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LIFE CYCLE ANALYSIS OF BEVERAGE PACKAGING

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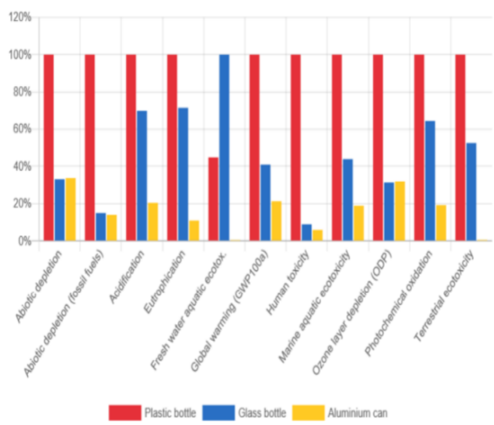
Graphical abstract



Abstract

Plastic is the leading food and item packaging material due to its lightweight characteristics. However, there have been alarming concerns over the past years since the large-scale introduction of plastic after the Second World War, and a total of 8.3 billion metric tons have been produced. This research aims to compare the environmental impact of the packaging design of several consumer products using life cycle analysis (LCA). Based on the openLCA open-source software, three beverage packaging types were compared: plastic bottles, glass bottles, and aluminium cans. The life cycle inventory (LCI) must be identified based on case studies, literature reviews and relevant assumptions to obtain the result. Then, each beverage packagings flows, process and product system was also required to be identified to run the openLCA software. The three types of packaging was compared within each CML category in terms of impact. The CML stands for "Centrum voor Milieukunde Leiden". It is a research institute of the Centre for Environmental Studies at Leiden University located in the Netherlands and a procedure used to estimate the measure of environmental impact caused by the product. Based on the CML eleven impact categories, the plastic bottle was ranked as the most impactful towards the environment, followed by glass bottles and aluminium cans as the least impactful. Other than that, it may be due to the quantity of material being used, the effect of the material during processing, and the recyclable ability.

Keywords: Life cycle analysis (LCA), openLCA, life cycle inventory (LCI), beverage packaging, plastic bottle, glass bottle, aluminium can

Abstrak

Plastik telah menjadi bahan utama untuk pembungkusan makanan dan barangan kerana cirinya yang ringan. Walaubagaimanapun, ia telah menjadi isu yang membimbangkan sejak beberapa tahun lalu sejak pengenalan plastik secara besar-besaran selepas Perang Dunia Kedua, sejumlah 8.3 bilion tan metrik telah dihasilkan. Tujuan projek ini adalah untuk membandingkan kesan alam sekitar reka bentuk pembungkusan beberapa produk pengguna menggunakan analisis kitaran hayat (LCA). Berdasarkan perisian bebas openLCA, tiga pembungkusan minuman telah dibandingkan: botol plastik, botol kaca dan tin aluminium. Untuk mendapatkan keputusan, inventori kitaran hayat (LCI) perlu dikenal pasti terlebih dahulu berdasarkan kajian kes, kajian literatur dan andaian yang berkaitan. Kemudian setiap aliran pembungkusan minuman, proses, sistem produk juga perlu dikenal pasti agar dapat menjalankan perisian openLCA.

Tiga jenis pembungkusan akan dibandingkan dalam setiap kategori CML dari segi kesan. CML bermaksud "Centrum voor Milieukunde Leiden". Ia adalah institut penyelidikan Pusat Kajian Alam Sekitar di Universiti Leiden yang terletak di Belanda dan prosedur yang digunakan untuk menganggarkan ukuran kesan alam sekitar yang disebabkan oleh produk tersebut. Berdasarkan sebelas kategori impak CML, botol plastik mempunyai impak tertinggi terhadap alam sekitar, diikuti oleh botol kaca dan aluminium sebagai yang paling kurang memberi kesan. Selain itu, ia mungkin disebabkan oleh kuantiti bahan yang digunakan, kesan bahan semasa pemprosesan, dan keupayaan kitar semula.

Kata kunci: Analisis kitaran hayat (LCA), openLCA, inventori kitaran hayat (LCI), pembungkusan minuman, botol plastik, botol kaca, tin aluminium

1.0 INTRODUCTION

Due to the world's increasing population, food demand has risen over the years. The growth of the food packaging market has actively promoted the development of the food system, while it has also generated severe environmental issues [1]. Approximately 95–99% of plastic material is manufactured from non-renewable sources (synthetic plastics) by petrochemical industries [2]. Post-consumer plastic trash collection figures don't match demand or four consumption because of plastics' wide variety of product lifespans (1 to 50 years or more). Over 23% of the waste was transferred to landfills, and more than 40% was delivered to energy recovery operations, even though more than a third of the waste was recycled. Most products are packaged in a large amount of film and paper, which the consumer then discarded in the landfill, increasing the number of landfills for rubbish [3]. However, because this material is rigid to degrade, it has the potential to pollute the environment. Many of the problems we confront and the solutions we must develop are tied to the food and beverage (F&B) business.

Packaging is a crucial aspect of the food industry. The functions are mainly to protect and contain information and act as details. It protects the food from unnecessary physical, chemical, and biological changes [4]. It also acts as a storage during transport and distribution during the supply chain and includes all the important information covering ingredients, allergens, and barcodes. However, non-degradable plastic cannot undergo physical, chemical, and biological degradation, increasing plastic waste that impacts pollution and the environment [5]. Aligned with this issue are many new ideas for packaging design improvement.

One of the new developments in ecology is using environmentally friendly, biodegradable, and edible packaging [6], [7]. Modern disposable eco-friendly dishes are manufactured by various companies using eco-friendly materials such as wood, bamboo, carbonized bamboo, sugar cane, and other natural materials, all without chemical preservatives. Ecological packaging has been increasingly popular in recent years, bringing us back to the basics of using natural resources that are readily biodegradable. The decomposition of biodegradable plastic produces water, carbon dioxide, inorganic compounds, and biomass. This will be good towards the environment as there is no accumulated waste. Based on the openLCA (https://www.openlca.org/), this paper aims to investigate and compare three main types of 500ml beverage containers: plastic bottles, glass bottles and aluminium cans. It will help better understand the environmental impact of products, mitigate the environmental impact, and develop an effective ecological marketing strategy at the end of the findings.

2.0 BACKGROUND

2.1 Single-Use Plastic as Food Packaging

Due to its cost-effectiveness, resilience, and unique characteristics, companies heavily depend on plastic packaging [8]. Plastic packaging accounts for the most significant portion of plastic use in the market and constitutes nearly half of the global plastic waste [9], [10], [11]. Single-use plastic is a material intended for one-time use only before being discarded. It has gained massive popularity since the '70s. It is a non-biodegradable product and will remain the same on the earth even for 100 years later. Single-use plastic packaging significantly contributes to the millions of tons of plastic waste that evade collection systems and end up in waterways annually [9], [12].

Most food packaging in the current market commonly uses this type of packaging. It was found that single-use plastic is a clear example of a waste culture problem [13]. People need to pay more attention to the long-term impacts it will cause and give more priority in terms of convenience. The long-term effect is that single-use plastic can cause harm to the environment, such as air, water, and land pollution, since it is composed of major toxic pollutants. One study found that regularly used plastic food packaging materials such as plastic bottles, containers, cups, or tea bags release microplastic in the respective food and beverages [14]. Microplastics are synthetic materials with a high polymer content; solid particles have a size smaller than 5 mm, are insoluble in water, and are undegradable. It is known that babies and adults who consume plastic packaged food, beverages, and water regularly have high exposure to millions of plastic particles from the packaging itself. Even plastic caps and sealing films of containers and bottles release plastic particles.

As a significant consumer and producer of single-use packaging, the food and beverage (F&B) industry is crucial in steering consumer goods companies toward sustainable solutions. The F&B sector constitutes a substantial portion of global consumer expenditure and is a key component of the fast-moving consumer goods (FMCG) sector. FMCG is distinguished by its high-volume turnover, low per-unit cost, and frequent transactions [15].

In recent years, leading F&B companies have significantly ramped up efforts to reassess their packaging strategies, with many endorsing the circular economy [9], [16]. Major multinational F&B players such as Nestlé, PepsiCo, Mars, The Coca-Cola Company, and Danone have committed to achieving 100% recyclable packaging and combating plastic pollution. Companies like Unilever, Nestlé, and The Coca-Cola Company have also pledged to invest in waste capture strategies to match their production levels [17]. Nonetheless, a lack of comprehensive investigation remains into the F&B sector's initiatives concerning plastic pollution.

2.2 Design of Food Packaging

A market survey indicates that only a few consumers base their purchasing decisions on food packaging. Nevertheless, they prioritize factors such as freshness and convenience, aspects often associated with packaging [18]. Good food packaging designs can offer protection, containment, convenience, and sustainability and provide information to consumers. While food containers made of glass, plastic, metal, and paper all fulfil the criteria for containment, each material possesses distinct properties that dictate its appropriateness for a particular product. For instance, the paper may not be the optimal choice for foods requiring thermal processing in the package or those with high moisture content. Glass offers complete protection from gases, water vapour, and external aromas/odours, yet it lacks shielding from light for light-sensitive products. The labels on packages convey marketing messages and legally mandated information about the product to consumers. Packaging design places significant emphasis on convenience, with criteria like ease of opening, product dispensing, and package resealing driving future innovations [18].

A framework has been developed to assess design options about environmental impact and consumer preferences from the packaging designer's perspective [19]. Based on their case study on potato salad packaging, they can find the 13 relationships between the environmental impact and consumer preferences of packaging functions and the most eco-efficient design option and redesign [20]. It further explains the interchange between ecological aspects and the functionality of packaging design, where the design choices that consumers consider best only sometimes have the highest efficiency. The packaging designs are determined based on food size, shape, and content [21]. A packaging manufacturer should consider several packaging properties before designing good food packaging. The different kinds of packaging show how different these variables are for the food contained in them. For example, pizza has a cardboard box as packaging, and soups have steam-release containers. The food packaging must maintain food integrity and fulfil functional purposes to support optimal delivery. Another requirement is that food packaging be able to secure the food in proper sequence or segregate it as needed for an appropriate amount of time. Other requirements include packaging, which should provide biological protection from outside elements such as oxidation, bacteria, and germs. Then, food packaging must offer convenience features such as reusable and resealable packaging, and storage features such as stack or collapse distribution needs must be considered.

Finally, they should include communication requirements that provide product information such as manufacturer and expiry date. Due to current food packaging mainly being found to cause environmental pollution, they have to consider the sustainability of the ecological design, resource efficiency, end-of-life recovery, use of recyclable materials, and others, which help make the packaging eco-friendlier.

2.3 Importance Safety Regulation

Materials with direct or indirect contact with food must be neutral and safe to ensure they will not affect the consumer's health and, simultaneously, prevent the loss of the food quality. Materials intended to come into contact with food in the European Union must meet the requirements as follows [22]:

1. All food packaging manufacturing must comply with good manufacturing practices (GMP). This ensures that under regular and predictable usage conditions, those materials will not transfer to the food in a quantity that can harm consumers' health. This regulation ensures that the packaging manufacturer must determine the scope of use of materials/packages or carry out a series of stress tests to determine the safe range of use.
2. The chemical composition of packaging materials must be included in the list of materials permitted for use, and detailed information on the manufacturing process must be provided.
3. The packaging materials used during the stages of the manufacturing process do not change their composition but are subject to mechanical or thermo-mechanical forming processes, e.g. bottle preforms and wrap sheets for thermoforming.
4. The final packaging product has a final shape and form and is not intended to come into contact with food.

2.4 Type of Packaging

The food packaging industry has significantly revolutionized in recent years with the advancement of novel food packaging technologies, such as active packaging, aseptic packaging, packaging, bioactive packaging, and edible packaging, which are research trends. Advances in such packaging technology may prevent food spoilage by maintaining the food standard to the highest possible degree, which may help satisfy the needs of consumers throughout the food supply chain and fulfil requirements as per Food Packaging Laws [23].

2.4.1 Bio-Based Packaging

Bio-based polymers, or resins, are derived from renewable sources such as algae, bacteria, microorganisms, plants, and other sustainable resources [24]. This type of packaging materials can be classified into three main groups depending on their origin and production method: extracted from biomass, synthesized from monomers, and produced by microorganisms. Starch is a polysaccharide that can mostly be found in extracted wheat, rice, potatoes, and corn. Polysaccharides are complex bio-macromolecules consisting of repeating mono or disaccharide units linked by glycosidic bonds [24]. It has sufficient oxygen (O2) and carbon dioxide (CO2) barrier properties under low-humidity conditions, which can be an advantage in controlling fruit ripening and preventing fatty food oxidation. However, most polysaccharides have hydrophilic properties and low water vapour barrier properties. To overcome this issue, these polysaccharides are modified by blending them with hydrophobic materials and subjecting them to nano reinforcement to resolve their limitation [25]. Corn starch is used as thermoplastic (TPS) in food packaging applications. It acts as an alternative to conventional plastic polymers. Recent research has been conducted in 18 complete biodegradable "green" composites called bio-composites, in which biodegradable polymers are blended with natural fibres that are also biodegradable. Chitin is the second most abundant polysaccharide material derived from shellfish waste. The other source is fungi cultivation, with 10 to 15% protein content. Through enzymatic or chemical de-acetylation, chitin can be converted to its most well-known derivative, chitosan [26].

2.4.2 Active Packaging

The active packaging technology provides the existing features of food packaging and other innovative features, such as oxygen and ethylene absorbers, gas absorbers or emitters, moisture absorbers and controllers, aroma/odour absorbers, and antimicrobial and antioxidant agent systems. It can be divided into two types of packaging, such as sachet/pad, which will be included inside the food packaging. The second type is that it can be directly input into the packaging material. Active packaging can interact with the environment to increase the shelf life of the food and, at the same time, maintain its quality [27]. It can further react to different types of food or environmental stimulation to monitor or maintain food quality and safety in real time. Hence, it plays an important role in the reduction of food waste. Their research showed that active packaging technologies can be adjusted based on specific foods.

2.4.3 Biodegradable Packaging

One of the many efforts to replace single-use plastic as a sole material for packaging has led to a new generation of plastic materials, also known as bioplastic C.S. It can be either bio-based, biodegradable or even both. One study on biodegradable packaging stated that biodegradable packaging consists of different generations [28].

First Generation

The material comprises synthetic polymers, a combination of low-density polyethene, starch fillers, and pro-oxidizing and auto-oxidative additives. It is mainly used for the production of shopping bags that can be found in grocery stores. It can be decomposed into smaller molecules that are not biodegradable. Hence, it has given a bad reputation to the consumer, which has put their trust in its biodegradability characteristics. Later on, a low-density polyethylene-LDPE was produced via a high-pressure process by free radical polymerization. It has good resistance towards acids, alcohols, esters, and a base, followed by resistance to various aldehydes, ketones, and vegetable oils, and low resistance to halogen hydrocarbons. The product which is produced can be available in transparent and opaque variations. It has flexible and rigid characteristics but is also fragile at the same time.

Second generation

The material comprises pre-gelatinized starch, low-density polyethene (LDPE), and hydrophilic copolymers such as ethylene acrylic acid. The degradation of this second-generation type takes about 40 days, and the other materials will take about two to three years.

Third Generation

Compared to the first and second generations, the third generation of biodegradable plastic materials is entirely biomaterial. It can be further divided into three main categories according to the origin and production methods:

1. Polymers extracted and isolated directly from the biomass
2. Polymers produced by the process of chemical synthesis and bio-monomers
3. Polymers extracted directly from natural or genetically modified organisms

Hence, biodegradable packaging has improved since the 90s and has a bright future in the food industry. Several factors, such as p, policy and legislative changes and world demand for food and energy, will influence biodegradable packaging development [28]. However, the production and demand of packaging can be predicted to increase due to the improved properties of biodegradable packaging and the price reduction compared to other packaging materials.

3.0 METHODOLOGY

Figure 1 shows the screenshot of the OpenLCA software. OpenLCA is a freely available open-source software tool designed specifically for Sustainability and Life Cycle Assessment (LCA) purposes. It enables the evaluation of the environmental impact of products, processes, or systems throughout their life cycle, from raw material extraction to disposal. OpenLCA software includes assessing resource use, energy consumption, emissions, and waste generation. With its open-source nature, it can access and modify the software. Therefore, OpenLCA is chosen because it provides a user-friendly platform for conducting comprehensive sustainability assessments, aiding in informed decision-making for sustainable development.

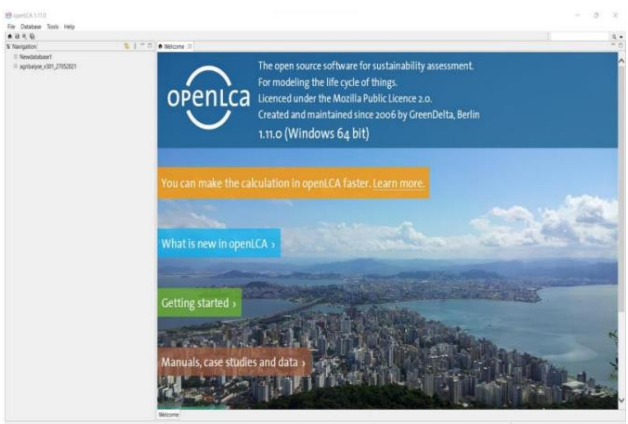


Figure 1 OpenLCA software

To run the software, a reference database containing flows, indicators and parameters, and background data must be downloaded from their website, openLCA Nexus. Various types of databases are offered, which can be downloaded for free or required to be purchased. In this research, the Agribalyse database (https://simapro.com/products/agribalyse-agricultural-database/) was used.

The previous findings have been utilized through the openLCA software. A literature review on the environmental impact of glass and PET bottles is conducted [29], followed by a comprehensive Life Cycle Assessment (LCA) comparing glass, ferrous metal, and plastic beverage bottles to analyze their environmental impacts thoroughly [30]. Additionally, this paper aims to calculate and compare the ecological sustainability of producing one PET bottle versus a PLA or aluminium refillable bottle for drinking water [31].

3.1 Database Elements

The elements database should be identified based on the available case study, literature review, and relevant assumptions, including the parameters, units, and others. Other than that, the processes of each beverage packaging should be defined from the raw material to the end product. Due to limited information on Malaysia's supply chain and logistics, this research only considers the cradle-to-gate scope for each packaging. Then, the processes will be combined under each product system for plastic bottles, glass bottles, and aluminium cans. Figure 2 shows an example of database elements used in this overall research.

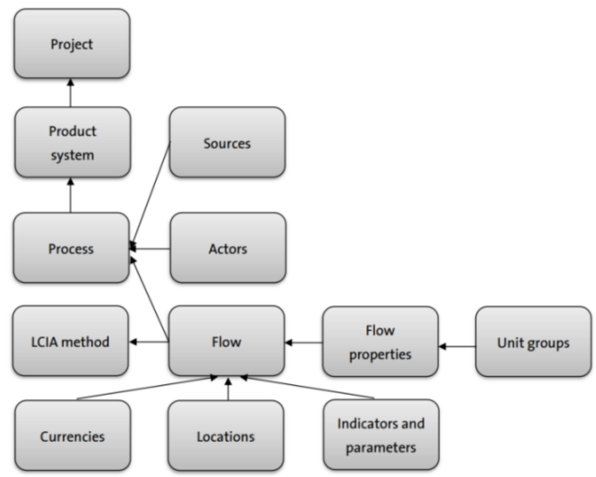


Figure 2 Database elements

3.2 System Boundaries

System boundaries in life cycle assessments (LCA) must be specified in several dimensions: boundaries between the technological system and nature, delimitations of the geographical area and time horizon considered, boundaries between production and production of capital goods and boundaries between the life cycle of the product studied and related life cycles of other products [32]. The product life cycle analysis will become easier if the sequence of operations associated with a product or material is broken down into a primary system and a series of subsystems [33]. Hence, system boundaries for each type of beverage were established to make it easier to understand the input and output of the manufacturing process. Figures 3 and 4 show the material used for each part of the plastic bottle, glass bottle and plastic can.

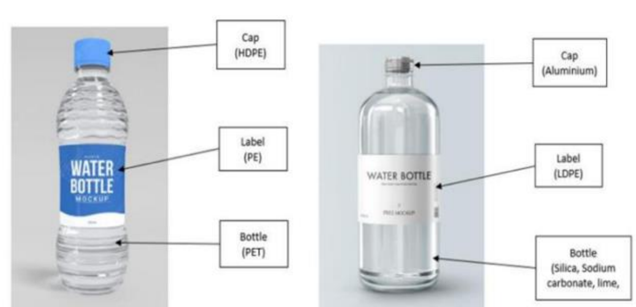


Figure 3 Material used for plastic and glass bottles

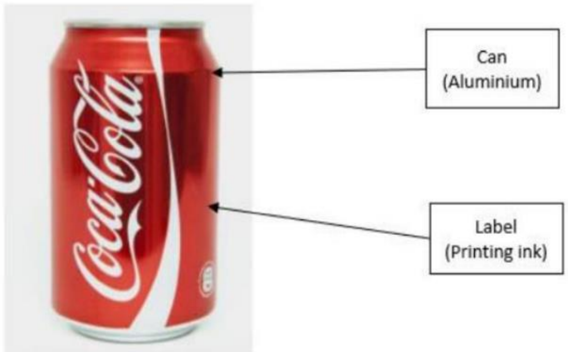


Figure 4 Material used for aluminium can

Figures 5, 6 and 7 show each system boundary covering cradle-to-gate scope. Energy, electricity, raw materials, processes such as moulding, packaging, distribution, and waste are defined based on data obtained from case studies, literature reviews, and necessary assumptions.

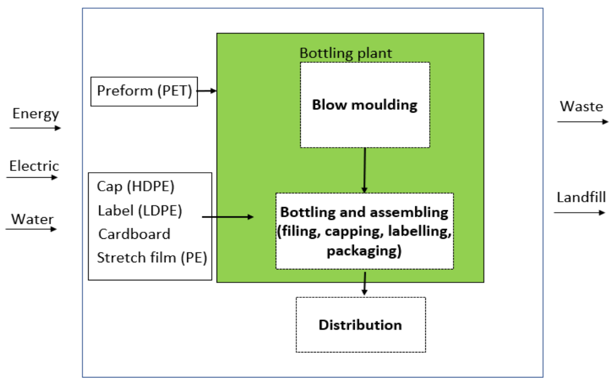


Figure 5 System boundary of plastic bottle

PET will be used at the initial stage, which is the blow moulding process for the packaging body. It forms a hollow object from the preform PET by inflating or blowing a thermoplastic molten tube called a "parison" in the shape of a designated mould cavity. At the same time, caps and labels will be processed during bottling, followed by cardboard and stretch film for packaging purposes before they are distributed.

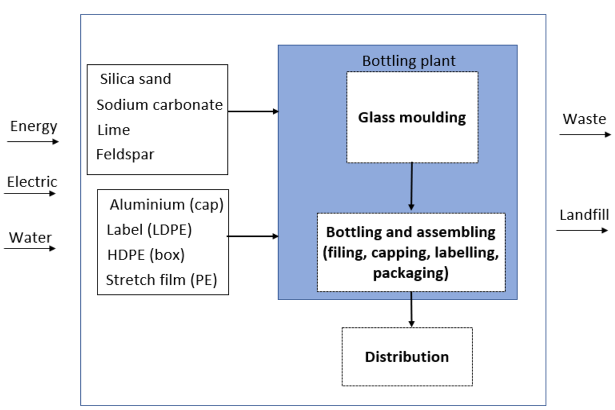


Figure 6 System boundary of glass bottle

Glass moulding is almost similar to blow moulding in the plastic beverage process. It is a non-isothermal process where a piece of glass is introduced to the heated mould in the moulding machine. Then, the aluminium cap and label are procured and used on the next princess. Due to the fragility and weight of the glass bottle, HDPE boxes are used for packaging to secure them from any external forces. The advantage of using HDPE is that the box is returnable to the manufacturers and can be reusable.

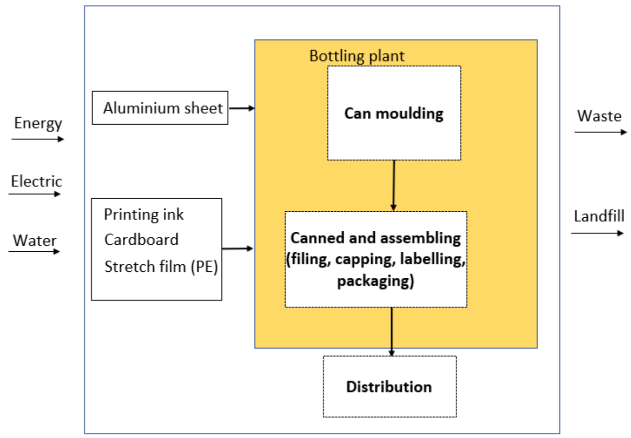


Figure 7 System boundary for aluminium can

The aluminium sheet will undergo the can moulding process to become the desired can shapes. After completion, printing ink will be labelled directly on the aluminium can surface. The aluminium can's final packaging is similar to a plastic bottle's due to its durability against external forces.

3.3 Life Cycle Inventory (LCI)

The LCI for each packaging system was tabulated before being put into open LCA to avoid repeating data and errors. The primary data regarding the production of the system's components were extracted and compiled from reliable sources such as existing databases, literature reviews and scientific reports. Each result was compared to identify which packaging has fewer environmental impacts. Tables 1, 2 & 3 showed the primary inventory data regarding the material and weight of all the components of the packaging systems considered. All the data are expressed in terms of the functional unit of the study. Each beverage packaging is assumed to be a 500ml beverage bottle and can.

Table 1 Weight and materials for plastic bottle

No	Plastic	Weight (kg)
1	Plastic bottle	0.3
2	Polyethylene high density granulate (PE-HD)	0.0017
3	Polyethylene low-density foil (PE-LD)	0.004
4	Polyethylene terephthalate (PET)	0.5
5	Cardboard	0.7

Table 2 Weight and materials for glass bottle

No	Glass	Weight (kg)
1	Glass bottle	0.5
2	Feldspar	0.0702
3	Hydrated lime dry-slaked	0.1252
4	Polyethylene low-density foil (PE-LD)	0.004
5	Sodium carbonate	0.14859
6	Silica sand	0.4305
7	Aluminium	0.02

Table 3 Weight and materials for aluminium can

No	Aluminium	Weight (kg)
1	Aluminium can	0.03952
2	Aluminium sheet	0.004
3	Printing ink	0.00006

Based on the weight of the beverage packaging, glass bottles can be seen as the highest, followed by plastic bottles and aluminium cans. Regarding material usage, glass bottles have the most material, while aluminium cans have the least. By using the openLCA, we can identify whether the weight and material usage of the beverage packaging will have an impact towards the environment.

4.0 RESULTS AND DISCUSSION

4.1 OpenLCA results

The final results from openLCA were obtained and will be discussed further. The three types of packaging will be compared within each CML category in terms of impact. The CML stands for "Centrum voor Milieukunde Leiden". It is a research institute of the Centre for Environmental Studies at Leiden University in the Netherlands. CML is a procedure used to estimate the environmental impact caused by the product [34]. Several CML categories are eutrophication, ionization radiation, aquatic ecotoxicity, land use, and human toxicity.

CML focuses on a series of environmental impact categories expressed in terms of environmental emissions, including classification, characterization, and normalization. The definition for each CML Impact category can be seen in Table 4.

Table 4 CML Impact categories and their descriptions [35].

No	CML Impact Category	Description of Impact Category
1	Acidification Potential-Average Europe	The potential of the product system to cause acidification
2	Climate Change GWP 100	The potential of the product system to impact climate change through global warming potential
3	Depletion of Abiotic Resources elements, ultimate reserves	The loss of resources due to the product system, such as chemical elements and overall reserves of resources
4	Depletion of Abiotic Resources-fossil fuels	The loss of fossil fuel resources due to the product system
5	Eutrophication-generic	The potential of the product system to cause eutrophication in all waters
6	Freshwater Aquatic Ecotoxicity	The potential of the product system to have toxic outputs in freshwater systems
7	Human Toxicity	The potential of the product system to have toxic impacts on human health
8	Ozone Layer Depletion	The potential of the product system to deplete the ozone layer in its current state
9	Photochemical Oxidization	The potential of the product system to generate NO and
10	Terrestrial Ecotoxicity	cause summer smog' due to air pollution
11	Marine Aquatic Ecotoxicity	The product system's potential to have toxic impacts on terrestrial environments

The following chart will show the relative indicator results of the respective types of packaging. For each indicator, the maximum result is set to 100%, and the results of the other variants are displayed as this result. The most effective packaging is those which have the lowest scoring compared to the other two. To compare the results obtained, CML-IA were chosen in the openLCA database. It is a procedure used to estimate the measure of environmental impact caused by the product [36]. It contains life cycle impact assessment (LCIA) characterization factors and can be used in a CMLCA software program like OpenLCA.

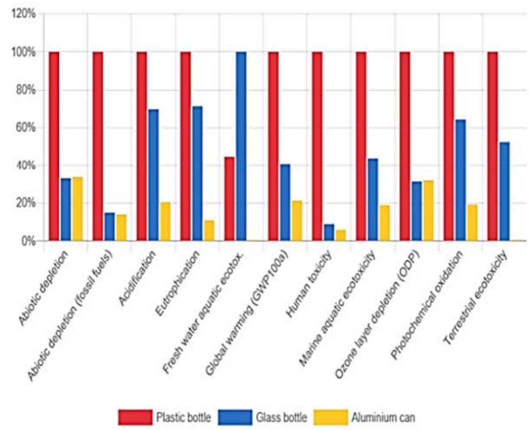
Table 5 shows the research variants' life cycle impact assessment (LCIA) results with the unit defined in the LCIA method. LCIA transforms inventories of environmental flows to environmental impacts in life cycle assessment (LCA) studies [37]. It can provide different characterization factor values and impact units for the same impact category.

Table 5 LCIA results for each beverage packaging and impact categories

No	CML impact category	Beverage type packaging		
		Plastic bottle	Glass bottle	Aluminium can
1	Abiotic depletion	1	3	2
2	Abiotic depletion (fossil fuels)	1	2	3
3	Acidification	1	2	3
4	Eutrophication	1	2	3
5	Freshwater aquatic ecotox.	2	1	3
6	Global warming (GWP 100a)	1	2	3
7	Human toxicity	1	2	3
8	Marine aquatic ecotoxicity	1	2	3
9	Ozone layer depletion (ODP)	1	3	2
10	Photochemical oxidation	1	2	3
11	Terrestrial ecotoxicity	1	2	3

**e: exponent of 10

Figure 8 shows the overall result for each CML impact category in chart form. This results from the input and weight being allocated in the LCA process. Based on the figure, it can be seen that plastic bottles are the most impactful in most of the categories, such as abiotic depletion, abiotic depletion (fossil fuels), acidification, eutrophication, global warming, human toxicity, marine aquatic ecotoxicity, ozone layer depletion, photochemical oxidation and terrestrial ecotoxicity. Hence, it shows the maximum impact, which indicates there are still high costs to using plastic material as beverage packaging. Glass bottle falls on the second most impactful, followed by aluminium cans, with the lowest impact in almost every category. The graph results were mainly due to the material being used, the outputs of each material during processes and parameters defined during the LCI stage, such as weight.



X-axis: CML impact categories
Y-axis: The maximum result is set to 100% and the results of other variants are displayed in relation to this result

Figure 8 Results from the plastic bottle, glass bottle, and aluminium can in the category CML impact methods

Table 6 Ranks for each beverage packing across all eleven CML impact categories: 1 is the highest rank for the most impactful packaging, and 3 is the lowest for the least impactful

Indicator	Plastic bottle	Glass bottle	Aluminium can	Unit
Abiotic depletion	1.89281e-9	6.24404e-10	6.37059e-10	kg Sb eq
Abiotic depletion (fossil fuels)	4.04018e+1	6.01005e+0	5.59248e+0	M.J.
Acidification	1.13446e-2	7.90842e-3	2.30322e-3	kg SO2 eq
Eutrophication	1.42872e-3	1.01944e-3	1.54353e-4	kg PO4--- eq
Freshwater aquatic ecotox.	9.14546e-2	2.04385e-1	7.75880e-4	kg 1,4-DB eq
Global warming (GWP100a)	2.71443e+0	1.10926e+0	5.74878e-1	kg CO2 eq
Human toxicity	8.62065e-1	7.56405e-2	4.96697e-2	kg 1,4-DB eq
Marine aquatic ecotoxicity	4.92923e+2	2.16026e+2	9.27477e+1	kg 1,4-DB eq
Ozone layer depletion (ODP)	9.15078e-8	2.85984e-8	2.91085e-8	kg CFC-11 eq
Photochemical oxidation	6.54302e-4	4.21275e-4	1.24862e-4	kg C2H4 eq
Terrestrial ecotoxicity	5.51263e-2	2.89349e-2	2.29537e-4	kg 1,4-DB eq

Table 6 was constructed to provide a more straightforward review of each CML impact category. Although plastic bottle shows the most impactful in the category. A glass bottle was ranked number 1 in freshwater aquatic ecotoxicity. This may be because the glass bottles have more raw material that needs to be processed, and the waste is generally an organic solvent that flows towards air and water, such as the river. Regarding weight, glass bottles are the heaviest fol, lowed by plastic bottles, and aluminium cans are the lightest but still fall under the second most impactful packaging. This shows that the heaviest weight only sometimes impacts the environment most, while the type of material and its effect during manufacturing should be more focused on. Aluminium can have the least raw material compared to the other two beverage packaging. This means that less energy is required to manufacture, so there are benefits to using plastics as packaging materials. The production of plastic granules such as PET, LDPE, and HDPE, which encompass inputs and outputs of raw mining materials, processing, and manufacturing preparation, may have the most significant impact.

Most plastic bottles on the current market are made of single-use plastic, which,h causes the depletion of resources and uses estimated reserves and fossil fuels. To overcome this issue, all sectors need to play their roles. As a consumer, there are currently more environment-friendly choices, such as installing a water filter at their homes, compared to the daily purchase of filtered bottled water in the market.

Food & beverage sectors like Starbucks have started the initiative by offering 10% off the original beverage price if consumers bring their tumblers when ordering. Other than that, companies such as Subways, Nando's, and other restaurants offer free refills when reusing the same beverage packaging from their first order. Hence, consumers can purchase either two or one beverage before ordering. These are some of the initiatives that can be implemented or have been implemented to help reduce plastic as beverage packaging usage.

Although the cost of manufacturing plastic is preferable by most companies, the long term may cause more effect. Other than that, because plastic is not indefinitely recyclable, raw materials not from renewable sources will always need to be extracted. Plastic has many benefits compared to glass bottles, such as being lighter, more durable and less fragile. However, the long-term effect it will have on the environment, fossil fuels, and health needs to be considered. An average consumption of 131 litres of bottled water equals 16,000 microplastics per year alone with drinking water [38]. Humans may experience oxidative stress, cytotoxicity, neurotoxicity, immune system disruption, and transfer of microplastics to other tissues after exposure [39]. Glass bottles are typically less used nowadays than plastic and aluminium. This may be due to the material processing that causes higher costs to the manufacturers, other than having less durability and more fragile characteristics.

An example is the V-soy drinks, which the manufacturer sold in glass bottles in previous years but has already shifted to plastic bottles. These changes may be affected by reducing manufacturing costs and transportation aspects. Since COVID-19, most consumers have preferred purchasing their goods digitally, such as Grabfood, Shopee, Lazada and other similar platforms, instead of buying them physically. Plastic bottles are more durable than glass and can avoid spillage and spoilage during delivery. Also, glass bottles can only be reused for 20- 40 cycles and must be disposed of afterwards. Hence, the extraction of raw materials is still required, although it is lower than single-use plastic.

Regarding health benefits, glass bottles are safer than plastic as they do not release microplastics. Producing a 16-ounce PET bottle generates more than 100 times the toxic emissions to air and water than making the same bottle out of glass [40]. Among the three types of packaging, aluminium can is found to be the least impactful type of packaging. Even when we walk down the market aisle, most beverage containers are made of aluminium instead of plastic and glass. Aluminium is considered the most sustainable in virtually every measure. It has a higher recycling rate and more recycled content. They are also lightweight, stackable and durable, allowing manufacturers to package and transport them using less material. It is also at the top of the recycling chain because of its infinite recyclability without any degradation in its quality. Compared to plastic bottles and glass bottles, it can save more energy during the recycling process. Since aluminium only requires 5% of the power when compared with the production of native aluminium from bauxite ore. Aluminium may be recycled and reused again and again at a fraction of the initial production costs without losing any of its characteristics or quality.

5.0 LIMITATION

There were several limitations to the study. The data for Malaysia is limited in terms of the LCIA database and literature reviews. Hence, most of the data collected from other countries are assumed to be almost similar to those in Malaysia. Since Malaysia's sources of electricity are natural gas and coal, there is little difference that can be compared in terms of electricity input for the three types of packaging. This is because renewable energy alternatives still need to be widely implemented in Malaysia. The transport and logistics were scoped out of the study due to the complexity and need for more information on the shipment and logistic storage method. Therefore, emissions such as carbon dioxide (CO2), nitrous oxide, and methane (greenhouse gases) that contribute to climate change and health issues cannot be compared.

6.0 CONCLUSION

In conclusion, many new alternative packaging are available in the market and studies by researchers based on the literature review are being conducted. Manufacturers can slowly implement alternative packaging instead of depending solely towards single-use plastics. Secondly, this research successfully compared the different types of beverage packaging by using openLCA software to determine which is less impactful towards the environment than plastic bottles. Aluminium can have less impact, followed by the glass bottle. This is due to the quantity of material being used, the effect of the material during processing, and the recyclable ability.

Along with current global issues of the single-use plastic problem, it showed that plastic bottles provide the most negatively impactful beverage packaging within this scope of the study. It is recommended that the packaging types of paper bottles be considered later in the study. To provide a more comprehensive comparison between the packaging types and propose a better packaging other than aluminium can. Also, Malaysia should increase its recycling incentives, enforce community recycling habits, and encourage a more sustainable lifestyle.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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