SO_2 eq*	0.000834	0.000849	0.000917	0.000825	0.000839	0.000891	0.000752	0.000766	0.00084	0.000723	0.000733	0.000769
Freshwater eutrophication	*kg P eq*	8.1E-05	8.16E-05	8.51E-05	7.93E-05	7.98E-05	8.29E-05	7.22E-05	7.27E-05	7.64E-05	6.75E-05	6.79E-05	7.05E-05
Marine eutrophication	*kg N eq*	2.73E-05	2.76E-05	2.85E-05	2.67E-05	2.69E-05	2.77E-05	2.42E-05	2.45E-05	2.54E-05	2.25E-05	2.27E-05	2.35E-05
Terrestrial ecotoxicity	*kg 1,4-DCB*	0.549736	0.546381	0.568945	0.563471	0.558295	0.544692	0.512502	0.506475	0.542178	0.532381	0.518806	0.470197
Freshwater ecotoxicity	*kg 1,4-DCB*	0.008356	0.00867	0.009814	0.008223	0.008532	0.009579	0.007519	0.007826	0.009005	0.007139	0.007425	0.008377
Marine ecotoxicity	*kg 1,4-DCB*	21.07522	23.37242	30.85243	20.60898	22.90616	30.38603	19.05442	21.3516	28.83167	17.86284	20.15999	27.6397
Human carcinogenic toxicity	*kg 1,4-DCB*	0.010432	0.010669	0.011577	0.010271	0.010501	0.011272	0.009367	0.009594	0.010552	0.008897	0.009095	0.009734
Human non-carcinogenic toxicity	*kg 1,4-DCB*	8.068038	9.310886	13.36294	7.908196	9.150863	13.19931	7.365739	8.608321	12.66168	6.955735	8.197564	12.24252
Land use	*m^2 crop eq*	0.011099	0.011158	0.011564	0.010903	0.010956	0.011239	0.009921	0.009971	0.010421	0.009368	0.009392	0.009556
Mineral resource scarcity	*kg Cu eq*	0.00042	0.000421	0.000435	0.000418	0.000419	0.000421	0.000381	0.000381	0.0004	0.000372	0.00037	0.000359
Fossil resource scarcity	*kg oil eq*	0.09534	0.097384	0.108317	0.094087	0.096057	0.105531	0.086005	0.087941	0.099405	0.082188	0.08382	0.091881

Impact is High — Impact is Low

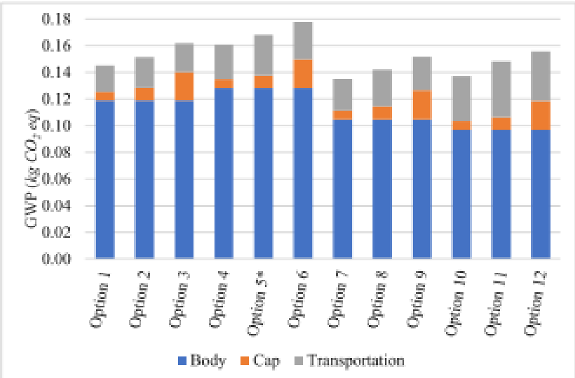


Fig. 8. Global warming potential from each option.

Here, GWP was selected as the representative category due to the current focus on climate change mitigation in sustainability interventions and policies across the world, and the above criteria (Persson, 2001). The packaging design with the highest GWP shows a 32% increment in GWP compared to the least impactful option. This shows there is a potential to reduce the environmental impact by merely changing the design, without changing the packaging type or materials. Global warming potential (GWP) was considered the representative category for analytical purposes. Fig. 8 shows the global warming potential of each option under the considered causes of environmental impact.

'Option 10' offers the least impact under GWP and is a more environmentally benign packaging option. Packaging 'Option 6' shows the highest amount of impact followed by 'Option 5' which is readily available in the market today. This highlights the significance of replacing the existing packaging with a more eco-friendly option.

The calculated environmental impact from transportation using the suggested model (considering both the volume and weight) is discussed in Section 3.2.2., and the conventional method (only considering the weight) is graphically presented in Fig. 10. The conventional model showed minor variations due to the weight difference between the packaging options. The suggested model showed a higher level of overall impact since it accounts for the impact created by the occupied volume in addition to the weight of the packaging. This novel approach uncovers the variation in the environmental impact due to the occupied volume, which has not been mathematically modelled earlier.

A graph was plotted to identify the relationship between the impact and the occupied volume of the packaging as shown in Fig. 11. The points in the graph show the 12 different packaging options discussed in Table 4.

The strong correlation between the impact of transportation and the occupied volume highlights the significance of the occupied volume in minimizing the transportation impact. The number of items transported at a time would decrease if the occupied volume were high and vice versa. Thus, a freight truck loaded with few items would cause a higher environmental impact per unit since the impact from the freight truck is shared among the number of items transported.

4.3. Cost estimation

The costs incurred for each component and transportation are shown in Fig. 12. The bottle body accounts for the highest fraction of the costs incurred, followed by the cap and transportation. Therefore, the material quantity could be identified as the most influential factor under economic criteria. Meanwhile, 'Option 6', which has the highest environmental impact, also dominates under the cost aspect. Inversely, 'Option 10', which has the minimum environmental impact, also has the least cost.

4.4. Normalized results

The calculated values for functional satisfaction, GWP, and costs are

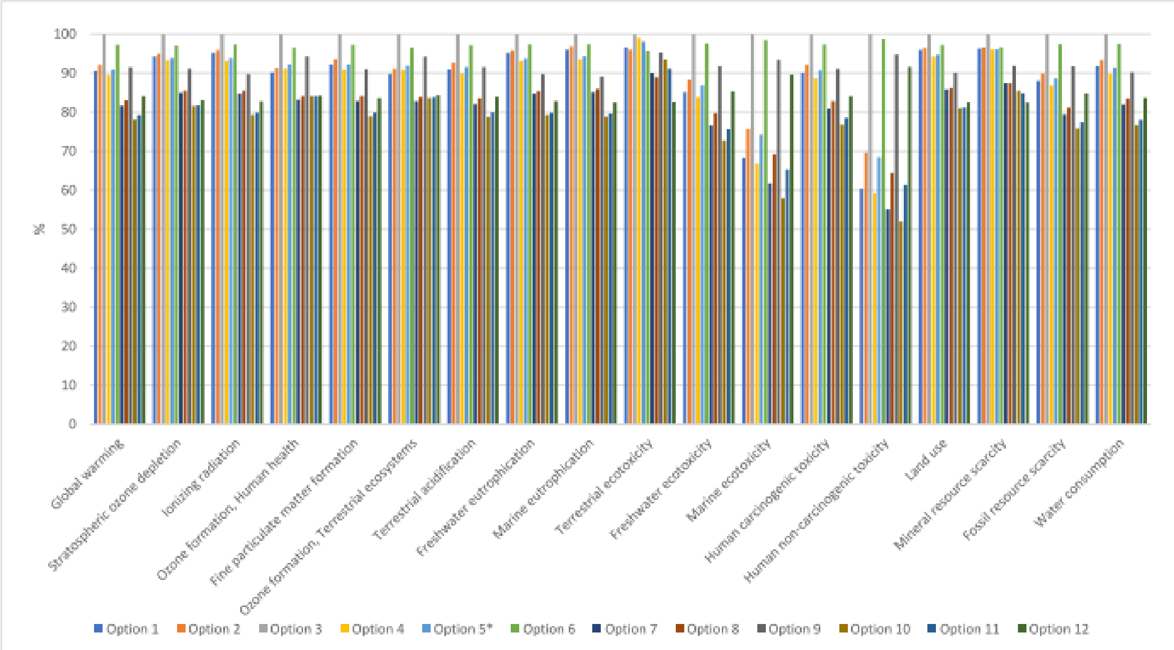


Fig. 9. Environmental impact of each packaging option.

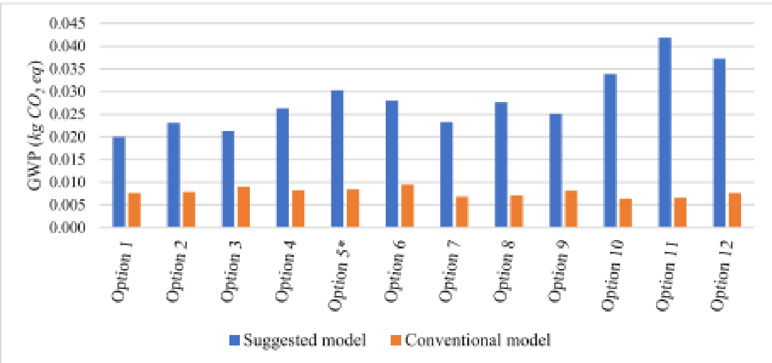


Fig. 10. Comparison between two transportation models.

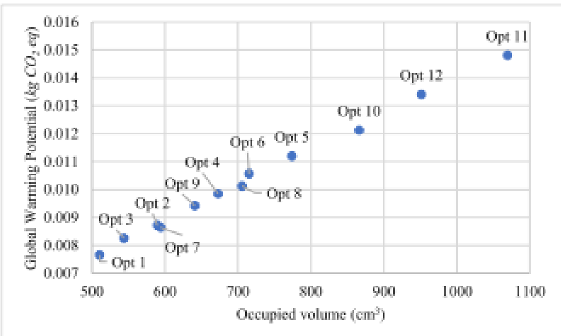


Fig. 11. GWP of transportation vs occupied volume.

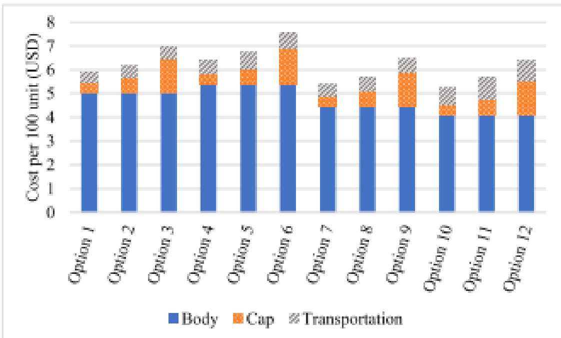


Fig. 12. Total cost for each option.

Table 7
Functional satisfaction, eco-impact, and cost estimations for each option.

	Option 1	Option 2	Option 3	Option 4	Option 5*	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11	Option 12
Functional satisfaction (%)	6.4	10	9.2	10	14	13	3.8	7.6	6.7	4.1	7.8	6.9
GWP per unit (kg CO_2 eq)	0.25	0.25	0.28	0.25	0.25	0.27	0.23	0.23	0.26	0.22	0.22	0.24
Cost per 100 units (USD)	5.90	6.18	6.96	6.43	6.73	7.50	5.38	5.69	6.46	5.27	5.66	6.38

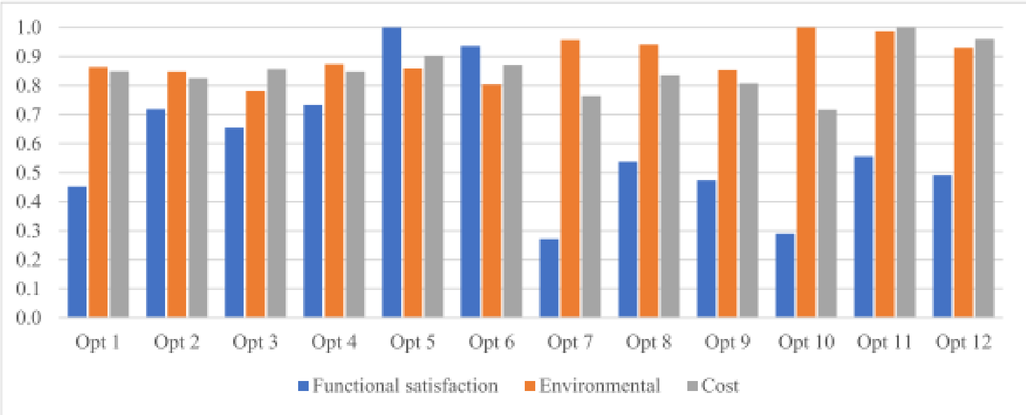


Fig. 13. Normalized criterion values.

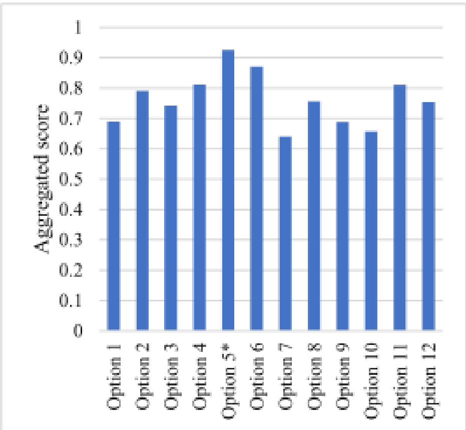


Fig. 14. Final score for packaging designs.

as in Table 7.

In an optimal design, functional satisfaction needs to be maximized while the other two parameters are to be minimised. Therefore, Equation (5) was used to normalise functional satisfaction. Then the eco-impact, which is indicated by the GWP, and the cost per unit was normalized using Equation (6). The normalized values were plotted in a bar chart as shown in Fig. 13.

The diagram shows that 'Option 5' has the highest functional satisfaction while 'Option 10' shows the lowest environmental impact and cost of production. For the considered case study, none of the packaging options performs best under all three parameters. Thus, the final decision for a suitable packaging option should be based on a compromise between these parameters. The environment or cost-biased decision will follow 'Option 10' and the market-oriented choice would be 'Option 5'. This phenomenon indicates the significance of aggregating results for screening the most appropriate design instead of suboptimal ones.

The criterion weights were obtained as 0.41, 0.41, and 0.17 for functional satisfaction, environmental impact, and cost respectively. The values obtained from weighted summation with FAHP are as given in Fig. 14.

'Option 5', which is currently available in the market, shows the highest aggregated score followed by 'Option 6'. However, the

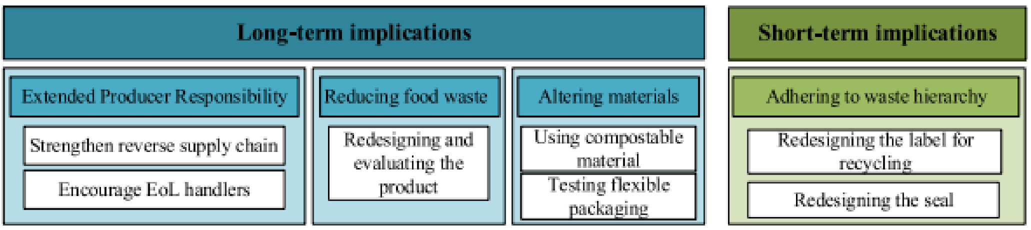


Fig. 15. Improvements for the existing packaging design.

discussion could be further extended towards improving the environmental sustainability aspect of this packaging design.

5. Discussion

The research suggests a novel methodological approach for the holistic assessment of the sustainability of FP. In the evaluation procedure, the triple bottom line of sustainability (i.e., social, environmental, and economic aspects) has been considered. Under the social aspect, consumer value addition has been given priority with a focus on improving the consumer experience of FP. The environmental burden and the costs incurred have been considered under environmental and economic criteria. Life environmental burden, economic impacts, and stakeholder preference were analyzed and quantified, and the scores have been aggregated to obtain a single sustainability index using fuzzy AHP technique. The environmental impact was assessed through the LCA, consumer preference through a questionnaire, and costs through an analytical approach considering different cost components. Thus, this work fills the gap in the existing knowledge base for a generalizable and holistic framework that supports a sustainable packaging design decision-making process. It also aggregates the consumer perspective with environmental and economic dimensions via a systematic approach for design decision-making.

Even though 'Option 5' (existing packaging in the market) shows the highest consumer satisfaction level, it could not be assumed that the respondents were not biased towards the available packaging option due to the convenience. There was no way to isolate the respondent-product relationship in data collection in the local community.

The packaging design (Option 5) prioritized through FAHP shows the third highest environmental impact among the developed designs. Therefore, there is room for improving environmental sustainability as illustrated in Fig. 15.

The improvements could be discussed under two categories as long-term and short-term implications. Some of these measures focus on integrating sustainable design guidelines for the packaging while the remaining focus on managerial measures.

5.1. Short-term implications

The environmental sustainability of packaging designs available in the market can be improved via multiple means. For example, the label of the packaging is made of paper and is attached to the body using an adhesive. This implies several challenges during the recycling process. In automated sorting machines (Near Infrared-NIR), the sorting process is not efficient when the paper or glue is attached to the PET body. Therefore, the paper and glue need to be removed before recycling which requires extra effort. In addition, the paper used for the label is laminated and therefore recycling it with paper material is also challenging. Replacing the paper label with a heat-shrink PET film would eliminate most of these challenges since it allows easy recycling. In addition, it simplifies the manufacturing process eliminating the necessity for a separate adhesive process.

The pilfer-proofing seal used in this design is made of using layers of paper, aluminium, and plastic and is applied to the top of the bottle body inside the lid. Due to the material composition of the seal, it is a bit difficult to recycle it with a simpler method. However, the same functionality could be achieved by applying a heat shrink PET film around the lid and the neck of the body. If replaced, it would eliminate the necessity of the composite seal and simplify the process.

When considered together, the use of both heat adhesive label and seal would ease the manufacturing process since it would allow using the same process at the end of the production line instead of using multiple processes. Therefore, beyond the environmental sustainability improvement, the suggested modification is expected to offer a technical advantage over the manufacturing process.

5.2. Long term implications

Proper waste treatment of disposed FP is a cost-intensive procedure that needs extended infrastructure. Extended Producer Responsibility (EPR) is a policy that intervenes in enforcing the producer to undertake the EoL handling of the product. Strengthening the reverse supply chain is an important action since the amount of waste escaping the circular supply chain is noteworthy. Deposit refund system is a concept that has been taken into action by several companies successfully. A similar approach could be taken within the local context by integrating the cost of the deposit at the purchase and refunding it when returned. Meantime, national policies could be implemented for organizing EoL handling facilities with financial support from the producer which motivates the producer to lean towards less impactful designs.

FP related waste minimization is another measure of reducing environmental impacts. Due to the complexity of this objective, several iterations should be executed between design and evaluation. Besides the environmental impact reduction, food waste reduction also improves the consumer satisfaction level which would add value to the effort made on it. The use of different packaging materials is another approach suggested by several researchers. Replacing conventional polymers with bio-degradable materials may influence the overall environmental impact in a situation where the waste handling of the packaging is highly distinctive. However, the cost of bio-degradable packaging is much higher than conventional material. Therefore, under current conditions, the use of bio-degradable material would not be a discussion at the industrial level. Despite that, national policies should be oriented towards encouraging bio-degradable packaging after reviewing the sustainability of this material alternative. In addition, flexible packaging is another feasible solution to be considered with consumer feedback that could lead to introducing more sustainable packaging. Though it is not readily available in the market, the consumer preference for a such product could be significant due to the low cost of production and ease of emptying. Meanwhile, after a few months of introducing it to the market, a consumer preference survey could be assisted to analyse the real-world market potential of the product.

6. Conclusions

The proposed methodology can be used to rationally validate design decisions and compare between alternate design options. The results show that the GWP from transportation contributes to approximately 18% of the entire impact of the product on average when the occupied volume of the packaging is considered. The analysis reveals the possibility of minimizing the environmental impact of transportation by reducing the occupied volume of the packaging. The overall results show a strong correlation between the amount of material used versus environmental impact. Therefore, the necessity of a framework for developing FP design with suitable material using the minimum quantity would lead to reducing both the environmental and cost impacts. Meanwhile, the functional attributes should not be compromised to maintain consumer preference and functional satisfaction and thus, the market demand.

In this study, functional satisfaction, environmental impact, and cost were identified as the factors which affect most when determining a suitable packaging for a food product. The proposed methodology has been able to validate and contrast these three parameters in a rational way that could be utilised by the relevant stakeholders. There can be other long-term environmental and social implications of design decisions. The environmental damage of using certain materials may well be translated to an economic burden in the long-term when it comes to recovering the impacted ecosystem as well as addressing the health and other impacts on humans. Moreover, design changes may have unforeseen consequences for consumers. One example of this is how certain packaging designs lack accessibility features for people with disabilities. Further, the consumer preference for designs can be changed with better awareness of the environmental costs associated with packaging. These long-range implications need to be assessed and presented via a future study. In addition, this study focuses only on design changes without considering the possibility of substituting conventional packaging materials with eco-friendly and biodegradable materials. That too is an aspect that should be integrated in the future. Further research is required to investigate the effects of using other materials such as PP and HDPE in packaging production instead of PET. In addition, the food waste and the other 'one-dimensional' attributes could have been evaluated using tangible prototypes with real-world experimental setups. A tangible product would have allowed the respondents to feel it on hand which will eventually help to provide more convenient and precise answers regarding user preferences. Efforts should also be directed toward developing and implementing policies to mandate and regulate sustainable FP.

CRediT authorship contribution statement

S.U.M. Jagoda: Conceptualization, Methodology, Data curation, and, Formal analysis, Writing – original draft. **J.R. Gamage:** Conceptualization, Supervision, and, reviewing. **H.P. Karunathilake:** Conceptualization, Visualization, Supervision, and, reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2023.136680.

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