EXPLORING ENVIRONMENTAL IMPACTS IN THE BICYCLE HELMET MARKET: A LIFE CYCLE ASSESSMENT APPROACH

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ABSTRACT

The global bicycle helmet market was worth €675 million in 2022 and is projected to reach €857 million by 2031, with a compound annual growth rate of 2.4%. Traditional materials used in the referred market can have a considerable environmental impact, making it imperative for manufacturers to conscientiously evaluate and address their products' sustainability. This study aims to evaluate the environmental impacts of one bicycle helmet composed mainly of expanded polystyrene (EPS) and polycarbonate (PC), using life cycle assessment, based on ISO 14040:44, and to compare two end-of-life scenarios. In the first scenario, only the recycling of paper and cardboard packaging was considered. In the second, the recycling of components composed of EPS and PC was included. The scope of analysis encompassed the entire life cycle from cradle to grave, including raw material transportation, component production, packaging, helmet transportation, distribution and disposal. The analysis was performed using SimaPro 9.5.0.1 software and ReCiPe Midpoint (H) (2016) v1.08 method, incorporating EcoInvent version 3.9.1 as the chosen database. As a result, the packaging stage emerged as the most negatively impactful, which is understandable considering that packaging is often the heaviest component of the product. Conversely, the disposal stage exhibited the most positive impact in both scenarios due to the environmental benefit associated with recycling. Finally, the second scenario was found to have 35.2% less environmental impact than the first, attributed to a greater proportion of recycled components.

Keywords: LCA, bicycle, environmental, impacts, helmet, sustainability, polymers.

1 INTRODUCTION

In recent years, the growing concern for environmental sustainability has driven the demand for more eco-friendly products across various sectors, including the bicycle helmet market. The bicycle helmet market grown significantly in recent decades, driven by the increasing popularity of cycling as a mode of transportation and recreational activity, but also by the growing awareness of cyclist safety [1]. In many cities around the world, initiatives to promote sustainable mobility have encouraged the use of bicycles, resulting in greater demand for safety equipment, including helmets. Additionally, the COVID-19 pandemic has brought a shift in transportation habits, with more people opting for bicycles to avoid public transport [2].

Technological innovations also play a crucial role in the bicycle helmet market. Manufacturers have been investing in research and development to create helmets that are lighter, stronger, and more comfortable, utilising advanced materials such as carbon fibres, Kevlar, and impact-absorbing technologies. Furthermore, the introduction of smart helmets, equipped with features such as Bluetooth connectivity, integrated safety lights, and impact sensors, has attracted cyclists looking for enhanced functionality and safety [3]. Given this increasing use of bicycles as a means of transportation and, consequently, the use of protective equipment, according to Custom Market Insights, the global bicycle helmet market was estimated to be worth USD 700 million in 2021. It is projected to reach USD 777 million

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in 2022 and is expected to reach approximately USD 1.4 billion by 2030, with a compound annual growth rate of around 3% between 2022 and 2030 [4].

Concerning the increasing popularity of cycling as both a mode of transportation and a recreational activity, the demand for bicycle helmets has significantly risen, bringing to light issues regarding the environmental impacts associated with the production, use, and end-of-life of these essential safety devices [5]. Bicycle helmets, predominantly made from plastics, foams, and other synthetic materials, have a lifecycle that involves multiple stages, each contributing differently to the overall environmental impact. From raw material extraction, through production and transportation, to use and final disposal, each phase presents challenges and opportunities to minimise environmental effects. The complexity of these processes necessitates a detailed and systematic approach to evaluate and mitigate environmental impacts [6].

To fully understand the environmental impacts throughout the entire lifecycle of a bicycle helmet, from raw material extraction to the end of its useful life, life cycle assessment (LCA) emerges as an indispensable tool. LCA allows for a detailed and holistic analysis of environmental effects at each stage of a product's life, providing valuable insights for reducing negative impacts and promoting more sustainable practices. According to ISO 14040:2006, LCA offers a methodology that enables the identification and quantification of inputs and outputs, as well as the assessment of associated environmental impacts [7], [8].

This article aims to evaluate the environmental impacts of a bicycle helmet primarily composed of expanded polystyrene (EPS) and polycarbonate (PC), using LCA based on ISO 14040:44 standards, and to compare two end-of-life scenarios. In the first scenario, only the recycling of paper and cardboard packaging was considered. In the second scenario, the recycling of components made of EPS and PC was included. Through this analysis, the study sought to identify critical areas and opportunities for environmental improvements. Therefore, it is crucial to consider all stages of the lifecycle to obtain a comprehensive and accurate view of the environmental impacts [9], [10].

The adoption of practices such as eco-design, which aims to minimise the use of non-renewable resources and reduce the environmental footprint of products by integrating resource efficiency principles into their design, promotes a more sustainable lifecycle [11].

The implementation of such practices can mitigate environmental impacts while also fostering innovations, aligning with the expectations of increasingly conscious and demanding consumers.

2 METHODOLOGY

The LCA methodology assesses the environmental impact of a product or service by quantifying potential burdens across its entire life cycle. While LCA studies were conducted as early as the 1960s, it was not until 1990 that SETAC initiated the standardisation process leading to the widely recognised ISO 14040:44 series. According to these series, an LCA involves four key steps, as shown in Fig. 1. The initial stage entails defining the study's goals and scope but also involves specifying the functional unit and selecting system boundaries. During the second step, a comprehensive life cycle inventory is constructed, meticulously identifying and quantifying inputs and outputs at each stage of the life cycle. Moving to the third step, supported by a software, the impact assessment phase involves categorising these inputs and outputs into various impact categories is calculated. Finally, in the interpretation phase, it is essential to analyse and interpret the LCA results.

In this study SimaPro 9.5.0.1 software [12] and the ReCiPe Midpoint (H) (2016) v1.08, method was used to carry out the LCA study. The Hierarchist perspective used is a

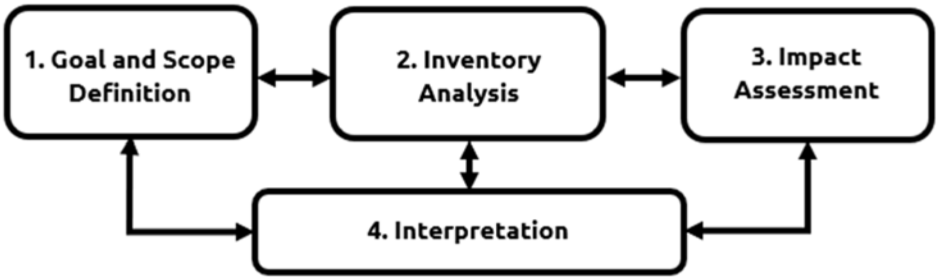

Figure 1: LCA methodology.

consensus-based model commonly found in scientific research, often regarded as the default approach [13]. The data considered was mostly secondary data from the EcoInvent database, version 3.9.1.

3 RESULTS

Firstly, following the LCA methodology, the objective was defined as the calculation of the environmental impacts of the helmet and the respective comparison between two scenarios. In Scenario 1, recycling of cardboard and paper packaging was considered. In Scenario 2 besides the packaging recycling, the recycling of components made of EPS (internal foam) and PC (thermoforming and padding) was also included. Regarding the scope, the functional unit chosen was the production and disposal of one helmet, considering a cradle-to-grave approach. The flowchart is presented in Fig. 2. Table 1 lists all the components of the helmet along with their respective masses.

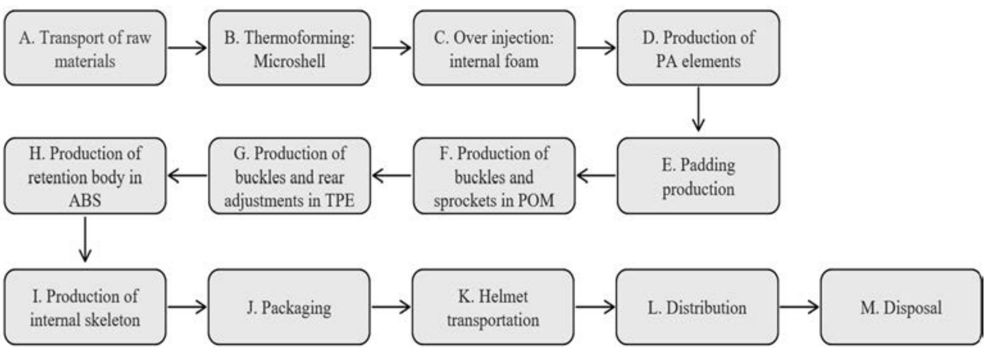

Figure 2: Flowchart.

The transport of raw materials stage considers the transportation by truck to the site where the helmet components will be produced, in China. Within this production process (which spans from stage B to I), two key processes stand out: thermoforming and over injection.

Thermoforming is the process by which a plastic sheet is moulded using heat and vacuum, employing an aluminium, wood, or resin mould. In essence, the plastic sheet takes the shape of the mould under high pressure and temperature. Over injection, on the other hand, can be performed in one or two steps and is designed to combine different components over natural fibres, thereby avoiding the need for individual welding assembly.

Table 1: Helmet components.

Components	Mass (g)
Internal foam	136.0
Microshell	50.0
PA components	42.4
Buckles and sprockets in POM	5.4
Padding	20.0
Buckles and rear adjustments in TPE	3.5
Rear adjustment – retention body	8.9
Internal skeleton	18
Cardboard boxes	490

Subsequently, the packaging stage involves the packaging of the helmet into cardboard boxes. Following this, the helmet transportation and distribution stages represent the transport from China (the production site) to the vendor located in Portugal, and then from the vendor to the final customer and resellers, respectively. Transporting goods from China to Portugal involves both truck transport (183 km) and sea transport (18,627 km). Distribution within Portugal consists of an average distance between the producer and the final customer, which is typically covered by truck (an average of 150 km). Finally, the disposal stage reflects the end of life of the helmet and its subsequent disposal. Furthermore, the electricity used in the production of the helmet was representative of China, and the data considered were mainly secondary, sourced from the EcoInvent database (version 3.9.1, 2022).

As previously mentioned, SimaPro software (version 9.6.0.1) and the ReCiPe Midpoint, Hierarchist perspective (2016 V1.1) impact assessment method was used. This method encompasses 18 environmental impact categories, as described in Table 2. It is also possible to observe the non-normalised results for each impact category for Scenarios 1 and 2 in this table.

As previously stated, the ReCiPe Midpoint impact assessment method presents a total of 18 impact categories. However, some categories exhibit a much higher contribution than others. In order to better understand which impact categories were responsible for the majority of impacts, a normalisation followed by the Pareto principle was applied. The normalisation allowed one to sum all impacts and calculate the contribution of each impact category in the total environmental impacts. After the normalisation, the Pareto principle was applied, which states that approximately 80% of the effects come from 20% of the causes. Thus, only the categories that accounted for 80% of the total impacts of both scenarios were considered, as demonstrated in Fig. 3 and Table 3. Subsequently, only the categories presented in the aforementioned table were considered for this study. Following this, the interpretation of the environmental impact assessment was carried out for each of the scenarios.

3.1 Study Scenario 1

In Scenario 1, for end of life, only the recycling of cardboard and paper packaging was considered, along with the environmental impact categories presented in Table 3. The results obtained are shown in Fig. 4. After interpreting the results, it is evident that the packaging (J)

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Table 2: Impact categories.

Category	Unit	Scenario1	Scenario2	Description
Global warming (GW)	kg CO_2 eq.	2.87E+00	2.06E+00	Climate change is characterised by the potential for global warming, based on the IPCC 2013 report. For the Hierarchist perspective, a time horizon of 100 years was used. Climate–carbon retroacts are included for non-CO_2 greenhouse gases in the Hierarchist perspective.
Stratospheric ozone depletion	kg CFC-11 eq.	1.29E-06	1.24E-06	The ozone depletion potential (ODP) measures the impact of a substance on the stratospheric ozone layer relative to CFC-11. It is calculated by comparing the substance's ODP to that of CFC-11 and multiplying by the amount of the substance's atmospheric emissions.
Ionising radiation	kBq Co-60 eq.	8.85E-03	7.68E-03	The release of radioactive material into the environment can result in health effects, which vary based on the extent of exposure.
Ozone formation, Human health	kg NOx eq.	7.53E-03	6.19E-03	Determined by the change in the ozone intake rate, due to a relative change in precursor emissions (NOx and NMVOC).
Ozone formation, Terrestrial ecosystem		7.90E-03	6.45E-03	
Fine particulate matter formation	kg PM2.5 eq.	3.83E-03	3.18E-03	The potential for particulate matter formation takes into account the intake by the human population of PM2.5.
Terrestrial acidification	kg SO_2 eq.	7.28E-03	5.46E-03	The acidification potential describes the fate and deposition of acidifying substances. These substances have impacts on soil, groundwater, organisms, ecosystems, and materials. It is primarily caused by the emissions of NOx, SO_2, and NH_3.
Freshwater eutrophication	kg P eq.	5.27E-05	9.67E-06	Eutrophication refers to the impact of excessive macronutrients, like nitrogen and phosphorus, in surface water due to nutrient emissions to the air, water, and soil, leading to rapid aquatic plant growth.
Marine eutrophication	kg N eq.	1.93E-04	1.76E-04	

Table 2: Continued.

Category	**Unit**	**Scenario1**	**Scenario2**	**Description**
Fossil resource scarcity	kg oil eq.	1.03E+00	6.47E-01	Depletion of resources containing hydrocarbons, including both volatile substances (like methane and gasoline) and non-volatile materials (such as anthracite coal).
Terrestrial ecotoxicity	kg 1.4-DCB	1.82E+01	7.78E+00	Human toxicity and ecotoxicity take into account the persistence in the environment (fate) and accumulation in the human food chain (exposure), as well as the toxicity (effect) of a chemical substance. Human toxicological effect factors have been separated into carcinogenic and non-carcinogenic effects, reflecting changes in disease incidence over a lifetime due to a change in substance intake.
Freshwater ecotoxicity		2.92E-03	1.98E-03	
Marine ecotoxicity		1.68E-02	6.79E-03	
Human carcinogenic toxicity		4.07E-03	2.94E-03	
Human non-carcinogenic toxicity		−1.36E-01	−1.56E-01	
Land use	m^2a crop eq.	9.87E-02	9.75E-02	Amount of land transformed or occupied over a specific period. It refers to the relative loss of species caused by a specific type of land use (annual crops, permanent crops, mosaic agriculture, forestry, urban areas, and pastures).
Mineral resource scarcity	kg Cu eq.	2.45E-03	2.33E-03	Characterised by the potential of fossil fuel, based on the higher heating value. It is defined as the ratio between the higher heating value of a fossil resource and the energy content of crude oil.
Water consumption	m^3	2.69E-02	1.92E-02	Quantity of water used.

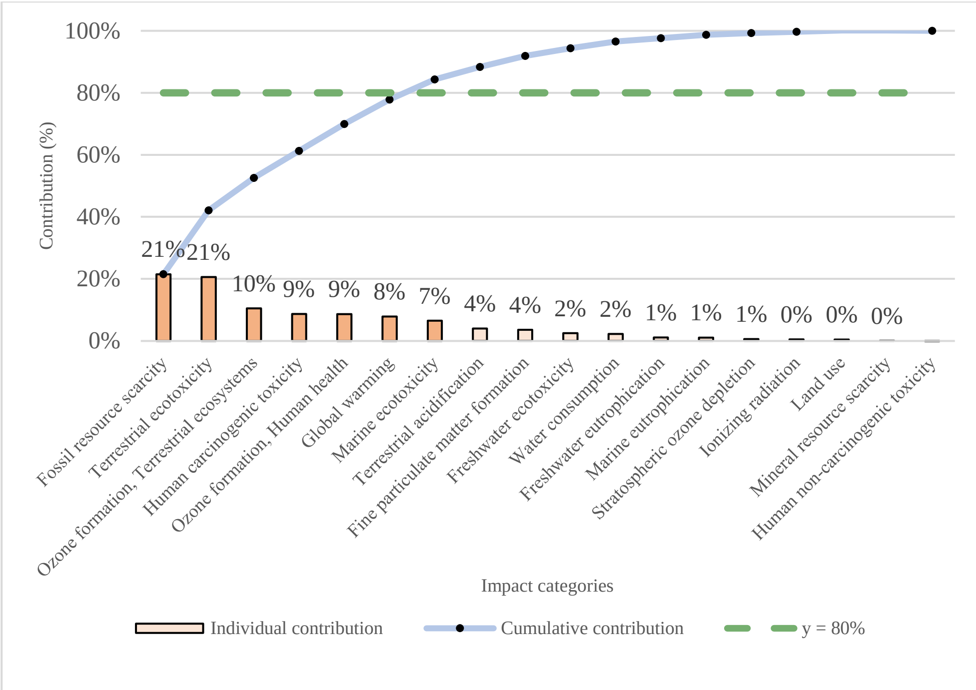

Figure 3: Application of Pareto's principle.

Table 3: Impact categories considered in the study and their contribution to the total impacts.

Category	Value (%)	Cumulative (%)
Fossil resource scarcity	21	21
Terrestrial ecotoxicity	21	42
Ozone formation, Terrestrial ecosystems	10	53
Human carcinogenic toxicity	9	61
Ozone formation, Human health	9	70
Global warming	8	78
Marine ecotoxicity	7	84

and thermoforming microshell (B) stages have the highest environmental impacts, primarily due to the production of the cardboard box and polycarbonate, respectively. Conversely, the disposal stage contributes most positively, having a negative impact, meaning it is beneficial for the environment. This positive effect is a result of the recycling of paper and cardboard packaging, which represents a significant portion of the product's mass (63%).

It is important to note that the impact values presented consider all the selected impact categories. Thus, the error value arises from the different contributions to each impact category from each lifecycle stage. The detailed results of each stage in each category are shown in Fig. 5.

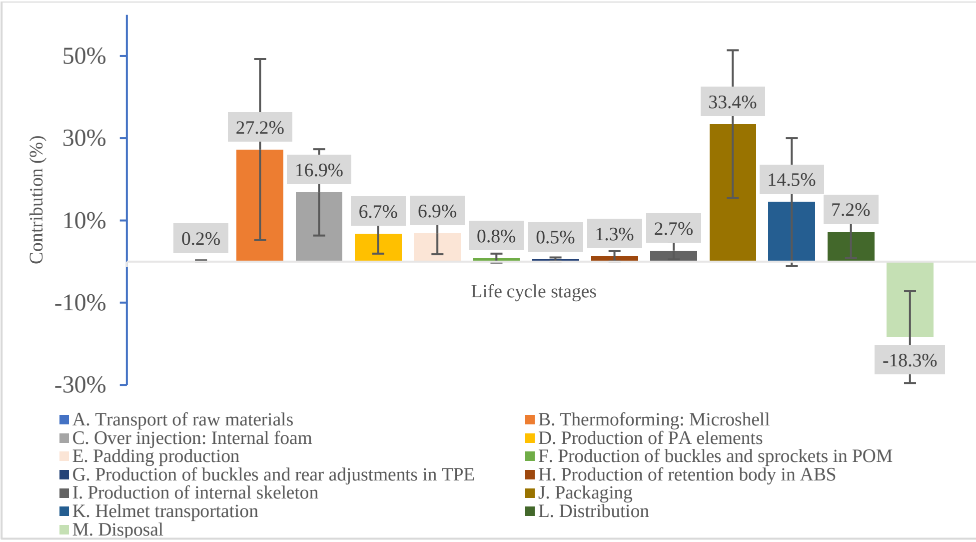

Figure 4: Average contribution of each life cycle stage for Scenario 1.

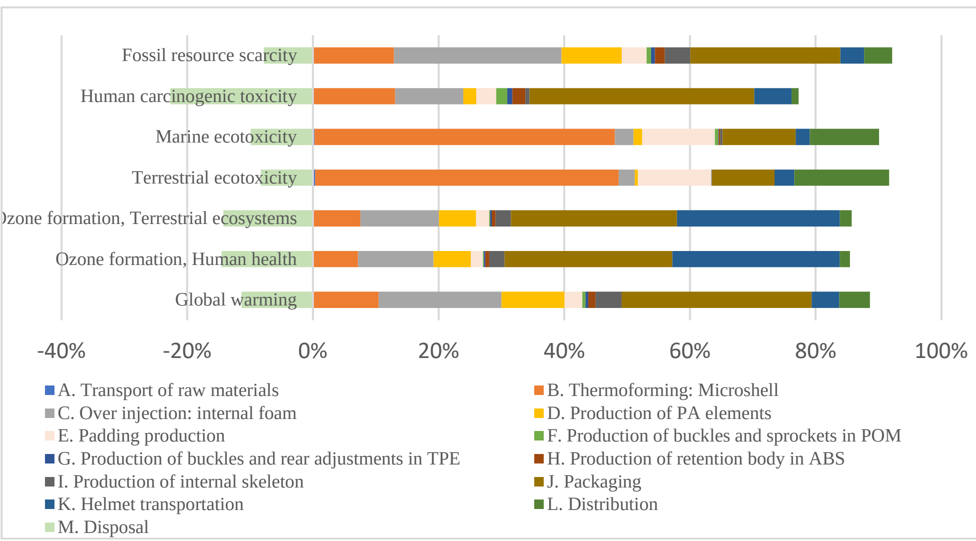

Figure 5: Detailed results for each stage in each category for Scenario 1.

As can be observed, the packaging stage contributes most negatively in the impact categories of global warming, ozone formation (human health and terrestrial ecosystems), and human carcinogenic effects, which is mainly due to the production of the cardboard box. The thermoforming microshell stage and the over injection has the highest impacts in the categories of ecotoxicity (marine and terrestrial) and fossil resource scarcity, respectively. This impact is primarily caused by the production of PC and EPS, respectively.

3.2 Study Scenario 2

In Scenario 2, the recycling of components made of EPS (internal foam) and PC (thermoforming and padding) in the final stage of the product's lifecycle was included. The results obtained are shown in Figs 6 and 7.

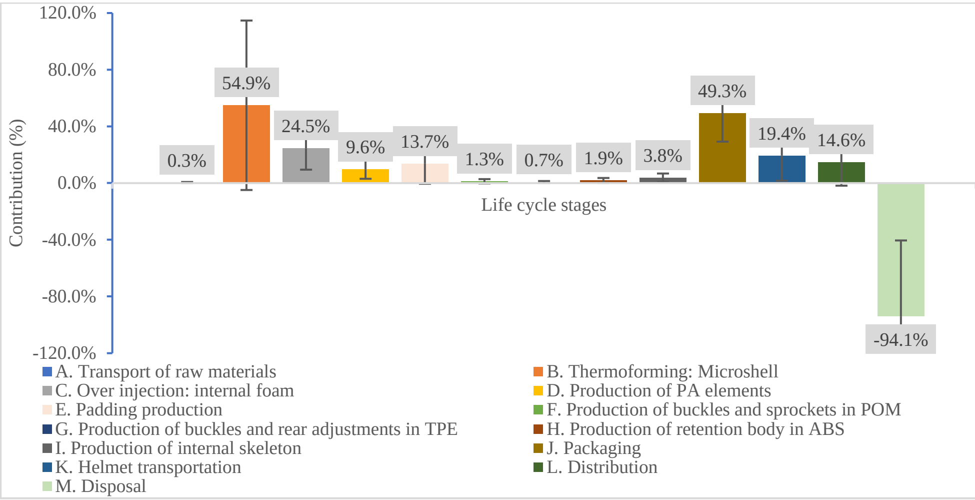

Figure 6: Average contribution of each life cycle stage for Scenario 2.

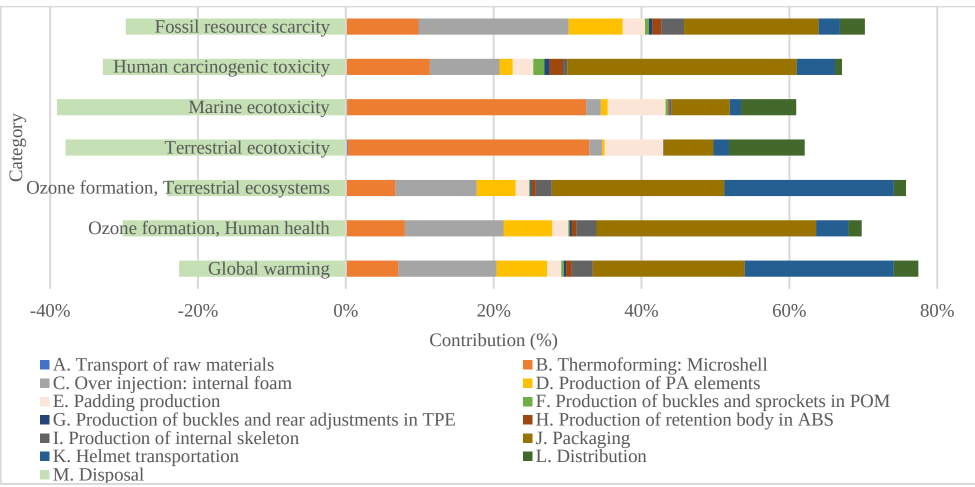

Figure 7: Detailed results for each stage in each category for Scenario 2.

As expected, the results obtained are generally similar to those of Scenario 1. The lifecycle phases with the highest impact contributions are thermoforming microshell and packaging, with an average contribution of 54.9% e 49.3%, respectively. This increased contribution is due to the increased negative impact, meaning a positive contribution, of the disposal stage. This increase is justified by the inclusion of the recycling of components made of EPS (internal foam) and PC (microshell and padding).

Interpreting it can be concluded that the packaging stage continues to contribute the most to the environmental impact categories of global warming, ozone formation (human health and terrestrial ecosystems), and human carcinogenic effects. The thermoforming microshell and over injection for internal foam stages still present the highest impacts in the categories of ecotoxicity (marine and terrestrial) and fossil resource scarcity, respectively, as previously observed.

Finally, Scenario 1 was compared with Scenario 2. The results obtained are presented in Table 4.

Table 4: Comparison between Scenarios 1 and 2.

Impact category	**Normalised results (dimensionless*)**	**Scenario 1**	**Scenario 2**	**Reduction (%)**
Global warming		3.59E-04	2.57E-04	28.2
Ozone formation (human health)		3.66E-04	3.01E-04	17.8
Ozone formation (terrestrial ecosystems)		4.45E-04	3.63E-04	18.4
Terrestrial ecotoxicity		1.20E-03	5.12E-04	57.2
Marine ecotoxicity		3.87E-04	1.56E-04	59.7
Human carcinogenic toxicity		3.95E-04	2.86E-04	27.7
Fossil resource scarcity		1.05E-03	6.60E-04	37.1
Average				35.2
Total		4.20E-03	2.53E-03	

* Normalised data to be comparable.

As observed, recycling components made of EPS and PC reduces the total impacts associated with the production and disposal of the helmet by 35.2%. The impact categories showing the greatest reduction are those where the PC and EPS components had the highest impacts, namely: ecotoxicity (terrestrial and marine) and fossil resource scarcity, respectively. Thus, recycling these materials contributes positively to the reduction of total impacts.

Through the literature review, the most common studies performed on helmets focus primarily on human ergonomics and safety aspects, mainly because the parameters for these aspects are already standardised [14], [15]. Only a few examples address environmental impact analysis to helmets were found in the literature [16]–[18], and the impact category analysed is commonly limited to GW [17], [18].

In the South Pole study [17], the author compares two different helmets, U101 (517 g), made using ABS, polyamide (PA), EPS, PC, produced in China, and U103 (495 g) with made by recycled PA, recycled PC and recycled EPS, produced in Portugal, both produced in the injection moulding processing. The study was conducted by considering the entire workflow, from raw material acquisition and manufacturing to packaging, distribution, and end-of-life. Although the authors used a different methodology than the one presented here (in this study the author evaluated 19 impacts categories and the software utilised was GaBi v10.7), it was possible to compare the values obtained for the GW category. The study results, referred to as Scenarios 3 and 4, are presented in Table 5, where a comparison with Scenarios 1 and 2 is also made. It is important to note that the authors chose not to normalise the data, and therefore, the results are presented in kg CO_2 eq.

Table 5: Comparison between obtained results and literature.

Impact category	**Units**	**Scenario 1**	**Scenario 2**	**Scenario 3 [17]**	**Scenario 4 [17]**
Global warming	kg CO_2 eq.	2.87	2.06	9.86	5.36

Results obtained for Scenarios 1 and 2 show a lower impact when compared to 3 and 4, with a reduction of 71% and 46%, respectively, for Scenario 1, and 79% and 62% for Scenario 2. This is mainly due to the choice of materials, which makes the helmet heavier – 513 g and 496 g for Scenarios 3 and 4, respectively – representing a total mass approximately twice that of Scenarios 1 and 2 (284 g). Additionally, the waste management chosen is predominantly landfill and incineration, which has a significantly higher impact compared to recycling.

Serra et al. [18] studied a traditional helmet made of PC, ABS, and EPS. Although the authors did not specify the helmet mass and the methodology used for the environmental impact analysis, they reported that the total emissions were 1.30 kg CO_2 eq. The results found by Serra et al. cannot be directly compared to the GW emissions found in this study due to differences in the boundary limits used in each study. But, as expected, the emissions reported by Serra et al. are lower because the authors did not consider the production process, which means that energy consumption was not accounted for.

4 CONCLUSIONS

Increasing environmental sustainability concerns have driven demand for eco-friendly bicycle helmets, however, few studies were found in the literature. In this study, the LCA methodology was applied to understand the environmental impacts linked to the production of a bicycle helmet. The results showed that the majority of impacts are connected to the production of the microshell by thermoforming, as well as to the packaging stage. The use of PC for the microshell production and the card boxes in the packaging phase are the main contributors to the overall helmet impacts. Improvement measures such as change of materials or reduction of packaging mass should be considered. Additionally, two end-of-life scenarios were compared. Scenario 2 showed a possibility of reducing the impacts by 35.2% once the recycling of the packaging is considered, also considered in Scenario 1, plus the internal foam, microshell and padding components. The results clearly demonstrated the significant impact of including the recycling stage on the overall environmental impacts. To conclude, LCA methodology helps identify critical areas where environmental impacts can be improved for products and processes and it should be integrated into the design and development of new products.

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