Duzce University Journal of Science and Technology
Düzce Üniversitesi Bilim ve Teknoloji Dergisi
14 (1), 2026, 177-188.
https://doi.org/10.29130/dubited.1770053
e-ISSN: 2148-2446
https://dergipark.org.tr/en/pub/dubited

Research Article

Environmental Impact Assessment for Packaging Materials

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Received: 22.08.2025
Revision: 01.12.2025
Accepted: 09.12.2025
Available Online: 21.01.2026

Abstract: This paper presents the eco-friendly design efforts carried out at the Daikin Türkiye R&D Center, addressing innovative approaches aimed at reducing carbon emissions and supporting sustainable production. In this context, the environmental impacts of different materials were examined in detail to reduce environmental effects in product development processes and to ensure compliance with sustainability criteria. Within this framework, the 13 sustainable product criteria published by Daikin Japan (DIL), which serve as a guide in sustainable product development processes, were reviewed, and one of these criteria was selected for in-depth analysis. An application example developed in line with the selected criterion is also presented as one of the focal points of this paper.

In the application example, the environmental impacts of different types of packaging materials used in boiler products were evaluated. Environmental impact calculations were supported with technical information in accordance with the Product Category Rules (PCR) and packaging-related regulations. This study aimed to determine the most suitable alternatives in terms of sustainability by comprehensively examining the environmental impacts of four different packaging materials (EPS, 100% recycled cardboard, cardboard honeycomb panel, and molded pulp). The consistency of the obtained data with the literature was also examined in detail.

As a result of the study, the packaging material with the optimum environmental impact value was identified in light of the determined design parameters. It is projected that this packaging material will prevent 62% more emission release compared to equivalent products.

Keywords: *Sustainable product, Environmental impact assessment, Packaging material*

I. INTRODUCTION

In today's world, climate change and environmental degradation pose serious threats to human health and ecosystems. One of the main sources of these problems is carbon emissions arising from industrial production processes and consumption habits. In particular, poor choices regarding energy consumption and waste management further exacerbate environmental impacts. In this context, adopting environmentally conscious approaches in the design and production of industrial products is of great importance in contributing to a sustainable future. Scientific studies reveal that companies prioritize environmental sustainability both in their internal processes and in their collaborations with suppliers, and they develop strategies in this direction. These efforts constitute concrete steps toward achieving sustainability goals and play a significant role in reducing the environmental impacts of industrial production.

In this regard, the literature shows various approaches addressing environmentally friendly designs and strategies to reduce carbon emissions. Absorption cooling systems stand out as a noteworthy alternative. Absorption cooling systems have the potential to reduce environmental loads by using refrigerants with zero global warming potential (Gebreslassiea et al., 2009). However, their use in the market has remained limited. Studies show that life cycle assessment (LCA) and mathematical programming techniques can be effective in optimizing eco-friendly designs (Kaya & Karaosmanoğlu, 2023).

Similarly, research on the environmental impacts of production processes for innovative cooling devices has shown that factors such as wind power and waste management can significantly reduce environmental impacts. For example, the use of wind power and effective waste management have been identified as effective strategies for reducing carbon and water footprints in production processes (Kaya & Karaosmanoğlu, 2023). In addition, flue gas waste heat recovery systems improve boiler efficiency by increasing return water temperature and reduce environmental impacts. The use of aqueous potassium formate solution has been shown to provide more effective heat recovery compared to conventional systems (Liao et al., 2022).

The use of hydrogen fuel is also important for energy efficiency and environmental sustainability. Mathematical modeling and simulations have shown that hydrogen fuel is economically viable and environmentally advantageous compared to other fuels (Varlamov et al., 2024). On the other hand, analyses of the performance of natural refrigerants indicate that CO_2 offers lower environmental impacts than other refrigerants such as R410A and R32, although it has some disadvantages in terms of energy efficiency and cost (Aljolani et al., 2024).

Cite as: Ceylan, A., & Pehlivan, H. (2026). Environmental impact assessment for packaging materials. *Duzce University Journal of Science and Technology, 14*(1), 177-188.
https://doi.org/10.29130/dubited.1770053

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Research on green marketing and eco-friendly products examines the factors influencing consumers' intention to purchase environmentally friendly products. Environmental concern, perceived price, quality, and risks have been identified as significant factors affecting consumer behavior (Arslan, 2023; Duru, 2013). In addition, recycling methods have been compared in terms of environmental impacts, with pyrolytic-biometallurgical methods found to have high environmental impacts. It has been suggested that the development of these methods could enable industrial symbiosis (Duman, 2019).

The design and production of eco-friendly products aim to contribute to sustainable development by minimizing energy and water consumption. Modern designs offer strategies to reduce environmental impacts (Warmhaus, 2024). In this regard, reducing environmental impacts, increasing energy efficiency, and adopting sustainable design approaches in various industrial applications are of great importance.

A review of current studies shows that various research has been conducted on the environmental impacts of PE (polyethylene)-based packaging compared to alternative materials such as paper, glass, aluminum, and steel. Key environmental indicators such as global warming potential (GWP), water scarcity, fossil energy use, and mineral resource use are considered as primary evaluation criteria. A study by Franklin Associates (Franklin Associates, 2014) found that PE-based flexible packaging has 73–79% lower GWP than paper-based alternatives. Similarly, a study by Meneses et al. (Meneses et al., 2012) showed that glass-based packaging has higher GWP than plastic- and cardboard-based alternatives.

In a study comparing PE-based shrink and stretch films with paper-based alternatives, it was found that PE shrink film has 71% lower GWP than corrugated cardboard boxes, and PE pallet wrap film has 70% lower GWP than kraft paper. However, evaluations of PE-based bags indicate that multilayer paper-based alternatives can have similar or lower GWP than PE-based packaging in certain cases.

For non-food liquid products, PE-based bottles have been shown to have lower environmental impacts than glass and metal alternatives. A study by Dhaliwal et al. (Dhaliwal et al., 2014) reported that PP (polypropylene) bottles have 46% lower GWP than glass bottles. PE-based bottles were found to have 41% lower GWP than glass, 85% lower than aluminum, 58% lower than steel cans, and 72% lower than steel bottles.

Packaging studies for food products show similar trends. PE-based flexible food pouches have lower environmental impacts than glass- and metal-based packaging. However, in some cases, lightweight multi-material paper pouches have lower GWP than PE-based pouches. For example, PE-based spice pouches have 15% higher GWP compared to multi-material paper pouches, but 87–89% lower GWP compared to glass jars and metal cans.

These studies indicate that packaging materials exhibit different environmental impacts throughout their life cycle and that factors such as material production, recycling rates, and transportation effects should be considered when evaluating alternatives. In particular, it is noted that material production contributes the most to GWP for glass and metal packaging, while in steel packaging, impacts vary depending on production process formats (Avery et al., 2025).

To broaden the scope of product diversity in the literature, this section also includes a study examining packaging systems used in the distribution of seafood. A study in Spain evaluated the environmental impacts of reusable plastic crates (RPCs) and single-use EPS boxes in short seafood supply chains. Life cycle analysis results showed that the highest environmental impact occurs in the transportation stage, particularly in road transport. Although packaging types generally exhibit similar environmental performance, the location of the washing process can influence this balance. When washing is done at the factory, EPS boxes are more advantageous, whereas washing at ports makes RPCs a more eco-friendly option for local transport. The use of recycled polymers was also highlighted as a way to reduce environmental impacts. This study contributes to the literature on evaluating sustainable packaging choices (Chen et al., 20245).

Unlike these studies, our research provides a detailed examination of the environmental impacts of different types of packaging materials used in boiler products and conducts an in-depth analysis based on one of Daikin Japan's 13 sustainable product criteria (Daikin, 2023, September 15)—packaging. As Daikin Türkiye R&D Center, we conduct studies aimed at developing sustainable product designs that target reducing carbon emissions, in line with our awareness of environmental responsibility. This article has been prepared to detail the steps we have taken and the findings we have obtained in this direction. In our study, environmental impact assessments supported by technical information were conducted in accordance with Product Category Rules (PCR) (EPD International, 2019), and tests and analyses were carried out on these materials in compliance with relevant standards. Furthermore, using the obtained data, the potential annual CO_2 emission reduction was determined, and the optimum material was selected in terms of sustainability.

A. Life Cycle Assessment

Life Cycle Assessment (LCA) is a method that systematically evaluates the environmental impacts of a product, process, or service throughout its life cycle (Laveglia et al., 2024; Matthews et al., 2014). LCA considers all life stages of a product or service, covering everything from raw material extraction to production, distribution, use, and final disposal (Duman, 2019). This evaluation helps in making decisions aimed at reducing environmental impacts and in developing more sustainable production and consumption models. LCA is used to understand the environmental footprint of a product or service and to identify opportunities for improvement.

LCA is generally carried out in four main stages, as shown in Figure 1:

1. Goal and Scope Definition

   This stage defines the objectives and boundaries of the LCA study. It specifies why the assessment is being conducted, which products or processes are being examined, and the scope of the study. This stage is critical for structuring the evaluation process correctly.

2. Inventory Analysis

   Inventory analysis creates a detailed inventory of all inputs (energy, water, materials) and outputs (waste, emissions) throughout the life cycle. At this stage, all data related to the product or process are collected, and all inputs and outputs are quantified.

3. Impact Assessment

   This stage evaluates the data obtained in the inventory analysis according to environmental impact categories. Examples include global warming potential, ozone depletion, acidification, and freshwater ecotoxicity. Potential environmental impacts are calculated for each impact category using specific indicators and factors.

4. Interpretation

   In the interpretation stage, the obtained results are analyzed and evaluated. The aim is to determine how the results can be used in decision-making processes and to identify opportunities for improvement. The accuracy and reliability of the findings are assessed, uncertainties in the results are analyzed, and the integration of the information obtained into environmental decision-making processes is ensured (Kaya & Karaosmanoğlu, 2023).

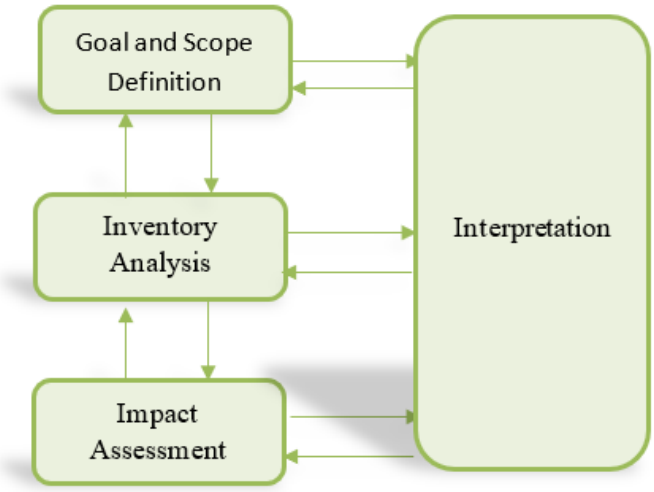


Figure 1. LCA processes (ISO, 2006a)

LCA is a comprehensive method used to analyze the environmental impacts of a product, and accurately defining the boundaries of the assessment is of great importance. When defining the scope of an LCA, three different boundary-setting approaches are generally used:

1. Cradle-to-gate
2. Cradle-to-grave
3. Cradle-to-cradle

The cradle-to-gate approach considers only the part of a product's life cycle from raw material extraction to the manufacturing facility, and is therefore regarded as the narrowest-scope method. In contrast, the cradle-to-grave approach covers the entire life cycle of the product — from raw material extraction, through manufacturing and use, to final disposal — thus enabling the evaluation of environmental impacts from a broader perspective. The most comprehensive method, cradle-to-cradle, not only covers the product's life cycle but also includes the reintegration of discarded products into the production process through recycling or reuse. This approach embraces the principles of waste minimization and efficient use of resources, aiming to meet sustainability goals (Chen et al., 2021; EPD International, 2024a; Sandaruwan et al., 2024).

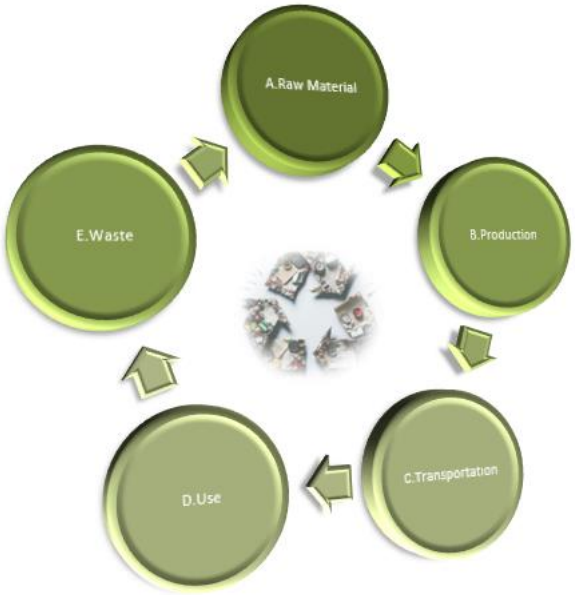


Figure 2. LCA boundaries
A→ B : cradle to gate, A→ E : cradle to grave, A→ A; cradle to cradle

When conducting a life cycle assessment, the choice of method depends not only on the functions of the product but also on the Product Category Rules (PCR) documents published for that product, which can provide guidance in defining system boundaries. Therefore, the appropriate boundary-setting approach should be carefully selected based on the information sought and the purpose of the assessment.

B. Product Category Rules (PCR)

PCR is a document that defines the rules and methodology to be followed when conducting a life cycle assessment for the purpose of preparing an environmental declaration (EPD, PEP) for a specific product category. PCRs provide a standardized framework to make the environmental performance of products comparable.

PCR documents include the following elements:

- Functional Unit Definition: A standardized measurement unit used to assess the product's performance. This is essential for accurately and fairly comparing the environmental impacts of products.
- System Boundaries: Determines which stages of the LCA will be covered (e.g., only production and distribution, or the entire life cycle).
- Data Quality Requirements: Provides guidelines on the type and quality of data to be used in the LCA.
- Impact Categories: Defines the categories in which the environmental impacts of products will be evaluated (e.g., global warming potential, ozone depletion, water consumption).

PCR plays a critical role in preparing environmental declarations because it ensures consistency in the methodology used to assess a product's environmental performance. This consistency enables meaningful comparisons between different products (ISO, 2006b).

The methodology and data quality used in conducting an LCA are crucial for the accuracy and comparability of the results. This is where PCRs come into play, as they specify how the LCA should be conducted for a specific product category. This means:

- Standardization and Comparability: PCR ensures that LCAs for products within the same category are conducted using a standardized method, making it possible to compare the environmental performance of different

products. For example, LCA results prepared in accordance with the same PCR can be used to compare the environmental impacts of cement production processes from two different manufacturers.

- Methodological Guidance: PCRs specify which environmental impact categories should be evaluated, which data sources should be used, and how this data should be collected and analyzed. This provides methodological consistency and ensures that assessments remain objective.
- Functional Unit and System Boundaries: PCR defines the functional unit and system boundaries to be used in the LCA to ensure product comparability. For example, when conducting an LCA for a plastic bag and a paper bag, the functional unit might be defined as "a bag with a carrying capacity of one unit," and calculations are made based on this unit.

In summary, the pathway and relevant standards to be followed for calculating and declaring the environmental impacts of a product are shown in Figure 3.

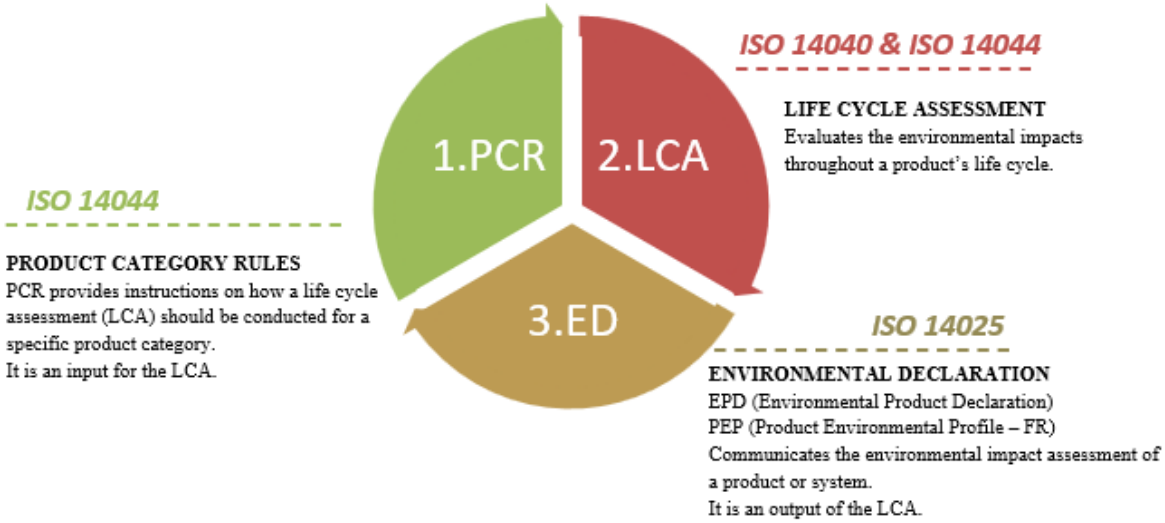


Figure 3. Roadmap for examining the environmental impacts of a product

C. Review of the PCR for Packaging Products

In this study, the PCR published by EPD as version 1.1.2 has been considered (ISO,2006b). The reviewed PCR is currently under revision, but it will remain valid and applicable until the deadline specified in the document. It is important to take the existing rules into account when conducting an LCA.

For the PCR concerning packaging products, the first step in defining the goal and scope is to specify the declared unit. The declared unit is one (1) packaging product unit.

The following technical information supports the definition of the declared unit:

- Primary material of the packaging product (e.g., polymer, wood, etc.)
- External dimensions of the packaging product (m)
- Internal volume of the packaging product (l)
- Weight of the packaging product (kg)
- Maximum load capacity (kg)
- Compression values (e.g., results of compression testing based on ISO 12048 or equivalent)
- Stacking values (e.g., results of stacking tests based on ISO 12048 or equivalent)

The declared unit must be specified in the EPD. Environmental impacts should be reported per declared unit.

A review of the EPDs for packaging products available in the literature shows that in the EPD published by the company Kotronis for packaging polypropylene cups, lids, and containers (Matthews et al., 2014), the declared unit is defined as one packaging product unit.
Similarly, Kunshan Jinhongkai Packaging Products Co., in its EPD for carton boxes (EPD International, 2024b), declared the assessed product as "1,000 kg of paper boxes with a moisture content of 3.9% and 1 m^2 of paper boxes with a nominal grammage between 80–145 g/m^2". This type of declaration aligns with the technical details specified in the PCR. Another EPD document from the same company (EPD International, 2024c), published for paper bags, also includes the technical specifications of the declared unit.

The PCR for packaging products defines the system boundaries and specifies which life cycle stages must be included (EPD International, 2024a), as shown in Figure 4. It explains how these boundaries should be considered and calculated.

Sector-specific PCR documents (Ankesh et al., 2021; Enarevba & Haapala, 2023; WeTheCA, 2024) also address system boundaries, as illustrated in Figure 2. The International EPD® System applies a cradle-to-grave approach, in which all relevant processes are included using the principle of "limited information loss in the final product." This is especially important for communication from business to consumer.

The scope of this PCR and the EPDs based on it can be cradle-to-gate, optionally cradle-to-gate with options, or cradle-to-grave. The EPDs reviewed for the declared unit in this study were assessed within the cradle-to-gate boundaries.

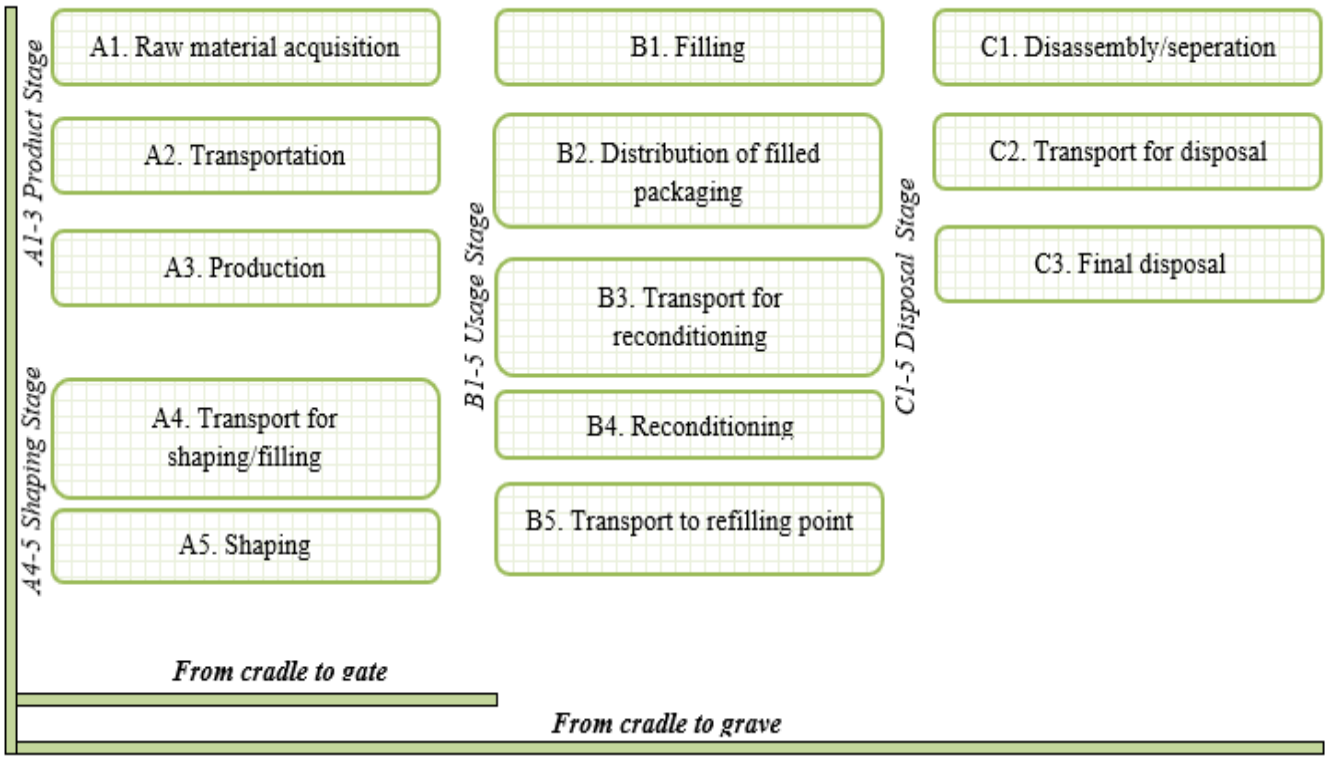


Figure 4. System boundaries included in the PCR for packaging products

II. MATERIAL AND METHOD

In this study, the environmental impact assessment of four different packaging materials was conducted. The environmental impact assessments are presented as environmental performance indicators in accordance with the guidance provided in section [4.9] of the PCR (EPD International, 2024d).

The environmental performance indicators include:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Photochemical Ozone Creation Potential (POCP)
- Ozone Depletion Potential (ODP)
- Abiotic Depletion Potential (ADP) for minerals and metals (non-fossil resources)
- Abiotic Depletion Potential (ADP) for fossil resources
- Water Deprivation Potential (WDP)

The environmental performance indicators of the four packaging materials were calculated using the cradle-to-gate approach with the Makersite software (Makersite, 2024), as illustrated in Figure 5.



Figure 5. LCA data of the unit packaging product

The packaging materials considered in this study are those used or planned to be used as packaging products for a combi unit, which have been designed and tested for strength and quality according to their field of application. These include: expanded polystyrene (EPS) supplied by Supplier A, 100% recyclable cardboard supplied by Supplier B, honeycomb panel supplied by Supplier C, and pulp mould (tray) supplied by Supplier D.
In assessing the environmental impacts of these four products, "1 kg of packaging material" was taken as the functional unit. The process inputs and outputs are presented in Figure 5.

III. RESULTS AND DISCUSSIONS

Table 1 presents the 'cradle-to-gate' environmental impacts of the four packaging materials. These environmental impacts may vary depending on supplier, production process, and raw material variability.

Table 1. Environmental impact results of four different packaging materials.

Parameter	EPS	%100 Recyclable Cardboard	Honeycomb Panel	Pulp Mould
Global Warming Potential (kg CO_2 eq.)	3,760E+00	2,240E+00	1,430E+00	2,250E+00
Acidification Potential (mol H^+ eq.)	1,280E-02	7,370E-01	7,760E-03	7,500E-03
Eutrophication Potential (kg P eq.)	1,100E-04	5,760E-04	1,120E-03	6,150E-04
Photochemical Ozone Creation Potential (kg NMVOC eq.)	1,120E-02	9,930E-01	5,100E-03	5,740E-03
Ozone Depletion Potential (kg CFC-11 eq.)	4,030E-08	1,260E-07	1,650E-08	5,260E-08
Abiotic Depletion Potential (fossil resources, minerals, and metals) (kg Sb eq.)	3,610E-07	8,810E-06	3,200E-06	4,780E-06
Abiotic Depletion Potential (fossil resources) (ADP) (MJ)	8,290E+01	2,520E+01	1,460E+01	2,240E+01
Water Deprivation Potential (m^3)	2,780E+00	1,080E+00	8,150E-01	1,010E+00

When Table 1 is examined, it is observed that EPS exhibits significantly higher values in environmental impact categories such as global warming potential, abiotic depletion potential, and water deprivation potential compared to the alternative materials, thereby constituting a considerable environmental burden. On the other hand, the cardboard honeycomb panel demonstrates the lowest values across all environmental impact categories, emerging as the most sustainable alternative. Based on these data, the life cycle assessment results can be summarized as follows:

Global Warming Potential (GWP):

EPS has the highest global warming potential with a value of 3.76 kg CO_2 eq. Recyclable cardboard (2.24), honeycomb panel (1.43), and pulp mould tray (2.25) exhibit 40%, 62%, and 40% lower global warming potentials, respectively.

Acidification Potential (AP):

EPS has the lowest acidification potential with 0.0128 mol H^+ eq., whereas recyclable cardboard has the highest with 0.737 mol H^+ eq., approximately 57.5 times higher than EPS. The honeycomb panel (0.00776) and pulp mould tray (0.0075) demonstrate 39% and 41% lower acidification potentials, respectively.

Eutrophication Potential (EP):

The honeycomb panel shows the highest eutrophication potential with 0.00112 kg P eq. Compared to EPS (0.00011), this corresponds to an approximately 920% higher impact. Recyclable cardboard (0.000576) and pulp mould tray (0.000615) also exhibit 424% and 459% higher values, respectively.

Photochemical Ozone Creation Potential (POCP):

EPS has the highest value with 0.0112 kg NMVOC eq., while the honeycomb panel (0.0051) and pulp mould tray (0.00574) display 54% and 49% lower impacts, respectively. However, recyclable cardboard (0.993) shows the highest value in this category.

Ozone Depletion Potential (ODP):

EPS records the lowest ozone depletion potential at 0.0000000403 kg CFC-11 eq. The honeycomb panel (0.0000000165) has 59% lower values, while pulp mould tray and recyclable cardboard show 30% and 213% higher impacts, respectively.

Abiotic Depletion Potential (Non-fossil Resources):

EPS has the lowest abiotic depletion potential at 0.000000361 kg Sb eq. Recyclable cardboard (0.00000881) is 2,340% higher, while the honeycomb panel (0.0000032) and pulp mould tray (0.00000478) are 787% and 1,324% higher, respectively.

Abiotic Depletion Potential (Fossil Resources):

EPS has a fossil resource depletion potential of 82.9 MJ. In comparison, recyclable cardboard (70% lower), honeycomb panel (82% lower), and pulp mould tray (73% lower) demonstrate considerably reduced values.

Water Deprivation Potential (WDP):

EPS has the highest water deprivation potential with 2.78 m^3. Recyclable cardboard (1.08), honeycomb panel (0.815), and pulp mould tray (1.01) have 61%, 71%, and 64% lower water consumption potentials, respectively.

IV. CONCLUSION

In this study, the environmental impacts of EPS, 100% recycled cardboard, honeycomb panel, and pulp mould materials were compared in light of the data presented in the table, highlighting the advantages and disadvantages of each material across specific categories. By employing percentage comparisons, the environmental performance of the materials was more clearly demonstrated.

Global Warming Potential (GWP): The honeycomb panel stands out as the most advantageous material in terms of climate change, as it has the lowest greenhouse gas emissions.

Acidification Potential (AP): In this category, the honeycomb panel and pulp mould exhibit the lowest acidification potentials, making them the least environmentally harmful options. By contrast, EPS and 100% recycled cardboard display higher impact values and thus a less favorable environmental profile. The higher acidification potentials of EPS and recycled cardboard are primarily linked to the type of energy and process inputs used during their production. Being a petroleum-derived material, EPS requires significant fossil fuel consumption in its production, which results in increased emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x), major contributors to acidification. On the other hand, although recycled cardboard is often considered environmentally friendly, the recycling process itself involves high energy consumption and the use of various chemicals. Since much of this energy is fossil-based and the processes release acidic by-products, the acidification potential increases. Therefore, rather than the final form of the materials, the environmental inputs of their production and recycling stages play a decisive role in determining their performance in this category.

Eutrophication Potential (EP): EPS records the lowest value in this category, while the honeycomb panel and other alternatives show higher levels of impact. The reason EPS scores lowest is that its raw materials and production

processes release fewer nutrients (particularly nitrogen and phosphorus) into the environment. Eutrophication is a process in which excessive nutrient accumulation in aquatic ecosystems leads to algal blooms and oxygen depletion. Since EPS production involves fossil-derived polymers that do not generate nitrogen- and phosphorus-rich effluents, its contribution to eutrophication remains limited. Conversely, the raw materials and chemicals used in the production of honeycomb panels and other alternatives can increase nutrient discharge into water systems, thus raising eutrophication potential. In particular, chemicals employed during recycling may leach into water systems, intensifying this effect.

Photochemical Ozone Creation Potential (POCP): The honeycomb panel and pulp mould perform better in this category compared to EPS, positioning them as more favorable alternatives. In contrast, recycled cardboard shows a disadvantage in this regard.

Ozone Depletion Potential (ODP): The honeycomb panel emerges as the least harmful material to the ozone layer, as its raw materials and processes release minimal ozone-depleting substances. Honeycomb panels are typically produced from synthetic materials, but the chemicals used in this process do not emit gases that degrade the ozone layer. Conversely, pulp mould and recycled cardboard may involve higher chemical use and energy consumption during production, with some recycling agents releasing compounds that damage the ozone layer. For example, certain solvents and chemicals used in recycled paper processing may increase ozone-depleting emissions. As a result, while honeycomb panels pose less risk to the ozone layer, pulp mould and recycled cardboard have higher impacts.

Abiotic Depletion Potential – Non-fossil Resources (ADP): EPS is considered the most advantageous option in this category. In contrast, the honeycomb panel and pulp mould demonstrate higher depletion of non-fossil resources.

Abiotic Depletion Potential – Fossil Resources (ADP): The honeycomb panel and pulp mould are regarded as more environmentally friendly than EPS in terms of fossil fuel consumption.

Water Deprivation Potential (WDP): The honeycomb panel and pulp mould rank among the most efficient materials in terms of water consumption, offering a sustainable alternative.

Overall, these findings demonstrate that EPS exerts significant impacts particularly in critical environmental categories such as fossil resource depletion and water consumption. In contrast, the honeycomb panel, with its lower global warming potential, can be considered a viable alternative packaging material.

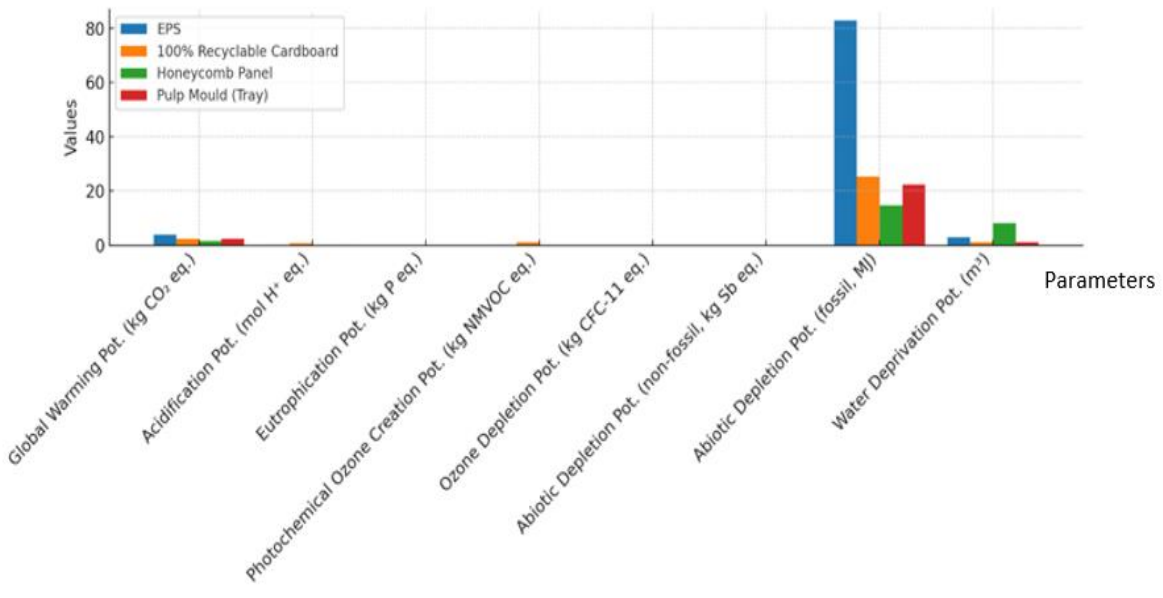


Figure 6. Environmental impact comparison of packaging materials

Studies in the literature (Ankesh et al., 2021) indicate that EPS is widely used due to its low cost and lightweight structure; however, its negative impacts on the environment and human health are increasingly being discussed. In particular, EPS poses significant challenges in terms of waste management, and the amount of such waste is projected to increase in the future.

A study conducted in Germany (Ankesh et al., 2021) estimates that EPS waste could increase by between 3,000 and 33,000 tons between 2020 and 2040, placing an additional burden on waste management systems.

Studies on alternative materials have shown that mycelium-based packaging is more advantageous than EPS in terms of environmental impacts. While the literature highlights that mycelium exhibits lower values in terms of global warming potential (GWP), materials such as the cardboard honeycomb panel evaluated in this study also offer significant advantages regarding GWP. For instance, whereas the GWP of EPS was calculated as 3.76 kg CO_2 eq., the cardboard honeycomb panel recorded only 1.43 kg CO_2 eq., which is remarkable. The literature further emphasizes the need for additional studies focusing on process optimization to reduce the environmental impacts of mycelium. In contrast, cardboard-based materials already provide a sustainable alternative, which is consistent with the findings of this research (Enarevba & Haapala, 2023).

In conclusion, the findings obtained in this study are consistent with the environmental results reported in the literature for EPS (Ankesh et al., 2021; Enarevba & Haapala, 2023). The environmental burden of EPS is considerably high, whereas bio-based alternatives such as mycelium have been shown in the literature to be more environmentally friendly.



Figure 7. EPS

According to the assessment of global warming potential (GWP), EPS has the highest value with 3.76 kg CO_2 eq. Among the alternative materials, the honeycomb panel demonstrates the lowest GWP at 1.43 kg CO_2 eq., which corresponds to 62% lower greenhouse gas emissions compared to EPS. Recyclable cardboard (2.24 kg CO_2 eq.) and pulp mould (2.25 kg CO_2 eq.) also exhibit approximately 40% lower global warming potential relative to EPS.

In this context, when considering only the global warming potential, the honeycomb panel emerges as the most suitable alternative to replace EPS. This comparison is illustrated in Figure 8.

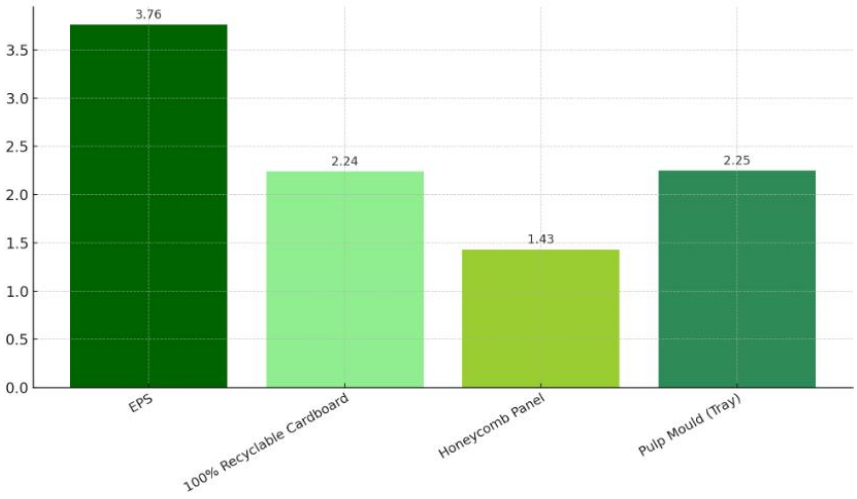


Figure 8. Comparison of the global warming potential of packaging materials

When these findings are evaluated together with the data in the literature, it becomes evident that environmentally friendly alternatives should be preferred over EPS. Therefore, in the long term, EPS must be replaced by more sustainable options. The honeycomb panel, in particular, along with other alternatives, offers more environmentally friendly solutions than EPS in the "global warming potential" impact category. This transition is critical not only for reducing environmental impacts but also for ensuring compliance with future regulatory frameworks. Stricter regulations, especially regarding carbon emissions and waste management, are expected to come into force in 2025 and 2026. Within this legal framework, materials with lower environmental impacts will play a key role in providing competitive advantages in the sector. Moreover, the use of environmentally friendly alternatives will not only improve companies' environmental performance but also strengthen their regulatory compliance and protect them from potential legal risks. In this context, adopting sustainability strategies will guarantee long-term success for companies, ensuring both environmental benefits and advantages in legal compliance and market competition.

DECLARATIONS

Acknowledgements: Mr. Hüseyin Can MENGÜÇ handled the environmental package product research as a project, including technical and design information. This article focuses on the results obtained through the support provided in calculating environmental impacts, a valuation criterion within the project. I would like to express my gratitude to Mr. H.C. MENGÜÇ and my managers for their dedication and knowledge sharing.

Author Contributions: Conceptualization, A.B.; Methodology, A.B. and C.D.; Validation, C.D.; Investigation, E.F.; Resources, E.F.; Data Curation, A.B.; Writing—Original Draft, A.B.; Writing—Review & Editing, E.F.; Supervision, C.D.

Supporting Institutions: This research received no external funding.

Ethical Approval: This study does not involve human or animal participants. All procedures followed scientific and ethical principles, and all referenced studies are appropriately cited.

Plagiarism Statement: This article has been evaluated for plagiarism and no instances of plagiarism were detected.

Data Availability: Data sharing is not applicable to this study.

Use of AI Tools: The author/authors declare that no Artificial Intelligence (AI) tools were used in the creation of this article.

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