Journal of Agricultural Engineering

https://www.agroengineering.org/

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Please cite this article as doi: 10.4081/jae.2026.2148

Submitted: 18 February 2026
Accepted: 1 July 2026

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Contributions: Piernicola Masella, conceptualization, methodology, project administration, software, supervision, writing - original draft. **Agnese Spadi**, conceptualization, investigation, methodology, validation, visualization. **Niccolò Gracci**, data curation, formal analysis, investigation, software. **Cristiano Vizzo**, investigation, writing: review and editing, validation, visualization; **Alessio Cappelli**, validation, visualization. **Alessandro Parenti**, validation, visualization. **Ferdinando Corti**, methodology, validation. **Lorenzo Bruchi**, validation, visualization. **Giulia Angeloni**, conceptualization, investigation, supervision, validation.

Competing interests: The authors declare no competing interests and all authors confirm accuracy.

Availability of data and material: the datasets used and/or analyzed during the current study are available upon reasonable request from the corresponding author.

Declaration of Generative AI and AI-assisted technologies in the writing process: the authors declare that they used LLMs only for language editing (ChatGPT). The authors reviewed and edited all generated content and take full responsibility for the accuracy and integrity of the final manuscript.

Acknowledgments: the authors would like to thank Alcas S.p.A. for supporting the present research.

Abstract

This study presents a comparative Life Cycle Assessment (LCA) of ice cream cups made from polystyrene (PS), polylactic acid (PLA), and paperboard (PAP), based on primary industrial data and a cradle-to-gate approach. The analysis was performed using the CML v4.8 (2016) method and complemented by the Environmental Footprint (EF 3.1) methodology to assess the robustness of the results. The results show that PLA exhibits the highest environmental impacts across most categories, mainly due to upstream processes associated with agricultural production and polymer synthesis. In contrast, PS is characterized by the highest fossil resource depletion and non-renewable energy demand, while PAP shows lower impacts in climate change but significantly higher land use. The comparison highlights the presence of trade-offs among materials, indicating that no single option is environmentally preferable across all impact categories. The consistency between the CML and EF 3.1 results confirms the robustness of the comparative assessment. These findings emphasize the importance of adopting a full life cycle perspective when evaluating alternative materials, particularly for bio-based products. The study provides a methodological basis for Environmental Product Declarations (EPDs) and supports informed decision-making in the food packaging sector.

Key words: LCA; PS; PLA; paperboard; carbon footprint; impact assessment; SUP Directive.

Introduction

In recent decades, environmental sustainability has become a central concern across industries, institutions, and society, driving both innovation and regulatory developments. The need to reduce environmental impacts has significantly influenced production systems, consumer behavior, and policy frameworks. In this context, Life Cycle Assessment (LCA) has emerged as a key tool for evaluating and designing products with reduced environmental burdens (ISO, 2006a; 2006b; de Bruijn *et al*., 2002). Sustainable development was formally recognized in 1987 by the Brundtland Report (United Nations, 1987), which introduced the principle of intergenerational equity. This concept has since been reinforced through international initiatives such as the United Nations 2030 Agenda, which promotes integrated approaches to environmental, social, and economic sustainability, including goals related to responsible consumption and production, climate action, and ecosystem protection (United Nations, 2024). At the European level, these principles have been translated into increasingly stringent regulatory frameworks. The Single-Use Plastics (SUP) Directive (European Union, 2019) aims to reduce the environmental impact of disposable plastic products by promoting recyclability and extended producer responsibility. More recently, the proposed Green Claims Directive (https://environment.ec.europa.eu/topics/circular-economy-topics/green-claims_en) requires that environmental claims be substantiated through robust and verifiable scientific evidence (European Union, 2023). These regulatory and market pressures are significantly reshaping the packaging sector, particularly in food service applications. Alternative materials such as bioplastics, including polylactic acid (PLA), and fiber-based materials such as paper and cardboard are increasingly being adopted. However, material substitution alone does not necessarily guarantee environmental benefits. The environmental performance of PLA is strongly influenced by agricultural inputs, processing, and supply chain characteristics, while paper-based materials, although renewable and recyclable, can be associated with significant energy, water, and land use requirements (European Bioplastics, 2023; Fonseca *et al*., 2023; Islam *et al*., 2026; Landis *et al*., 2022; Sun *et al*., 2018). LCA provides a systematic framework for evaluating environmental impacts across the life cycle of a product, supporting the identification of trade-offs and the avoidance of burden shifting between impact categories or life cycle stages (Guinée *et al*., 2011; Villanueva and Wenzel, 2007). It is widely applied in the packaging sector, which accounts for a significant share of material consumption and waste generation in Europe (Plastics Europe, 2023; Eurostat, 2022). Previous studies have shown that the environmental performance of alternative packaging materials is highly context-dependent and varies depending on system boundaries, functional units, and modelling assumptions (Walker and Rothman, 2020). Single-use ice cream cups represent a relevant case study, as they must meet specific functional requirements, including mechanical resistance, thermal insulation, and food safety. Conventional polystyrene (PS) cups are widely used due to their low cost and good insulating properties, but they are difficult to recycle. PLA cups are often considered a more sustainable option due to their bio-based origin and potential biodegradability, although they typically require industrial composting conditions. Paper cups, while perceived as environmentally friendly, often include polymer coatings that complicate recycling processes (Vink *et al*., 2010; Deshwal *et al*., 2019; Walker and Rothman, 2020; Moretti *et al*., 2021). In this context, the present study applies a comparative Life Cycle Assessment to evaluate the environmental performance of ice cream cups made from PS, PLA, and paperboard (PAP). The analysis adopts a cradle-to-gate approach, focusing on the production phase from raw material extraction and upstream processing to manufacturing and packaging. The study is based on a combination of background data from databases and literature and primary industrial data provided by Alcas S.p.A. (Florence, Italy), a company specialized in the production of ice cream cups. The use of primary data enhances the representativeness of the analysis and allows the assessment to reflect real industrial conditions. This is particularly relevant in a context where companies are required to adapt to evolving regulatory frameworks and increasing demand for environmentally sustainable products. Over time, Alcas S.p.A. has transitioned from conventional plastics to bioplastics and, more recently, to paper-based solutions, raising the question of which material offers the most favorable environmental profile under current conditions. The objective of this study is to provide a transparent and scientifically robust comparison of the environmental impacts associated with these three material options across multiple impact categories. The results aim to support decision-making by manufacturers, policymakers, and other stakeholders involved in the food packaging sector, contributing to the broader goal of reducing the environmental footprint of single-use products.

Materials and Methods

The LCA methodology applied in this study is based on the international standards ISO 14040 and ISO 14044. The analysis was conducted in full compliance with them.

Goal and scope definition

This study applies a comparative cradle-to-gate LCA to evaluate the environmental performance of single-use ice cream cups made of PS, PLA, and PAP, all manufactured by Alcas S.p.A. The study was carried out according to ISO 14040 and ISO 14044 standards. The goal of the assessment is to compare the three packaging systems under the same modelling assumptions and to identify the main contributors to their environmental impacts at the production stage.

System boundaries

This study adopts a cradle-to-gate approach, including raw material extraction and processing, transport, and manufacturing up to the exit gate of the Alcas S.p.A. facility, where the final product is a cardboard box containing 1,000 ice cream cups. End-of-life processes were not included in the system boundary. The assessment also includes the contribution of production machinery and building infrastructure through amortization over their useful life.

Functional unit

A comparative LCA requires a consistent and well-defined reference to ensure equivalence among the compared systems. The functional unit provides this benchmark by defining the shared functionality in both quantitative and qualitative terms. In this study, the functional unit is defined as one cardboard box containing 1,000 ice cream cups, representing the commercial unit typically purchased by artisanal ice cream shops. This unit corresponds to the output of the manufacturing process and ensures the same function is fulfilled, namely serving approximately 1,000 medium-sized ice cream portions. The cardboard box has the following dimensions: 27.00 cm × 43.00 cm × 32.00 cm, with a total weight of 0.900 kg. Inside, the cups are further grouped into polypropylene (PP) sub-packaging with a total mass of 0.15 kg. The comparative analysis was carried out on ice cream cups produced by the same company (Alcas S.p.A.) but made from different materials: polystyrene, polylactic acid, and paperboard. The PS and PLA cups have a nominal capacity of 130 cc, whereas the PAP cups have a nominal capacity of 125 cc. This difference corresponds to approximately 4% of the nominal volume and was considered not to materially affect the functional equivalence among the compared systems. In the intended use scenario, artisanal ice cream is typically served manually, and the variability in actual filling conditions is expected to exceed this nominal difference. Therefore, the original functional unit was maintained. The functional equivalence among the compared systems was summarized in Table 1. Cup weight is a critical parameter in the analysis, as it directly affects the amount of resources required throughout the production processes. The observed weight differences between the cup types are primarily due to the specific density of the materials used. The PS and PLA cups share identical geometries, as they are thermoformed using the same mold, whereas the paperboard cups differ slightly in shape. All features are reported in Table 2. PAP cups feature a kaolin-based coating on the external surface (used for graphic printing), while the internal surface (in contact with food) is lined with a polyethylene (PE) film, which represents about 5% of the cup's total weight. This PE layer ensures waterproofing and makes the cups suitable for holding ice cream. To ensure a balanced comparison, the environmental impact of graphic printing was assessed based on a hypothetical design covering 30% of the printable surface of each cup.

Data sources, software, and database

Primary (foreground) data were collected at Alcas S.p.A., an Italian manufacturer of disposable food packaging located in Florence (Italy). The analyzed systems refer to ice cream cups produced within the company's industrial setting. Foreground data included information on material consumption, electricity use, transport distances, printing inputs, and production equipment. Electricity consumption refers to grid electricity and was modelled using country-specific datasets available in the Ecoinvent database. The LCA modelling was carried out using

OpenLCA 2.1 software. Background data were obtained from the Ecoinvent 3.9.1 database (cutoff_upr_regionalized system model). Whenever available, regionalized datasets were selected to reflect the geographical specificity of the analysed processes. Background data were used to model upstream processes, including raw material production, energy supply, transport services, and capital goods. Transport modelling follows the assumptions embedded in the selected Ecoinvent datasets. The cut-off system model was selected due to its widespread application in LCA studies and its consistency with Environmental Product Declaration (EPD) frameworks. Under this approach, recycled materials entering the system are considered free of upstream environmental burdens, while recycling processes within the system are fully accounted for. The modelling framework distinguishes between upstream processes, based on Ecoinvent datasets, and core manufacturing processes, based on primary data collected at Alcas S.p.A. The specific production steps for each system are described in the following sections.

Environmental impact categories considered

The life cycle impact assessment (LCIA) was primarily performed using the CML v4.8 (2016) midpoint method, which is widely applied in packaging-related LCA studies and allows comparison with existing literature. The following impact categories were considered: acidification potential (AP), global warming potential over a 100-year time horizon (GWP100), freshwater aquatic ecotoxicity potential (FAETP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), abiotic depletion potential for fossil fuels (ADP fossil), eutrophication potential (EP), human toxicity potential (HTP), abiotic depletion potential for metals and minerals (ADP minerals), ozone depletion potential (ODP), and photochemical ozone creation potential (POCP). In addition, cumulative energy demand (CED) was assessed to quantify total primary energy consumption, distinguishing between renewable and non-renewable energy sources. To support the interpretation of results across different impact categories, EU25 normalization factors from the CML-IA baseline method were applied. As a complementary analysis, the Environmental Footprint method (EF 3.1) was also applied to assess the robustness of the comparative results. The use of EF 3.1, which represents the current European reference framework for product environmental assessment, allowed verification of the consistency of the observed trends across different LCIA methodologies.

Life cycle inventory modelling

The life cycle inventory modelling was developed for each system according to the defined functional unit, including both upstream processes and core manufacturing operations. A summary of the main inventory parameters and modelling assumptions for the three systems, including material composition, energy use, transport modelling, and scrap generation, is reported in Table 3. Detailed inventory results for each system are reported in Tables 4–6. These tables report the main elementary flows associated with each system, including material inputs, energy use, and emissions to air, water, and soil, as derived from the life cycle inventory modelling.

PS system

The life cycle inventory scheme for the PS system is shown in Figure 1. The environmental impact of PS ice cream cups was assessed by modelling the main production stages, including raw material production and sheet extrusion, transport, thermoforming, printing, and packaging. The system includes both primary material inputs and internally recycled production scraps, which are reprocessed on-site and reintroduced into the production chain. The detailed inventory results for this system are reported in Table 4. PS production was modelled using Ecoinvent datasets for general-purpose polystyrene granules ("polystyrene, general purpose, cutoff, U – RER") and subsequent sheet extrusion ("extrusion, plastic sheets, cutoff, U – RER"). A total of 7.65 kg of PS in roll form is required per functional unit. The transport of PS rolls to the Alcas S.p.A. facility was modelled based on an average distance of 1,061 km from major European suppliers, using Euro 6 lorry transport datasets (16-32 t). Thermoforming was modelled based on industrial data for a WM FC 780 E machine, with an energy consumption of 0.704 kWh per functional unit. Production scraps generated during trimming (3.36 kg per functional unit) are reprocessed on-site through grinding, with an associated energy consumption of 0.503 kWh per functional unit. Scrap material is sold as secondary raw material and therefore not treated as waste within the system boundaries. Offset printing was modelled using industrial data for a MOSS MO2063/6 printer, with an energy consumption of 0.407 kWh per functional unit and an ink consumption of 0.016 kg per functional unit. Ink production was modelled using Ecoinvent datasets for printing inks. The contribution of machinery was included through amortization based on machine mass, lifetime, and annual production, using Ecoinvent datasets for industrial equipment. Finally, packaging includes PP film (0.15 kg per functional unit) and a cardboard box (0.90 kg per functional unit), both modelled using Ecoinvent datasets. The packaging configuration is identical across all analyzed systems.

PLA system

The life cycle inventory scheme for the PLA system is shown in Figure 2. The environmental impact of PLA ice cream cups was assessed by modelling the main production stages, including raw material production and sheet extrusion, transport, thermoforming, printing, and packaging. Similarly to the PS system, production scraps are reprocessed on-site and considered as secondary material within the system. PLA production was modelled using Ecoinvent datasets for polylactide granulate ("polylactide production, granulate, Cutoff, U – GLO") and sheet extrusion ("extrusion, plastic sheets, Cutoff, U – GLO"). The production process includes agricultural cultivation of corn and subsequent biochemical conversion into lactic acid and polymerization into PLA. A total of 10.157 kg of PLA in roll form is required per functional unit. PLA rolls are supplied by NatureWorks LLC., (Plymouth, MN, USA), and transport to the Alcas S.p.A. facility was modelled through a multi-modal route, including rail transport from Nebraska to New York (2,018 km), transoceanic shipping from New York to Livorno (7,700 km), and road transport from Livorno to Florence (84 km), using the corresponding Ecoinvent datasets. Thermoforming was modelled using the same equipment and assumptions adopted for PS cups. Due to the higher density of PLA, a greater amount of production scrap is generated (4.80 kg per functional unit), resulting in increased energy consumption for grinding (0.72 kWh per functional unit). Scrap material is reprocessed on-site and not treated as waste within the system boundaries. Offset printing was assumed to have the same energy and ink consumption as for PS cups, as the material does not significantly affect the printing process. Packaging includes PP film (0.15 kg per functional unit) and a cardboard box (0.90 kg per functional unit), modelled using Ecoinvent datasets. The packaging configuration is identical across all analyzed systems.

PAP system

The life cycle inventory scheme for the PAP system is shown in Figure 3. The environmental impact of PAP ice cream cups was assessed by modelling the main production stages, including paper production, transport, conversion into blanks and bottoms, printing and die-cutting, cup forming, and packaging. The system includes multiple material components (paperboard and polyethylene coating) and separate processing steps for sidewall blanks and bottoms, as reflected in the inventory data. Paper production was modelled using the Ecoinvent dataset "paper production, woodfree, coated, at integrated mill, Cutoff, U – RER", representing coated paper produced *via* Kraft pulping. A PE coating was included using the dataset "packaging film production, low density polyethylene, Cutoff, U – RER" to account for the water resistance required for food contact applications. Paper supply is provided by a single supplier (Stora Enso

Oyj, Helsinki, Finland). Transport to the processing facilities was modelled using Euro 6 lorry datasets (16-32 t), with distances of 2,622 km for paper sheets (used for sidewall blanks) and 2,573 km for paper reels (used for cup bottoms). The cup structure consists of two main components: a fan-shaped sidewall blank and a circular bottom. For one functional unit, 5.00 kg of paper is required for the blanks and 1.83 kg for the bottoms. Printed blanks are supplied by a subcontractor and transported over a distance of 57.3 km to the Alcas S.p.A. facility. Printing and die-cutting of sidewall blanks were modelled based on industrial data, with an electricity consumption of 0.1538 kWh and 0.0769 kWh per functional unit, respectively. Ink consumption was estimated at 0.023 kg per functional unit, assuming 30% printed surface coverage. Cup forming, including bottom insertion, welding, and rim forming, was modelled using a Debao-138S machine with an electricity consumption of 3.61 kWh per functional unit. The contribution of machinery was included through amortization based on machine mass (3,500 kg), lifetime (20 years), and annual production, using the Ecoinvent dataset "industrial machine production, heavy, unspecified, Cutoff, U – RER". Finally, packaging includes PP film (0.15 kg per functional unit) and a cardboard box (0.90 kg per functional unit), modelled using Ecoinvent datasets. The packaging configuration is identical across all analyzed systems.

Infrastructure and capital goods

The environmental impact associated with the Alcas S.p.A. facility was included in the assessment through the amortization of capital goods, including production equipment and building infrastructure, over their useful life. For machinery, impacts were allocated to the functional unit based on machine mass, lifetime, and estimated annual production. The environmental burdens associated with equipment manufacturing were modelled using the Ecoinvent dataset "industrial machine production, heavy, unspecified, Cutoff, U – RER". Building infrastructure was also included in the system boundaries. Its contribution was estimated by allocating the total building mass over an assumed lifetime of 100 years and distributing it according to the annual production of the facility. The dataset "building construction, hall, Cutoff, U – RoW" was used for modelling purposes. These contributions were consistently applied across all analyzed systems to ensure comparability.

Results

Environmental impact assessment - life cycle impact assessment

The environmental impact assessment was carried out using the CML v4.8 (2016) impact assessment methodology. The results for the functional units under study are reported in Table 7. It should be noted that comparisons with previous studies are only indicative, as several literature sources include end-of-life stages or adopt different functional units and modelling assumptions, which limit the direct comparability of absolute impact values. Overall, the results highlight clear differences among the three systems. The PLA functional unit exhibited the highest environmental impacts in the majority of the considered impact categories, while PAP generally showed lower values in climate-related categories and PS exhibited higher impacts in fossil resource depletion. For the PAP system, the Global Warming Potential (GWP100) was 15.7 kg CO_2-Eq, with relatively low values also observed for acidification (0.0427 kg SO_2-Eq) and photochemical ozone formation (0.0058 kg ethylene-Eq). These results are consistent with literature data when accounting for differences in system boundaries. In contrast, PAP showed comparatively higher values in marine aquatic ecotoxicity (MAETP), confirming the relevance of this category in the overall impact profile. For the PLA system, GWP100 reached 37.1 kg CO_2-Eq, confirming its higher environmental burden compared to both PAP and PS. This trend is consistent across several categories, including acidification, eutrophication, and toxicity-related indicators. The higher impacts observed for PLA are directly linked to upstream processes, particularly agricultural production and polymer synthesis, as reflected in the inventory data (Tables 4-6). For the PS system, GWP100 was 33.8 kg CO_2-Eq, with intermediate values across most categories. However, PS exhibited the highest impact in fossil resource depletion (ADP fossil), reflecting its petrochemical origin and dependence on non-renewable resources. A comparative analysis shows that PLA is the most environmentally burdensome system in 9 out of the 11 impact categories considered. In contrast, PAP generally performs better in climate-related categories, while PS shows a trade-off profile, with lower impacts than PLA in several categories but significantly higher fossil resource use. Figure 4 illustrates the comparative performance of the three systems across the considered impact categories. Beyond the aggregated results, the contribution analysis indicates that raw material production is the dominant stage for all systems and impact categories. This is particularly evident for PLA, where the production of polylactic acid drives the majority of the impacts. Transport also contributes significantly to the PLA system, due to the long-distance, multi-modal supply chain, particularly affecting acidification and photochemical ozone formation. In contrast, the contribution of manufacturing processes (forming and printing) and infrastructure was found to be relatively minor. The cumulative energy demand (CED) analysis further supports these findings. The total energy demand was highest for PS (1691 MJ-eq), followed by PLA (1688 MJ-eq), while PAP exhibited a significantly lower value (1047 MJ-eq). In the case of PS, 94.45% of the total energy demand was derived from non-renewable sources. PLA showed a high contribution from both renewable and non-renewable energy sources, reflecting the combined influence of agricultural production, transport, and polymer processing. In contrast, PAP exhibited a more balanced energy profile, with approximately 47.06% renewable and 52.94% non-renewable energy contributions. The application of normalization factors (EU25) resulted in overall scores of 3.78×10^{-10} for PAP, 4.09×10^{-10} for PLA, and 3.53×10^{-10} for PS, confirming the higher overall impact of PLA and the comparatively lower impact of PS. The EF 3.1 results, reported in Table 8, confirmed the general trends observed with the CML method. In particular, PLA remained the most environmentally burdensome system across most impact categories, including climate change (37.33 kg CO_2-Eq), acidification, eutrophication, and toxicity-related indicators. PAP showed lower impacts in climate change (15.77 kg CO_2-Eq) but significantly higher values in land use (1084.95), reflecting the contribution of biomass-based resources. PS, while showing intermediate values in most categories, exhibited the highest fossil resource use (741.63 MJ), confirming the trade-offs associated with petrochemical materials. These results demonstrate the robustness of the comparative assessment, highlighting consistent patterns across different LCIA methodologies and confirming that the environmental performance of the systems is primarily driven by upstream processes and material production. Figure 5 shows the normalized impact scores for the three systems. Finally, for all systems, marine aquatic ecotoxicity (MAETP) was identified as the dominant impact category, contributing up to 89.73% of the total normalized score for PAP, 78.38% for PLA, and 85.18% for PS.

Discussion

Life cycle interpretation

The results consistently indicate that the PLA system is the most environmentally burdensome among the three analyzed alternatives. This outcome is strongly linked to upstream processes, particularly those associated with agricultural production and polymer synthesis, as highlighted by both the CML and EF 3.1 results. The higher impacts observed for PLA can be primarily attributed to corn cultivation and subsequent biochemical conversion processes. The inventory data show that this stage involves intensive use of fertilizers, water, and energy inputs, which directly contribute to eutrophication, ecotoxicity, and climate-related impacts. In particular, nutrient emissions associated with fertilizer application are responsible for the elevated eutrophication potential, while the overall agricultural and industrial chain contributes to increased energy demand and emissions. These findings confirm that, in the case of bio-based polymers, the environmental burden is largely driven by feedstock production rather than by manufacturing processes alone. In addition to raw material production, transport plays a relevant role in the PLA system due to the long-distance, multi-modal supply chain. The contribution of transcontinental logistics is reflected in higher values for acidification and photochemical ozone formation, further reinforcing the importance of supply chain configuration in the overall environmental performance. The PS system exhibits a different impact profile, characterized by a strong dependence on fossil resources. This is reflected in the highest values for abiotic depletion of fossil resources and in the dominance of non-renewable energy within the CED results. These impacts are directly linked to the petrochemical origin of polystyrene and the associated energy-intensive production processes. However, PS shows intermediate values in most other impact categories, highlighting a trade-off between resource depletion and overall environmental performance. The PAP system generally shows lower impacts in climate-related categories, particularly for GWP100, which can be attributed to the biogenic carbon uptake during tree growth. However, this apparent advantage is accompanied by significantly higher impacts in land use, as confirmed by the EF 3.1 results. This highlights an important trade-off: while paper-based materials may reduce greenhouse gas emissions, they can require substantial land resources, raising concerns related to land occupation and ecosystem pressure. The analysis of cumulative energy demand further supports these findings. PAP exhibits the lowest overall energy demand, with a relatively balanced contribution between renewable and non-renewable sources. In contrast, PS is dominated by non-renewable energy, while PLA shows a mixed profile, reflecting the combined influence of agricultural inputs, transport, and polymer processing. The application of two LCIA methods (CML and EF 3.1) provides an additional level of robustness to the results. Despite differences in characterization models and impact category definitions, both methods consistently identify PLA as the most impactful system and confirm the presence of trade-offs among the alternatives. This consistency strengthens the reliability of the comparative assessment. Finally, the normalization results highlight the dominant role of marine aquatic ecotoxicity (MAETP) across all systems. This contribution is mainly associated with upstream emissions embedded in background datasets, particularly those related to energy production and material processing. As the study adopts a cradle-to-gate perspective, these impacts are not influenced by end-of-life scenarios but rather by the characteristics of the supply chains and energy systems. It should be noted that the results are subject to uncertainties associated with background data, modelling assumptions, and variability in industrial processes. However, the consistent application of system boundaries, data sources, and modelling choices across all three systems ensures that the comparative conclusions remain robust. A summary of the main impact categories, the relative performance of the analyzed systems, and the key contributing factors linking inventory flows to environmental impacts is provided in Table 9.

Conclusions

This study presented a comparative LCA of ice cream cups made from PS, PLA) and PAP, based on a cradle-to-gate approach and supported by both CML and EF 3.1 impact assessment methods. The results consistently indicate that PLA is the most environmentally burdensome system across the majority of impact categories. This outcome is primarily driven by upstream processes, particularly agricultural production and polymer synthesis, which involve intensive use of fertilizers, water, and energy inputs. These processes significantly contribute to eutrophication, ecotoxicity, and climate-related impacts, highlighting that the environmental performance of bio-based materials is strongly dependent on feedstock production rather than solely on their renewable origin. In contrast, PS and PAP exhibit distinct impact profiles, revealing important trade-offs. PS shows a strong dependence on fossil resources, resulting in the highest impacts in abiotic depletion of fossil fuels and a predominance of non-renewable energy use. PAP, while demonstrating lower impacts in climate change and overall energy demand, shows significantly higher impacts in land use, as confirmed by the EF 3.1 results. These findings emphasize that no single material emerges as environmentally optimal across all categories, and that material substitution alone does not guarantee improved environmental performance. The application of two LCIA methods (CML and EF 3.1) confirmed the robustness of the comparative results, with consistent ranking of the systems and only minor variations in specific impact categories. This strengthens the reliability of the conclusions and highlights the importance of multi-method approaches in LCA studies. It should be noted that the present study focuses exclusively on the production phase. End-of-life scenarios, such as composting, recycling, or energy recovery, were not included and may influence the overall environmental performance of the analyzed systems. In particular, the potential benefits associated with PLA at the disposal stage remain to be further investigated. Overall, the results highlight the need to adopt a full life cycle perspective when assessing alternative materials, particularly in the context of bioplastics. The findings are consistent with current European regulatory approaches, such as the Single-Use Plastics Directive, which do not assume intrinsic environmental advantages for bio-based polymers. Finally, this study provides a robust basis for the development of Environmental Product Declarations (EPDs) for ice cream cups, supporting transparent communication of environmental performance and informed decision-making. Future research should integrate end-of-life scenarios and explore improvements in agricultural practices, material efficiency, and supply chain configuration to further reduce environmental impacts.

References

de Bruijn H, Van Duin R, Huijbregts MAJ, Guinee JB, Gorree M, Heijungs R, et al., 2002. Handbook on life cycle assessment: operational guide to the ISO Standards. Dordrecht, Springer.

Deshwal GK, Panjagari NR, Alam T, 2019. An overview of paper and paper based food packaging materials: health safety and environmental concerns. J Food Sci Technol 56:4391-4403.

European Bioplastics, 2023. Bioplastics market development update 2023: global production capacities 2023-2028. Berlin, Germany. Accessed on April 10, 2026. Available from: https://docs.european-bioplastics.org/publications/market_data/2023/EUBP_Market_Data_Report_2023.pdf

European Union, 2019. Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment. In: Official Journal, L 155/1, 12.6.2019, pp. 1-19. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32019L0904

European Union, 2023. Proposal for a Directive of the European Parliament and of the Council on substantiation and communication of explicit environmental claims (Green Claims Directive). COM/2023/166 final. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0166

Eurostat, 2022. Municipal waste by waste management operations. Available from: https://ec.europa.eu/eurostat/databrowser/product/page/ENV_WASMUN

Fonseca A, Ramalho E, Gouveia A, Figueiredo F, Nunes J. 2023. Life cycle assessment of PLA products: a systematic literature review. Sustainability 15:12470.

Guinée JB, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, et al., 2011. Life cycle assessment: past, present, and future. Environ Sci Technol 45:90-96.

International standards: ISO, 2006a. Environmental Management – Life Cycle Assessment – Principles and Framework. Norm ISO 14040:2006. International Organization for Standardization Publ., Geneva.

International standards: ISO, 2006b. Environmental Management – Life Cycle Assessment – Requirements and Guidelines. Norm ISO 14044:2006. International Organization for Standardization Publ., Geneva.

International standards: ISO, 2006c. Environmental Labels and Declarations – Type III Environmental Declarations – Principles and Procedures. Norm ISO 14025:2006. International Organization for Standardization Publ., Geneva.

Islam Md.M, Haque N, Lau D, Bhuiyan M, Pramanik BK, 2026. Environmental footprints of biological end-of-life strategies for residual post-consumer polylactic acid: A comparative life cycle assessment. Resour Conserv Recycl 231:108921.

Landis AE, Hobbs SR, Newby D, Wilson J, Pincus T, 2022. Environmental footprint and life cycle assessment of poly (lactic acid). In: RA Auras, L Lim, SEM Selke, H Tsuji (Eds.), Poly(Lactic Acid). Chichester, J Wiley & Son, pp. 541-558.

Moretti C, Hamelin L, Jakobsen LG, Junginger MH, Steingrimsdottir MM, Høibye L, Shen L, 2021. Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET. Resour Conserv Recycl 169;105508.

Plastics Europe, 2023. Plastics – the fast facts 2023: Enabling a sustainable future. Brussels. Accessed on: April 10, 2026. Available from: https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/

Sun M, Wang Y, Shi L, Klemeš JJ, 2018. Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: A systematic review and meta-analysis. Renew Sustain Energy Rev 92:823-833.

United Nations, 1987. Report of the World Commission on Environment and Development : "Our common future" [Brundtland report]. Report No. A/42/427. New York, United Nations. Accessed on: April 10, 2026. Available from: https://digitallibrary.un.org/record/139811?v=pdf

United Nations, 2024. Highlights 2023-2024: towards sustainable development for all. New York, United Nations, Department of Economic and Social Affairs. Accessed on: April 10, 2026. Available from: https://www.un.org/sites/un2.un.org/files/desa-highlights-report-2023-2024.pdf

Villanueva A, Wenzel H, 2007. Paper waste – Recycling, incineration or landfilling? A review of existing life cycle assessments. Waste Manag 27:S29-S46.

Vink ETH, Rábago KR, Glassner DA, Gruber PR, 2003. Applications of life cycle assessment to NatureWorks™ polylactide (PLA) production. Polym Degrad Stab 80:403-419.

Walker S, Rothman R, 2020. Life cycle assessment of bio-based and fossil-based plastic: A review. J Clean Prod 261:121158.

Table 1. Description of the functional unit used in the comparative LCA of ice cream cups.

Parameter	**Value / Description**
Functional unit	1 cardboard box containing 1,000 ice cream cups
Function served	It serves approximately 1,000 medium-sized ice cream portions
Box dimensions	27.00 cm × 43.00 cm × 32.00 cm
Box weight	0.900 kg
Sub-packaging inside the box	Polypropylene (PP)
Sub-packaging weight	0.15 kg
Materials of the cups analyzed	Polystyrene (PS), Polylactic Acid (PLA), Paperboard (PAP)
Nominal capacity of PS and PLA cups	130 cc
Nominal capacity of PAP cups	125 cc
Justification for capacity difference	Considered negligible
Mass of the functional unit (incl. cups + packaging)	PS: 5.35kg PLA: 6.40 kg PAP: 5.99 kg

Table 2. Physical characteristics of the different ice cream cups under study.

	PS	**PLA**	**PAP**
	46.0 mm	46.0 mm	44.0 mm
	80.0 mm	80.0 mm	75.5 mm
Mass	4.3 g	5.4 g	4.9 g

Table 3. Summary of main inventory parameters and modelling assumptions for the three systems.

Parameter	PS	PLA	PAP
Main cup material	Polystyrene	Polylactic acid	Paperboard + PE coating
Cup mass (g/cup)	4.3	5.4	4.9
Main material required per FU (kg)	7.65	10.157	5.00 kg blanks + 1.83 kg bottoms
Scrap generated per FU (kg)	3.36	4.80	Not separately quantified
Forming energy (kWh/FU)	0.704	0.704	3.61
Grinding energy (kWh/FU)	0.503	0.72	Not applicable
Printing energy (kWh/FU)	0.407	0.407	0.1538
Die-cutting energy (kWh/FU)	Not applicable	Not applicable	0.0769
Ink consumption (kg/FU)	0.016	0.016	0.023
Transport modelling	Road transport	Rail + ship + road transport	Road transport
Main transport distances	1,061 km	2,018 km rail + 7,700 km ship + 84 km road	2,622 km sheets + 2,573 km reels + 57.3 km printed blanks
Packaging	0.15 kg PP + 0.90 kg cardboard box	0.15 kg PP + 0.90 kg cardboard box	0.15 kg PP + 0.90 kg cardboard box

Table 4. Inventory data for a functional unit of PS cups.

	Amount	Unit
Input		
Natural gas	7.740	Sm^3
Energy, gross calorific value, in biomass	30.764	MJ
Energy, potential (in hydropower reservoir), converted	8.143	MJ
Energy, kinetic (in wind), converted	4.323	MJ
Energy, solar, converted	0.652	MJ
Water	47.789	m^3
Land	0.294	m^2
Oil, crude	8.441	kg
Carbon dioxide, in air	2.567	kg
Coal, hard, unspecified	1.943	kg
Gravel	1.839	kg
Carbon dioxide, non-fossil, resource correction	0.898	kg
Coal, brown	0.835	kg
Gangue	0.628	kg
Oxygen	0.582	kg
Calcite	0.343	kg
Shale	0.254	kg
Output		
Carbon dioxide, fossil	26.513	kg
Carbon dioxide, non-fossil	1.842	kg
Radon-222	1023.745	kBq
Noble gases, radioactive, unspecified	206.345	kBq
Water waste	47.443	m^3
Heat waste	5.692	MJ

Table 5. Inventory data for a functional unit of PLA cups.

	Amount	Unit
Input		
Natural gas	5.864	Sm^3
Energy, gross calorific value, in biomass	272.048	MJ
Energy, potential (in hydropower reservoir), converted	43.428	MJ
Energy, kinetic (in wind), converted	8.229	MJ
Energy, gross calorific value, in biomass (primary forest)	7.511	MJ
Energy, solar, converted	3.547	MJ
Water	201.678	m^3
Land	58.673	m^2
Carbon dioxide, in air	26.388	kg
Gravel	5.268	kg
Coal, hard, unspecified	6.031	kg
Gangue	5.292	kg
Calcite	2.693	kg
Oil, crude	1.845	kg
Coal, brown	1.979	kg
Shale	1.399	kg
Carbon dioxide, non-fossil, resource correction	0.915	kg
Oxygen	0.678	kg
Output		
Carbon dioxide, fossil	29.938	kg
Carbon dioxide, non-fossil	2.377	kg
Carbon dioxide, from soil or biomass stock	1.269	kg
Sulfate	0.715	kg
Radon-222	1576.468	kBq
Noble gases, radioactive, unspecified	439.272	kBq
Hydrogen-3 (Tritium)	39.327	kBq
Water waste	201.686	m^3
Heat waste	11.515	MJ

Table 6. Inventory data for a functional unit of PAP cups.

	Amount	Unit
Input		
Natural gas	2.486	Sm^3
Energy, gross calorific value, in biomass	222.654	MJ
Energy, potential (in hydropower reservoir), converted	12.771	MJ
Energy, kinetic (in wind), converted	5.972	MJ
Water	79.675	m^3
Land	1.404	m^2
Carbon dioxide, in air	20.044	kg
Gravel	4.604	kg
Oil, crude	2.092	kg
Coal, brown	2.039	kg
Carbon dioxide, non-fossil, resource correction	1.931	kg
Calcite	1.550	kg
Coal, hard, unspecified	1.431	kg
Kaolinite	1.239	kg
Gangue	0.990	kg
Oxygen	0.965	kg
Shale	0.639	kg
Output		
Carbon dioxide, fossil	13.704	kg
Carbon dioxide, non-fossil	11.977	kg
Sulfate	0.418	kg
Radon-222	1083.601	kBq
Noble gases, radioactive, unspecified	219.568	kBq
Radioactive species, other beta emitters	106.154	kBq
Water waste	79.643	m^3
Heat waste	8.676	MJ

Table 7. Environmental impact results for a functional unit of PAP, PLA, and PS cups according to CML methodology v4.8 (2016).

Impact category	PAP	PLA	PS	Unit
Acidification potential (AP)	4.27E-02	1.74E-01	1.01E-01	kg SO_2-Eq
Climate change – global warming potential (GWP100)	1.57E+01	3.71E+01	3.38E+01	kg CO_2-Eq
Ecotoxicity: freshwater aquatic ecotoxicity potential (FAETP)	1.10E+01	2.93E+01	8.66E+00	kg 1,4-DCB-Eq
Ecotoxicity: marine aquatic ecotoxicity potential (MAETP)	4.00E+04	3.77E+04	3.52E+04	kg 1,4-DCB-Eq
Ecotoxicity: terrestrial ecotoxicity potential (TETP inf)	1.74E-01	2.37E+00	1.09E-01	kg 1,4-DCB-Eq
Abiotic depletion potential (ADP): fossil fuels	2.26E+02	4.20E+02	6.88E+02	MJ
Eutrophication potential (EP)	3.18E-02	1.01E-01	1.98E-02	kg PO_4-Eq
Human toxicity potential (HTP)	1.55E+01	4.18E+01	1.11E+01	kg 1,4-DCB-Eq
Abiotic depletion potential (ADP): metals/minerals	5.67E-05	2.44E-04	3.32E-05	kg Sb-Eq
Ozone layer depletion potential (ODP)	4.43E-07	5.49E-07	1.64E-07	kg CFC-11-Eq
Photochemical ozone creation potential (POCP/NOx)	5.81E-03	1.03E-02	8.23E-03	kg ethylene-Eq

Table 8. Environmental impact results according to EF 3.1 methodology.

Impact category	**Unit**	**PAP**	**PLA**	**PS**
Acidification	mol H^+-Eq	0.0546	0.2425	0.1203
Climate change (GWP100)	kg CO_2-Eq	15.77	37.33	34.15
Climate change – Biogenic	kg CO_2-Eq	0.1547	0.0879	0.1193
Climate change – Fossil	kg CO_2-Eq	15.50	35.94	33.99
Climate change – Land use and land use change	kg CO_2-Eq	0.1237	1.304	0.0466
Ecotoxicity, freshwater	CTUe	81.88	564.00	35.95
Eutrophication, freshwater	kg P-Eq	0.00641	0.0140	0.00309
Eutrophication, marine	kg N-Eq	0.0160	0.0902	0.0204
Eutrophication, terrestrial	mol N-Eq	0.1523	0.7778	0.2133
Human toxicity, carcinogenic	CTUh	1.00E-08	1.94E-08	7.75E-09
Human toxicity, non-carcinogenic	CTUh	1.90E-07	4.42E-07	1.03E-07
Ionising radiation	kBq U235-Eq	1.767	2.810	1.664
Land use	dimensionless	1085	533.1	165.2
Ozone depletion	kg CFC-11-Eq	5.12E-07	6.26E-07	1.93E-07
Particulate matter	disease incidence	1.90E-06	2.11E-06	1.49E-06
Photochemical ozone formation	kg NMVOC-Eq	0.0589	0.1700	0.0896
Resource use, fossils	MJ	259.0	464.5	741.6
Resource use, minerals and metals	kg Sb-Eq	6.04E-05	2.40E-04	3.31E-05
Water use	m^3 world eq. deprived	16.94	76.49	20.05

Table 9. Summary of main impact categories, relative performance of the analyzed systems, and key contributing factors.

Impact category	Highest impact functional unit	Relative performance of others	Main contributing factors
Eutrophication potential (EP)	PLA	Dominated by agricultural phase (>95%); PAP and PS significantly lower	Agricultural inputs, nutrient emissions (nitrate and phosphate), eutrophication processes
Acidification potential (AP)	PLA	PS ≈ 58% of PLA; PAP ≈ 25%	Agricultural emissions; transport of PLA (rail and shipping)
Photochemical ozone creation potential (POCP)	PLA	PS ≈ 80% of PLA; PAP ≈ 56%	Agricultural phase and PLA transport
Global warming potential (GWP100)	PLA	PS ≈ 91% of PLA; PAP ≈ 42%	Agricultural energy inputs, transport; CO_2 sequestration reduces PAP impact
Abiotic depletion potential – fossil fuels (ADP fossil fuels)	PS	PLA ≈ 61% of PS; PAP ≈ 33%	Dependence on crude oil extraction and transformation
Abiotic depletion potential – metals/minerals (ADP metals/minerals)	PLA	PAP ≈ 23%; PS ≈ 14%	Agricultural inputs and processing chain
Freshwater aquatic ecotoxicity potential (FAETP)	PLA	PAP ≈ 38%; PS ≈ 30%	Agricultural runoff, pesticide use
Marine aquatic ecotoxicity potential (MAETP)	PAP	PLA ≈ 94%; PS ≈ 93%	Mainly linked to upstream background processes and energy-related emissions
Terrestrial ecotoxicity potential (TETP)	PLA	PAP ≈ 7%; PS ≈ 5%	Agricultural chemicals and soil emissions
Human toxicity potential (HTP)	PLA	PAP ≈ 37%; PS ≈ 27%	Agrochemical use and upstream processing
Ozone depletion potential (ODP)	PLA	PAP ≈ 81% of PLA; PS ≈ 30%	Upstream chemical processes
Cumulative energy demand (CED)	PS (highest)	PLA ≈ 1688 MJ-eq; PAP ≈ 1047 MJ-eq	PS: 94.5% from non-renewables; PLA: high share of both renewable and non-renewable; PAP: balanced mix (≈47% renewable, 53% non-renewable)

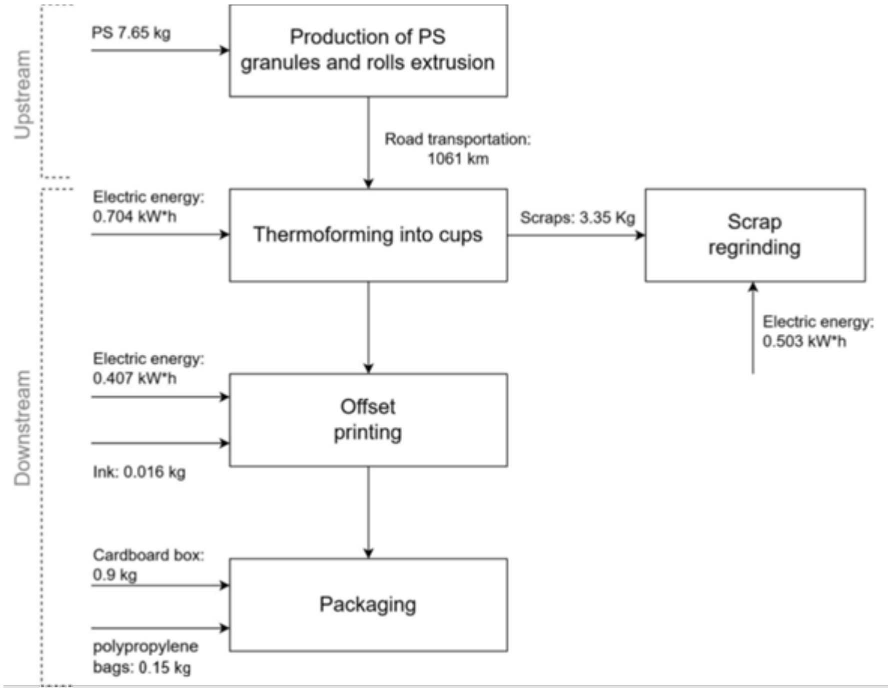

Figure 1. Life cycle inventory (LCI) associated with the production of a functional unit of PS cups (1,000 cups).

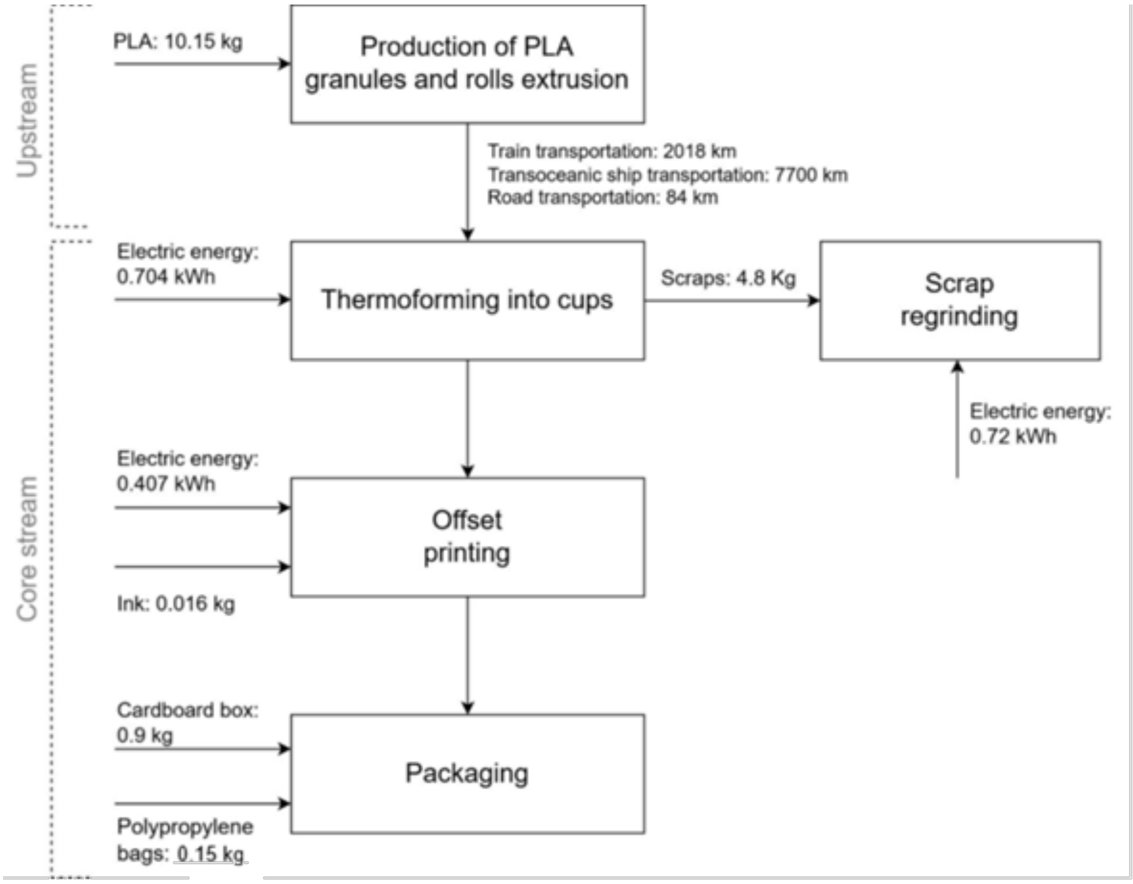

Figure 1. Life cycle inventory (LCI) associated with the production of a functional unit of PLA cups (1,000 cups).

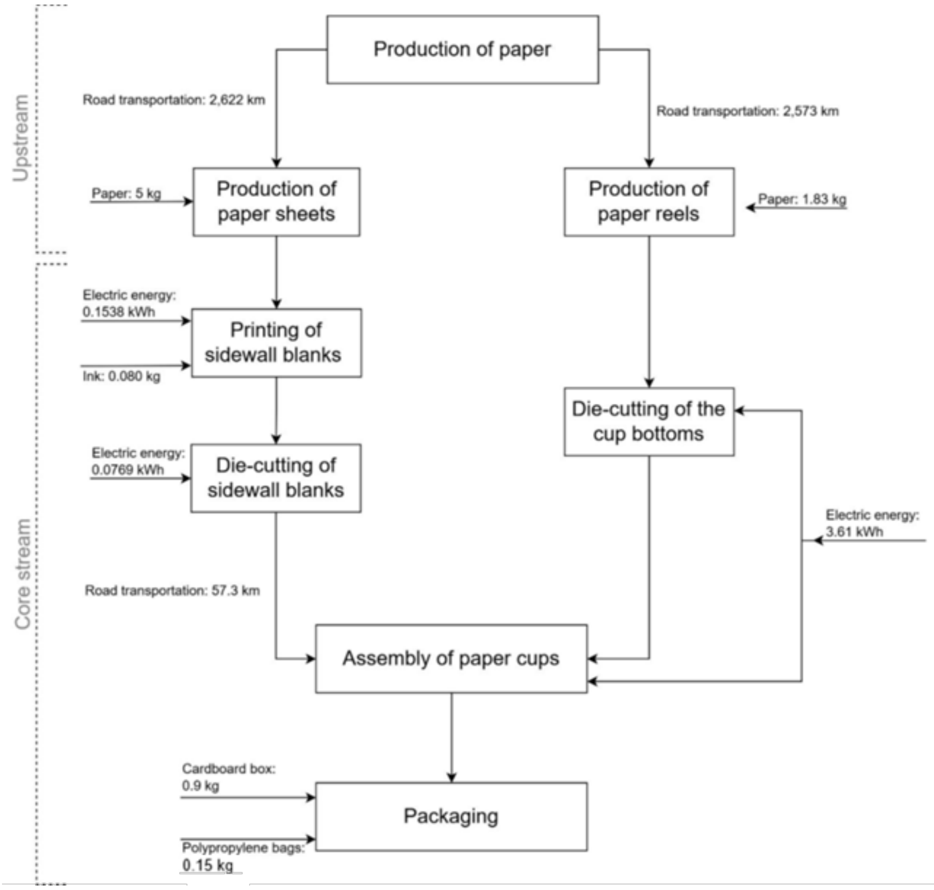

Figure 2. Life cycle inventory (LCI) associated with the production of a functional unit of paper cups (1,000 cups).

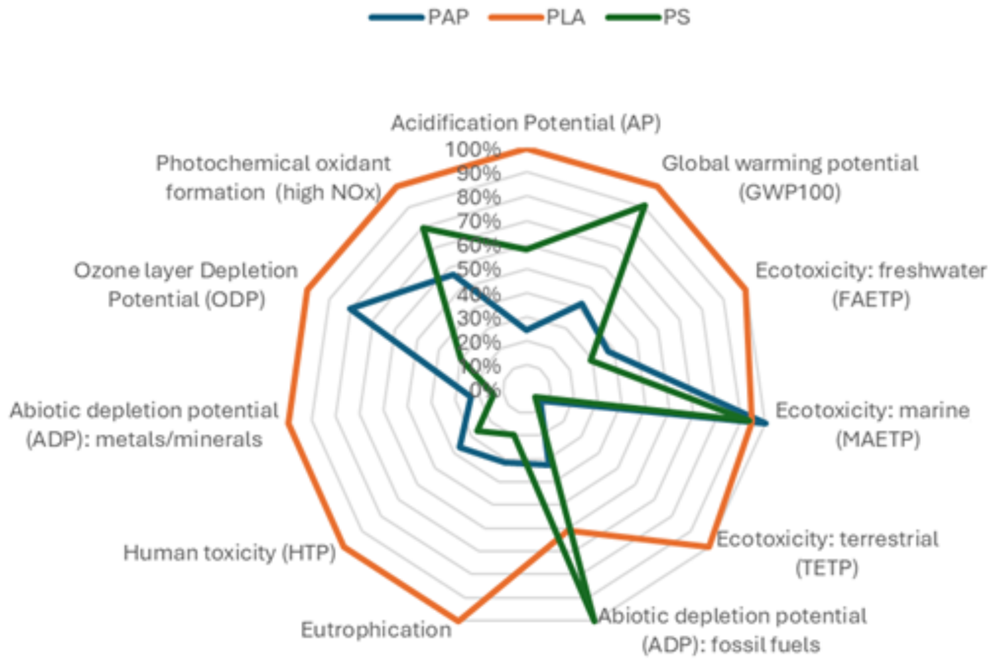

Figure 3. Spider plot of percentage scores for the functional units compared across impact categories defined by CML v4.8 impact assessment methodology (2016).

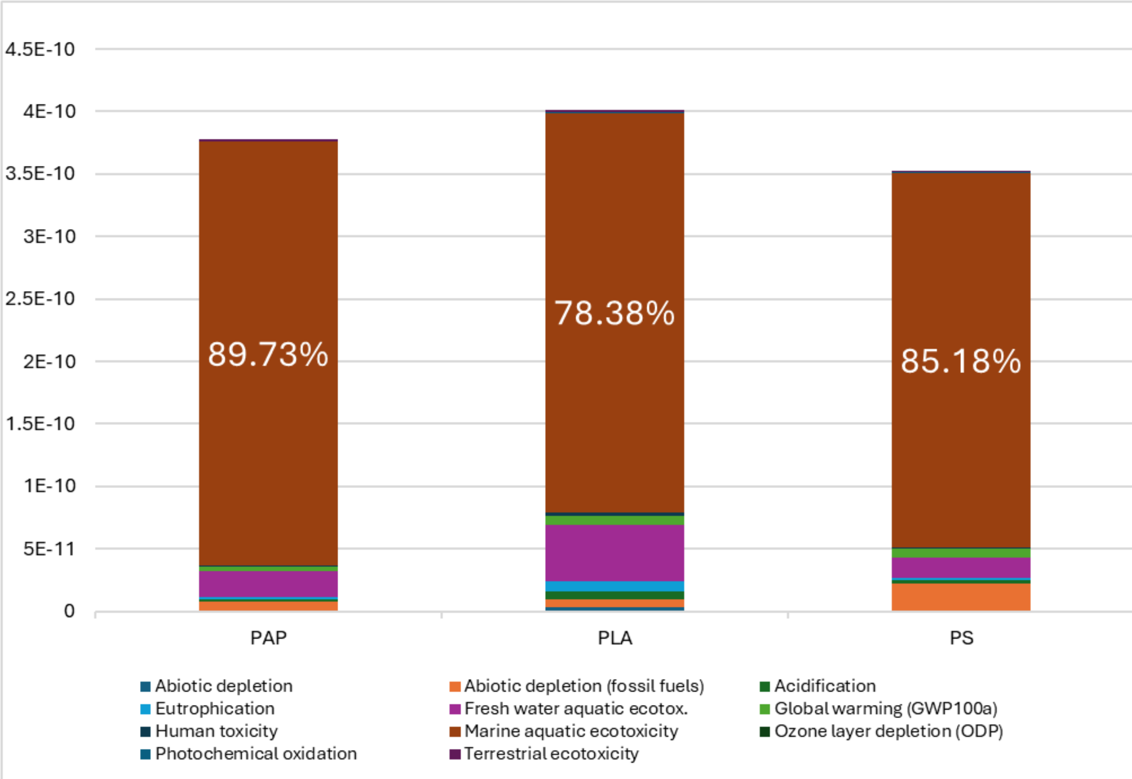

Figure 5. Normalized impact scores (EU25) for PAP, PLA, and PS units (bars show total impacts, with colors indicating category contributions. Y-axis values are normalized to the EU25 reference).