Biodegradable polymers for cosmetic packaging: A technical and life cycle perspective

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Abstract. The packaging industry is a significant contributor to the plastic pollution burdening our environment. One main issue with plastics is that they are designed to be durable, and so they persevere in the environment even after they have fulfilled their use. This study aims to analyse the potential benefits of switching to biodegradable and biobased polymers in the cosmetic packaging industry to lessen their environmental impact once disposed of. This assessment commenced with a sustainable material selection process to shortlist a set of viable biodegradable candidate materials (polylactic acid and wood plastic composites), for cosmetic compacts and then comparing them to acrylonitrile butadiene styrene as the benchmark material for this application. The functional, environmental and cost implications of such a change were quantified to validate the suitability of using biodegradable polymers. Functionally, polylactic acid and acrylonitrile butadiene styrene only passed the testing conducted making wood plastic composites an unviable option. wood plastic composites and polylactic acid were found to cost 40-53 per cent more than acrylonitrile butadiene styrene. In terms of the environmental impact, polylactic acid and wood plastic composites reduced the lifecycle impact by 18-30 per cent and the end-of-life impact by 26-42 per cent. The results obtained suggest great potential in shifting to such an alternative.

Introduction

People have become more aware of their impact on the environment, allowing sustainability to shape the way current businesses make long term decisions. This paradigm shift to sustainability is mainly brought about by consumer demand and legislation. Society demands that organisations become responsible corporate citizens and puts their money behind these demands. Therefore, businesses must shift to sustainable practices to remain competitive in today's market [1]. In the cosmetics industry, customers are seeking more eco-friendly products, this is substantiated by a projected natural and organic cosmetic market growth from €11.42 billion in 2021 to €17.35 billion by 2027 [2]. Moreover, fossil-based polymers are made from fossil fuels, a finite resource which is projected to run out by 2042 [3]. One benefit of using such materials is their relatively cheaper cost due to their popularity in the market. However, this will soon change, as the introduction of new regulations to cut down manufacturers' dependence on fossil fuels will lead to higher costs. In 2019, the global plastic production and incineration carbon footprint was estimated to be 850 Mt of CO_2. Such emissions could reach 1,340 Mt by 2030 and gradually increase to 2,800 Mt by 2050 [4]. By noting the accelerated growth of the bioplastic market, going from 2.11 million tonnes in 2018 to a projected 2.62 million tonnes in 2023, it is safe to assume that costs will be reduced as time progresses [5]. Therefore, it is imperative to explore alternative materials with lower carbon footprints throughout their whole life cycle.

A study conducted by Cinelli et al. commented on the unfeasibility of reusing or recycling cosmetic packages due to issues with post-use packaging collection and cleaning of residue contamination. Therefore, attaining a full circular economy proves to be challenging for the cosmetic packaging industry. They also commented on the vitality of considering the functional requirements of the cosmetic packaging when opting for a biodegradable alternative [6]. Various researchers discussed renewable materials such as PLA and WPC as being suitable candidates for cosmetic packaging due to their decent mechanical properties and affordable cost [7, 8]. Sebastião et al. took a Life Cycle Engineering cradle-to-grave approach to biodegradable material selection. When selecting a biodegradable polymer alternative, they evaluated each candidate material's environmental, financial, and functional benefits, correlating the three through a ternary diagram. Furthermore, by creating a Multi-Attribute Decision-Making process, Sebastião et al. could analyse the performance of the materials by correlating their mechanical properties with the product requirements. The environmental and economic effects were then defined using life cycle analysis (LCA) and life cycle costing methodologies. Finally, the suitability of biodegradable materials was determined, confirming that PLA was well suited for their application [9]. One limitation in this approach is the lack of consideration of biodegradability at EoL; moreover, a more detailed decision matrix would have corresponded to a more inclusive analysis.

After reviewing various literature in this field, the goals of this study were set to select and compare different biodegradable polymers suitable for the cosmetic packaging industry, from functional, environmental, and cost perspectives. Thus, concluding whether biodegradable materials are superior to fossil-based non-biodegradable materials in the cosmetic packaging industry.

Method and Materials

The method followed throughout this study is summarized in Fig. 1. The product definition was the first step in which the case study part for this assessment was selected by following the recommendations of the industrial partner of this study (Toly Products Ltd). The *infinity round compact* made from Acrylonitrile Butadiene Styrene (ABS) material, as seen in Fig. 2, was chosen having a production volume of 2 million compacts per year. In this assessment the term compact will be used to refer to the cosmetic packaging made up of the base and lid excluding any stainless-steel pins, mirrors or powder inserts.

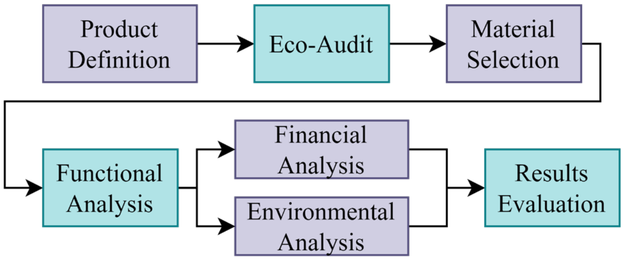


Fig. 1. Method Summary.

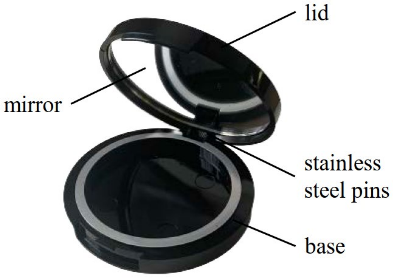


Fig. 2. Case Study Part.

Ansys Granta EduPack 2020 was used to conduct an 'eco-audit' on the case study part. This was used to establish the baseline energy and carbon footprints of the ABS compact at each life stage as shown in Fig. 3. This, together with the design requirements set by the industrial partner were used to create a translation table (Table 1) following the Ashby methodology [10]. By using the relative penalty function method, five materials were shortlisted: Polylactic acid (PLA), PLA with 30% natural fiber, PLA impact modified, Polyhydroxyalkanoates (PHA), Polycaprolactone (PCL) and wood plastic composites (WPC). The Ansys Granta EduPack synthesiser tool was used to create a material made of non-fibrous wood particles and PLA. This allowed for the inclusion of WPC in the assessment by incorporating it in the decision matrix constructed to rank the materials. The direct rating method was used to assign a unique weighting to each criterion in the decision matrix. Three main categories were highlighted and given equal importance: (i) *functional* (flexural strength, impact strength, density, and mould shrinkage), (ii) *financial* (cost), and (iii) *environmental* (biodegradability and carbon footprint). The ranking resulted in WPC placing first, followed by the datum ABS and then PLA placing third. ABS HI121H, PLA 4043D and WPC Sulapac Universal grades were procured.

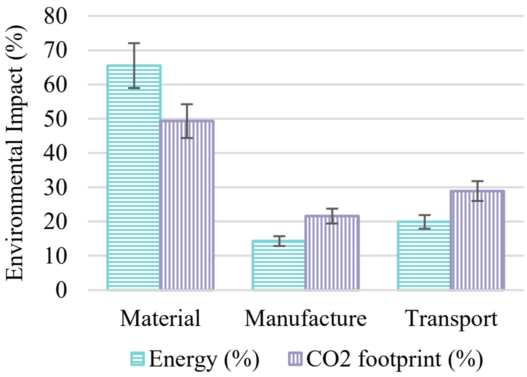


Fig. 3. Eco-Audit results for the Case Study Part.

Table 1. Material selection constraints and objectives.

Constraints	Geometrical: Radius; Thickness; Width Functional: 1. Must be biodegradable 2. Must be injection mouldable 3. Must support a flexural strength of F *[78MPa]* 4. The shrink rate must be like S *[0.4-0.7%]*
Objectives	1. Minimise Carbon Footprint 2. Minimise Embodied Energy 3. Maximise Impact Strength 4. Minimise Density 5. Minimise Cost

A thermal analysis using identiPol QA2 was performed on the materials to understand how their properties change with temperature. Three samples of ABS, PLA and WPC were run to build a database of these materials to be analysed by plotting Tan Delta and Stiffness vs Temperature plots. This equipment also allows the user to identify the contents of the tested material by running a quality index score test (QIS). Since WPC Sulapac Universal is a commercial material, this test was run to compare it to PLA due to an assumption that PLA was used as the biodegradable polymer matrix to which wood fibers were added. Therefore, ten samples of PLA were run through the identiPol QA2 to create a PLA reference dataset that could then be compared with WPC Sulapac Universal. Then, a score was generated between 0 and 10, 0 implying no match and 10 corresponding to a perfect match allowing the user to assume the composition of the material.

In terms of the quality analysis the standard procedure followed by the industrial partner to validate the compact's quality was adhered to. For the package integrity testing, an open-close cyclic test was performed, for which 400 open and close cycles were simulated. After 100 cycles, the compacts were checked to confirm whether the pins remained in the hinge. Furthermore, a drop test was performed on the compacts in which, five compacts were dropped with the compact base parallel and perpendicular to the ground from a height of one meter. The Mecmesin MultiTest 2.5dv force gauge was used to carry out the hinge break test, to determine the minimum force required to break the hinge, and a clip open test to determine the maximum force required to open the compacts' clip.

For the cost assessment the Part Cost Estimator tool available in Ansys Granta EduPack was used to allow for a cost comparison between the different materials. The tool required a series of cost and feature-related input data, from which it could estimate the manufacturing cost for one compact made from the different materials selected.

For the environmental assessment, a four step Life Cycle Assessment as shown in Fig. 4 (following ISO 14040:2006) using SimaPro 9.2 was used. Ecoinvent v3.3 was used for the inventory and impact assessment stages [11]. Furthermore, ReCiPe2016 (Hierarchist) was used as the impact assessment method to convert the life cycle inventories to a list of harmonised impact scores on a midpoint and endpoint level.

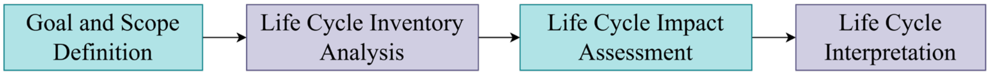


Fig. 4. LCA methodology.

The goals of the environmental LCA were as follows:

- Analyse and compare the impacts of the whole lifecycle of a PLA and WPC compact to those of an ABS compact.
- Compare the effects of different End-of-Life (EoL) scenarios i.e. (i) industrial composting, (ii) landfill, (iii) incineration, and (iv) recycling, for ABS, PLA and WPC compacts.

As for the scope of this assessment, the LCA was conducted for the base and lid of the compact, disregarding any pins and aluminium pans. Furthermore, a cradle-to-grave assessment was followed, neglecting the use and transportation phases. The use phase was ignored as the compact is a static object and thus consumes no energy or resources during its use phase. The transportation phase was also disregarded as it was assumed that similar routes would be followed by all three materials, thus having no significant influence on the overall environmental impact, given their relatively similar densities. Additionally, the functional unit, which is a quantified description of the system's performance was taken to be *2 million Infinity* Round Compacts. During the life cycle inventory assessment stage, the necessary inputs and outputs to evaluate the life cycle impacts of the compact were realised as highlighted in Table 2. The PLA and ABS readily available in SimaPro were selected for the raw material production phase. For WPC, the material was synthesised by first reviewing the material patent as in [12] and then relating this with the thermal analysis QIS test results. By noting that WPC Sulapac scored an 8 compared to PLA, it was assumed that it comprises 80% PLA and 20% wood fibers. As for the manufacturing phase, the injection moulding process was considered for all materials. For the EoL phase, landfilling, incineration, recycling, and industrial composting were considered. In Ecoinvent v3.3, there was no EoL scenario for industrial composting which was considered as an EoL scenario for the biodegradable polymers; thus, this was created by assuming that when the biodegradable compact is placed in an industrial composting facility, it transforms into carbon dioxide, water and humus as stated by NatureWorks in [13].

Table 2. Mass of raw material used per component.

Raw Material	Component	Volume (cm^3)	Density (g/cm^3)	Mass (g)
ABS	Lid	9.543	1.05	10.020
	Base	12.733		13.370
PLA	Lid	9.543	1.35	12.883
	Base	12.733		17.190
WPC	Lid	9.543	1.26	12.024
	Base	12.733		16.044

Following this, two assessments were conducted, (i) an EoL assessment and (ii) a Life Cycle assessment. For the latter, the EoL scenario considered was a mix of all scenarios. This was done as the probability of all the compacts ending up in the same waste disposal environment is highly unlikely as this depends on a series of factors such as the geographical location and product material. Therefore, the method adopted by Moretti et al. in [14] was implemented to model a complete life cycle of the compacts. For ABS, it was assumed that 30% was recycled, 39% was incinerated, and 31% was landfilled; for WPC and PLA, it was assumed that 15% was industrial composted, 15% was recycled, 39% was incinerated, and 31% was landfilled.

The results were interpreted by following the ReCiPe 2016 impact assessment method. This method follows a cause-and-effect pathway that allows for assessing the relationship between the inventories and their potential impacts. This addresses various environmental concerns at the midpoint level and then combines them into three endpoint categories, (in terms of damage to

Human Health, Ecosystems, and Resource Availability) allowing for a detailed and generalised assessment. The results obtained were then interpreted by first noting the impacts on the whole life cycle by switching from ABS to PLA and WPC, together with the effect of different EoL scenarios chosen. As highlighted in ISO 14040:2006, this phase must include the identification of significant issues highlighted throughout the assessment and an evaluation of the study itself [15]. This was done by first reviewing the life cycle inventory to confirm that the methods and data applied across the different materials were consistent and ensuring that long term emissions were considered in all scenarios.

Results and Discussion

Following the series of analyses conducted, the results were analysed to generate a comprehensive understanding of the impacts on the functional, cost and environmental factors when switching to PLA and WPC from ABS for the cosmetic compact case.

Thermal Analysis. From the Tan Delta vs Temperature graph shown in Fig. 5, the material's viscous to elastic response ratio was analysed. From the Tan Delta values at room temperature obtained, PLA registered the most significant Tan Delta value of 0.05 ± 0.01, followed closely by WPC at 0.03 ± 0.01 and then ABS at 0.02 ± 0.01. These values could imply that PLA has the relatively best energy absorption at room temperature. However, one must acknowledge that this is not related to the material's impact strength; thus, further functional testing is required to confirm such an assumption.

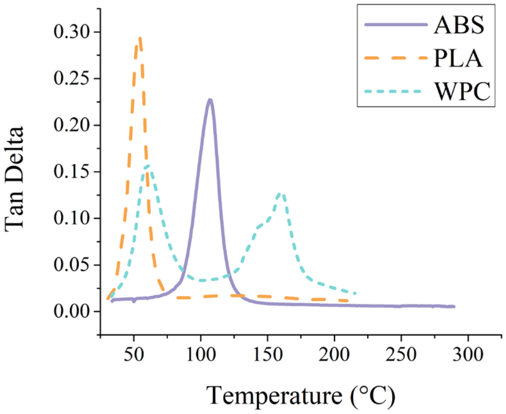


Fig. 5. Tan Delta vs. Temperature (˚C).

Furthermore, by noting the glass transition temperatures of the materials, ABS was the most thermally stable material, followed by PLA and WPC, which are relatively similar. The onset glass transition temperature for both PLA and WPC was initiated at approximately 40˚C, relatively close to room temperature. Therefore, when both compacts are used at temperatures above 40˚C (such as when the cosmetic compact is left in a car in summer), their structural integrity may not be upheld, and the compacts may warp or shrink depending on how excessive the temperatures are.

Table 3 summarises all thermal analysis results. ABS is an amorphous material, so no melting temperature was measured for this material. Furthermore, although PLA is a semicrystalline polymer, it behaved amorphously as no melting point was recorded. This is firstly due to its low crystallisation rate and secondly due to a relatively high cooling rate during the preparation of the testing samples. Therefore, the melting temperature of PLA listed in Table 3 was taken from its datasheet instead [16]. When comparing the WPC to PLA it was observed that the crystallisation rate increased for WPC, due to the presence of the wood particles, thus, resulting in a higher melting point.

Table 3. Thermal analysis results (Mean ± St. Deviation).

Material	Tan Delta at Room Temperature	Glass Transition Temperature (˚C)	Melting Temperature (˚C)
ABS	0.02 ± 0.01	108.50 ± 5.78	NA
PLA	0.05 ± 0.01	61.47 ± 2.25	145-160 [16]
WPC	0.03 ± 0.01	57.77 ± 1.85	187.77 ± 2.32

Quality Analysis. The results from the quality tests conducted were as seen in Fig. 6-9. Considering the overall performance of all three materials, PLA and ABS passed all tests, making PLA a viable biodegradable material for this case study part. WPC, on the other hand, while being visually attractive, was functionally inadequate. Throughout all the tests, the WPC compact was repeatedly failing from the hinge as a result of a low-quality weld line which was formed here, leading to the premature failure of the compact. It was assumed that the wood powder portion of WPC hindered the proper mixing of the two PLA melt flow fronts during injection moulding.

The injection moulded compacts were produced, having a relatively smooth surface finish. The PLA compact had a slight yellow tint which was not as attractive as the others. This may be improved by adding a colorant or master batch to cancel out the yellow tint. Furthermore, the PLA compact had visible streaks along the base, close to the injection point, as seen in Figure 6. These could be due to the low mobility of the polymer and could be avoided by increasing the melt temperature and back pressure during the injection moulding process as well as by adding a colorant. In all cases, there were no pronounced defects on the compact surfaces and all in all, they had a good surface finish.

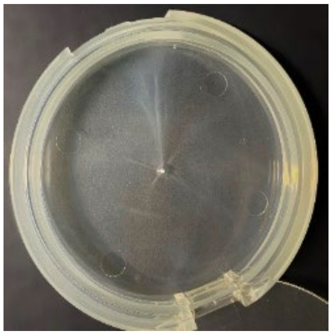


Fig. 6. Streaks along PLA base.

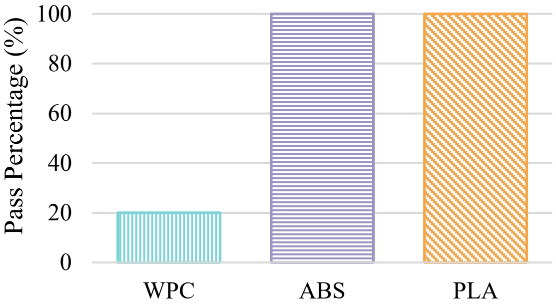


Fig. 7. Drop Test.

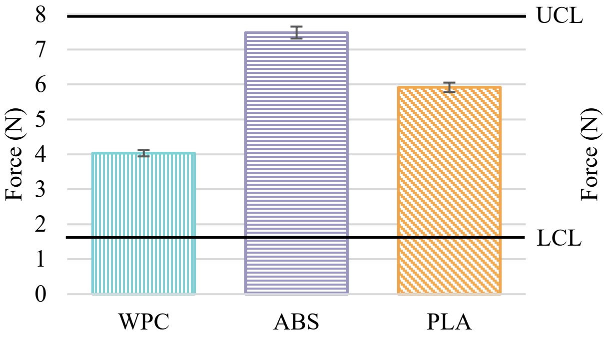


Fig. 8. Clip Opening Test (UCL = 8N, LCL =1.5N).

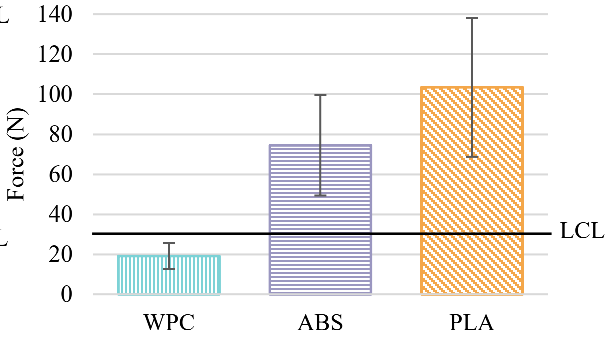


Fig. 9. Hinge Break Test (LCL = 26.5 N).

Cost Assessment. The cost per compact of ABS was €0.15, WPC was €0.21, and PLA was €0.23. The first observation was that biodegradable alternatives cost 40-53% more than ABS. This may be attributed to ABS's relatively more significant market presence. WPC and PLA compacts cost relatively alike, having only a 9% difference between them, which may seem minuscule, however, considering the yearly production of two million compacts, this difference will sum up to 40,000 EUR/yr. This distinction in price may be mainly attributed to the discrepancy in material cost rather than processing related costs.

Environmental Analysis. During the environmental assessment, three endpoint indicators were examined to obtain an understanding of the impact in terms of the effect on human health, resource availability and the ecosystem. To then generate a more in-depth assessment, the midpoint categories were used, allowing for a detailed understanding of the generated impact.

Life Cycle Assessment. After modelling the whole life cycle of the compacts, the relationship as seen in Fig. 10 was obtained by considering the total weighted impact of the three endpoint categories, which is the summation of the impact of the three endpoints. ABS had the overall highest environmental impact throughout its lifecycle. Opting for a WPC compact was found to correspond to a 35.2% reduction in life cycle environmental impact when compared to an ABS compact. Alternatively, opting for a PLA compact would lower the environmental impacts of the whole life cycle by 19.5%. During the material production phase, PLA generated the relatively most significant impact, 23.3% higher than that of ABS. WPC, however, generated relatively the same impact as ABS material production. Therefore, one may conclude that by increasing the content of wood powder in the PLA matrix for WPC, the impact during this life phase may be reduced. Moreover, for the manufacturing phase the biodegradable materials generated a more significant impact on the environment than ABS. The injection moulding of the PLA compact generated a 16.3% higher environmental impact than ABS, and WPC generated a 17.8% higher impact than ABS. This distinction corresponds to the relatively higher energy required and carbon footprint linked to the injection moulding of WPC and PLA [10].

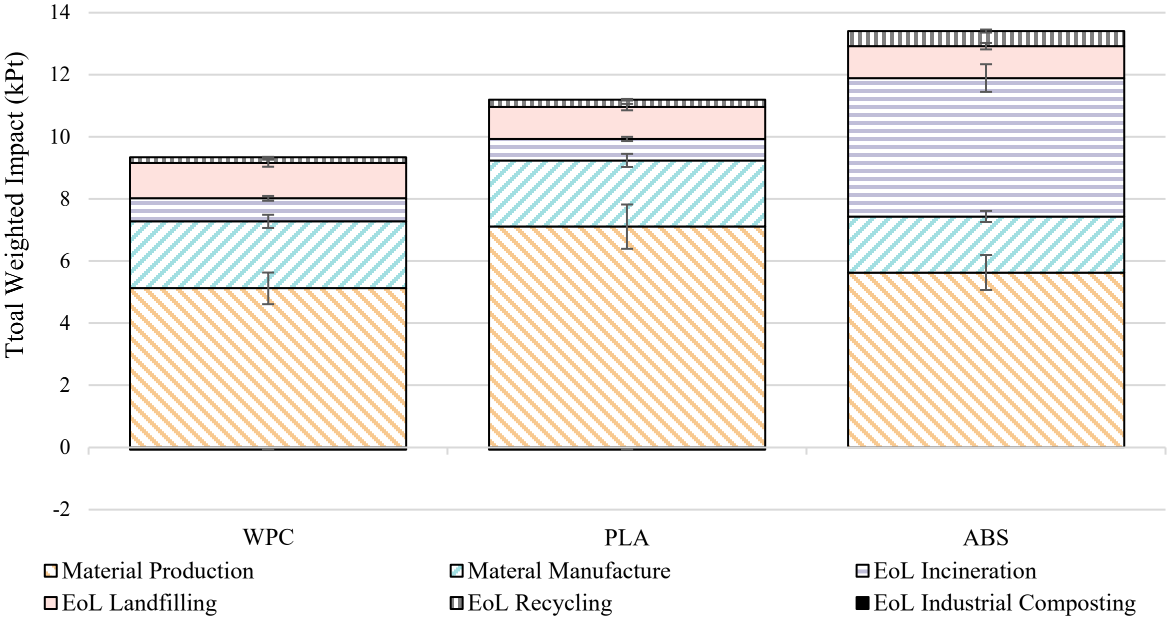


Fig. 10. Total weighted impact of the compact life cycle.

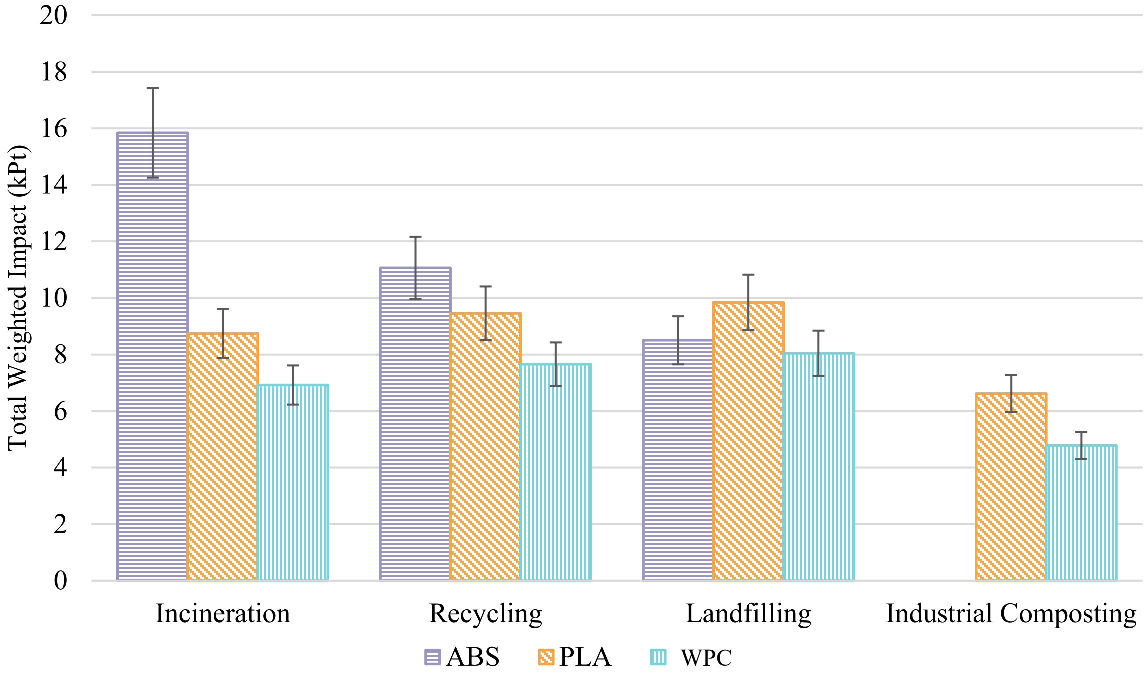
End-of-Life Assessment. In this assessment the EoL scenario was analysed by generating a total weighted impact score of the three endpoints as seen in Fig. 11. This allowed for the complete visualisation of the environmental impact of each EoL scenario.

If one were to assume that the compacts would be incinerated at EoL, opting for PLA would generate a 57.8% smaller environmental impact than ABS and WPC would generate a 78.4% smaller impact than ABS. This distinction could be linked to the carbon dioxide given off during incineration, corresponding to 314,000 kg CO_2 eq for ABS, which was found to be 62.2% more than PLA and 82.9% more than WPC. Additionally, ABS contributed to the emission of 49,600 kg CO_2 eq of methane, which was significantly much more than that of PLA and WPC.

In terms of recycling and landfilling the variation in the results is not as significant as with incineration. With recycling, opting for PLA would reduce the environmental impact by 15.6% and opting for WPC would reduce the impact by 36.3% than ABS. From a midpoint analysis, recycling ABS ranked relatively high, as a substantial amount of waste was being generated, which in turn was ending up being incinerated. Furthermore, in terms of carbon dioxide emissions during recycling, ABS was found to emit 155,000 kg CO_2 eq, which was 37.5% higher than PLA and 76.2% higher than WPC.

When considering landfilling as an EoL option, PLA generated the most significant impact, while ABS and WPC had relatively the same overall impact. The 14.6% difference between PLA and WPC and the 20.1% difference between PLA and ABS may be attributed to the higher biogenic methane gas emissions of biodegradable materials when landfilled. When a biodegradable material is placed in a landfilling facility, it undergoes anaerobic digestion due to the lack of oxygen, resulting in the emission of excessive biogenic methane gas [17]. When landfilling WPC and PLA, more than 650 kg/year of biogenic methane gas would be given off than when landfilling ABS.

In terms of the industrial composting scenario, the impacts of both WPC and PLA were the lowest out of all other scenarios. The 32.3% difference in environmental impact between the two may be attributed to the 20% wood fibres considered in the WPC material. In fact, one common trend across all EoL scenarios is the relatively lower impact of WPC to PLA which is linked to the wood fibre in the PLA matrix. Therefore, it may be assumed that by increasing the wood content, the environmental impact may be reduced.



Summary

The target objectives of this study were met as the evaluation of using biodegradable materials in the cosmetic industry was made in terms of the functional, cost and environmental categories. Following this assessment, PLA was recommended as a viable biodegradable alternative to ABS, as it generated a 19.5% lower life cycle environmental impact to ABS and when considering the EoL scenarios for PLA, it generated a 57.8% lesser environmental impact during incineration which is the most likely EoL scenario for cosmetic packaging [6]. Furthermore, PLA was recommended as it passed all functional tests carried out at the industrial partner, at times performing better than ABS, the datum material of this study. The downside of using PLA is that it costs 53% more than ABS. However, this distinction is projected to decrease once biodegradable polymers establish themselves more on the polymer market. Also, by considering the ever-increasing costs of the fossil-based polymers, ABS may no longer be a viable option in the near future. One must mention that WPC was not recommended as the biodegradable alternative to ABS simply because of its failure to pass the quality functional tests. Had WPC passed the hinge break test, and the drop tests it would have been a relatively better material than PLA in terms of both cost and environmental impact, and so should not be completely disregarded for its application in the cosmetics packaging industry. The results of WPC break test can significantly be improved simply by positioning the weld line away from the hinge area, which in turn can be accomplished by changing the position of the injection gate.

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