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# Eco-design of the remembrance poppy: a life cycle assessment study†

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The Remembrance Poppy is an iconic artificial flower that is prevalently worn in Commonwealth countries in the period preceding the Remembrance Day to commemorate their military personnel. The current version of the Remembrance Poppy is a multi-material design made of fossil plastic (*i.e.*, light-density polyethylene, LDPE) and paper; this prevents its widespread recycling and ascribes the Poppy to the realm of single-use plastics. In this study, we quantify the environmental performance of the current and alternative designs of the Remembrance Poppy *via* a detailed Life Cycle Assessment (LCA), with the objective of supporting decision-making by the Royal British Legion Group, whose group charities provide the Remembrance Poppy across the UK. We consider two alternative designs: (i) one envisaging an increased recycled content (30% for LDPE and 50% for paper) compared to the current design and (ii) a novel, mono-material design fully made of paper. For the latter we consider three sub-scenarios with increasing recycled content from 50% to 100%, as well as two options considering or not recycling of the Poppy at the end of its life. The system boundaries are cradle-to-grave. The inventory data combines primary data collected from RBL group and a paper supplier, and secondary data from LCA databases. The environmental impacts are quantified *via* the Environmental Footprint 2.0 method. The LCA study indicates that the paper-based design is overall the environmentally preferable option, yielding environmental benefits (after normalization and weighting) ranging from 39% to 59% compared to the current design, according to the specific scenario. The recycled-content plastic-based design is also preferable but by a smaller amount (11%). The study highlights the importance of using increasing percentages of recycled content, as well as that of designing product that are recyclable at the end of their life, which are tenets of the Circular Economy paradigm.

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### Sustainability spotlight

Plastics production has increased twentyfold since 1964 but only a small portion is recycled globally, with the majority being incinerated, landfilled or, even worse, leaked to the oceans. The Ellen MacArthur Foundation estimates that about 8m tonnes of plastics leak into the ocean every year and that by 2050 there will be more plastics than fish (by weight). Plastic waste is a failure of design that generates significant environmental impacts as well as economic burdens. This study shows how Life Cycle Assessment can be used to support the re-design a product (the iconic Remembrance Poppy) by reducing environmental impacts across its life-cycle. The study therefore supports SGD 12 Responsible Consumption and Production. It also links to SDG 13 (Climate action), SGD 14 (Life Below Water) and 15 (Life on Land) by reducing carbon emissions and waste generation that can pollute land and oceans.

## 1 Introduction

The Remembrance Poppy is an artificial flower that is worn in some countries – most commonly in the Commonwealth – to commemorate their military personnel who died in war. In the United Kingdom (UK) and most other Commonwealth countries, the Poppy is worn in the weeks leading up to the Remembrance Day, a Memorial Day observed since the end of World War One. The Poppy was adopted as a symbol of remembrance because it was the only flower that grew on the battlefields after World War One ended, as described in the famous poem "In Flanders Fields".

In the UK, the Remembrance Poppy is sold by the Royal British Legion and Poppyscotland, which are British charities providing financial, social and emotional support to members and veterans of the British Armed Forces, their families and dependants, as well as all others in need. The UK yearly Poppy Appeal has expanded significantly, now including 40 000 volunteers distributing approximately 30 million poppies. In its current design, both the RBL's and Poppyscotland's Poppy is made of multiple materials including fossil plastics, paper and metal, and is worn from one day and up to a week on average, after which it is disposed of. Although the Poppy is re-used by some supporters

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and is recyclable if disposed of at specific collection points (*e.g.* some supermarkets) in practice it is rarely re-used or recycled and most commonly it is disposed of as part of general household waste which is destined to incineration or landfilling.[1]

The Poppy's current designs can thus be considered in the realm of single-use plastics, which have attracted increasing public attention in the UK and elsewhere, particularly in relation to ocean pollution but also because of the connection with the fossil fuel industry which drives climate change. In addition to this, the single-use aspect comes in contrast with the principles of the circular economy, a new paradigm that promotes moving away from the "take-make-dispose" of the traditional linear economy to a more efficient use of natural resources and minimisation of waste.[2] For the above reasons, RBL has committed to remove and/or reduce the use of single use plastics from their products, including the Poppy, and investigate alternative materials – which is the focus of this study.

The practice of including environmental aspects in the design (or re-design, as in this case) of a product is named "eco-design". It is key because the vast majority (up to 80%) of environmental impacts are determined in the very early phases of product development.[3] The goal of eco-design is to minimise environmental impacts throughout the product's life cycle, without compromising other essential criteria such as performance, functionality, aesthetics, quality and cost.[4,5]

Life Cycle Assessment (LCA) is arguably the most appropriate tool to support eco-design, and has been widely applied to this end,[6,7] for example in the automotive sector,[8] bio-based products,[9] photovoltaic technologies,[10] aquaponics for food and vegetables production[11] and as part of CAD (Computer-Aided Design) software applications.[12] LCA is a standardised methodology for quantifying the environmental impacts of products or services in a holistic way.[13,14] It considers a wide range of environmental issues, which include but are not limited to climate change, and quantifies impacts that arise throughout the life cycle, from the extraction of raw materials to the disposal of waste (*i.e.* from "cradle to grave"). This holistic approach enables identifying trade-offs amongst alternative scenarios, thus supporting robust decision-making.

This article showcases how LCA can support the decision-making process to re-design the iconic RBL Remembrance Poppy with the objective of reducing its environmental impact. The article has three specific objectives: first, to quantify the environmental impact of the current and alternatives designs of RBL's Poppy and identify key hot-spots; second, to develop a detailed comparative analysis considering alternative designs made from different materials; and third, to identify the most environmentally advantageous design. Although this study is specifically focused on RBL's version, the results can be extended to the Poppyscotland version because of their similar design, as explained in Section 2.

## 2 Methods

### 2.1 System description

RBL's Poppy is comprised of 5 parts: a green stem, a black pistil, green leaves, a red petal and a metallic pin, which binds together all parts (Fig. 1). In the current design (termed baseline; Fig. 1, left), the stem and pistil are made of virgin low-density polyethylene (LDPE) plastic, and the leaves and petal of virgin paper. Although each individual part is recyclable, the mix of materials and weight makes this practically unattainable in a country like the UK where recyclable materials are not separated at the source. For this reason, at the end-of-life the Poppy is commonly disposed of as general household waste, which in the UK is either incinerated (primarily) or landfilled.[1]

Fig. 1 Image of RBL's Remembrance Poppy. Left: baseline design. Right: Paper-based design.

To reduce the environmental impacts of the Poppy, RBL is considering either increasing the use of recycled materials and/or replacing the plastic components. The scenarios that we considered in this work are summarised in Table 1. The first scenario (S1) envisages increasing recycled content whilst keeping the plastic components. Specifically, S1 assumes the use of LDPE plastic with a recycled content of 30% for both the stem and black pistil, whilst the paper parts (leaves and petals) are made of paper from a mix of 50% virgin and 50% recycled pulp. The 30% recycled content is based on technical feasibility of existing machineries used by RBL suppliers, but it also aligns with current policy direction for plastic products.[15] An additional aspect worth considering is that in the UK plastic product with 30% recycled content are exempt from the plastic packaging tax.[16] The recycled pulp is assumed to be produced from clean coffee cups (post-industrial waste) *via* a process known as developed by James Cropper,[17] a paper supplier in the UK; the 50% ratio is based on an existing product from James Cropper. The alternative scenario assumes a new mono-material design made of paper (depicted in Fig. 1, right), with the same composition as mentioned above (named S2-50). As a sensitivity analysis, we also considered two additional scenarios for the paper-based Poppy with increasing ratios of recycled pulp from clean coffee cups of 75% (S2-75) and 100% (S2-100), with the objective of investigating the effects on the environmental performance of increasing the recycled content of paper.

In S1, the recycled-content plastic-based Poppy is assumed to be disposed of as general waste because of the multi-material nature of the Poppy which is similar to that of the baseline. However, the paper-based mono-material design (S2) can be

Table 1 Summary of current and alternative scenarios for the Remembrance Poppy. PIW: Post-Industrial Waste

| | Stem | Black pistil | Leaves | Petal | Pin |
|---|---|---|---|---|---|
| Baseline | Virgin LDPE | | Virgin paper | | Metal wire |
| Scenario 1 (S1): plastic recycled content | 30% recycled LDPE + 70% virgin LDPE | | 50% recycled pulp from PIW + 50% virgin pulp | | |
| S2: paper design | S2-50: 50% recycled pulp + 50% virgin pulp<br>S2-75: 75% recycled pulp + 25% virgin pulp<br>S2-100: 100% recycled pulp | | | | |

disposed of in the recycling bin. Therefore, for S2 we considered two different end-of-life pathways: a pessimistic scenario where the paper Poppy continue to be disposed of as general waste (like in S1), and an optimistic scenario foreseeing disposal with recyclable materials and complete recycling.

## 2.2 Goal and scope

This LCA study is aimed at evaluating the environmental impacts of current and alternative designs of the Remembrance Poppy to support decision-making by RBL. The main function of the Poppy is to raise charitable funding for the Royal British Legion. The functional unit is the production of Poppies to be sold to and used by the public, and the reference flow has been taken equal to one Poppy. The latter implies that inventory data (reported in Table 3) and the estimated environmental impacts (discussed in Section 3) refer to one Poppy.

The system boundaries are "cradle-to-grave", meaning that they include all activities along the life cycle of the Poppy from the extraction of raw materials to the waste treatment; these are shown in Fig. 2 for the baseline and S1 designs and Fig. 3 for S2. The foreground system includes the production of the Poppy's components whilst the background system includes all other processes that are outside RBL's direct influence and that typically interact with the foreground system *via* a market.[18] The distribution (*e.g.* to volunteers) and sale of poppies are considered out of the scope of the study. The material composition of the Poppy (described in Section 2.1) was provided by RBL. Secondary data from technical reports, scientific literature and LCA databases, *i.e.* Sphera and ecoinvent[19,20] was used to fill gaps in primary data as well as for activities in the background system.

We developed the LCA model using the software GaBi (now "LCA for Experts"),[19] and quantified LCA results *via* the environmental characterisation models collated by the European Commission within the Environmental Footprint (EF) package 2.0;[21] the environmental categories considered are reported in Table 2. Notably, we chose to use version 2.0 of the EF instead of the more recent 3.0 due to compatibility with weighting factors, as explained below.

We normalised and weighted environmental impacts to rank the design options and thus support decision-making. We first normalised environmental impacts using the factors developed by Sala *et al.*[22] for the EF2.0 method, which are reported in Table 2. These represent global carrying capacities for categories of the Area of Protection (AoP) Natural Environment and tolerable/acceptable level of pollution for the AoP Human Health, whilst they adopt a "Factor 2" approach, *i.e.* reduction of 50% of resources use, for the AoP Resources. The normalised results were aggregated to obtain a single environmental score using weighting factors developed by Sala *et al.*[23] for use with the EF2.0 and then modified by Chau *et al.*[24] to be consistently adopted with the normalisation factors mentioned above.[22]

## 2.3 Inventory data: modelling and main assumptions

The bill of materials for one Poppy was provided by RBL and is reported in Table 3. The baseline and scenario 1 have the same

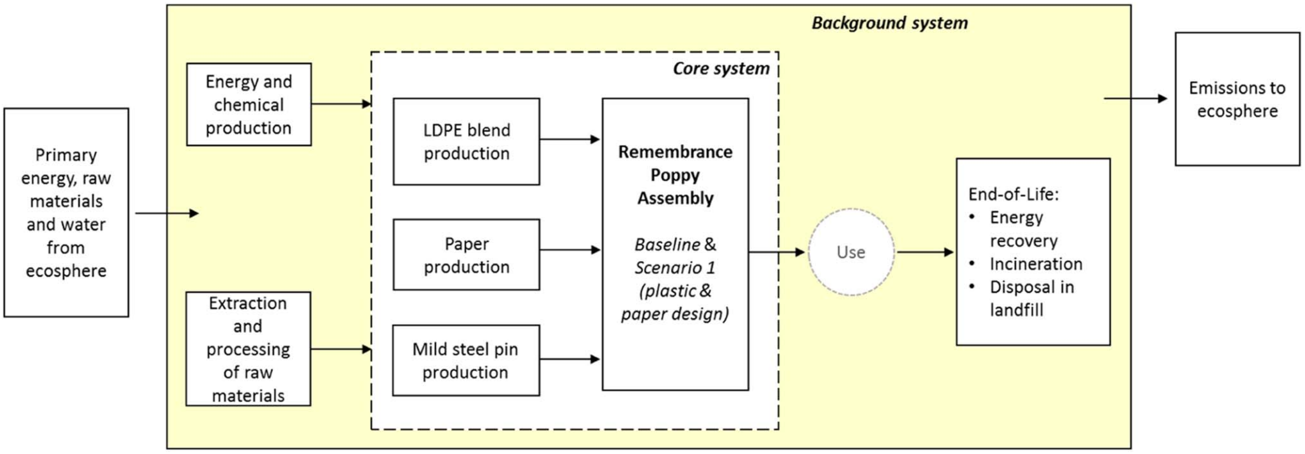

Fig. 2 Schematic of the "cradle-to-grave" system boundaries considered for baseline and scenario 1 (S1) designs. *Incineration refers to the option without energy recovery.

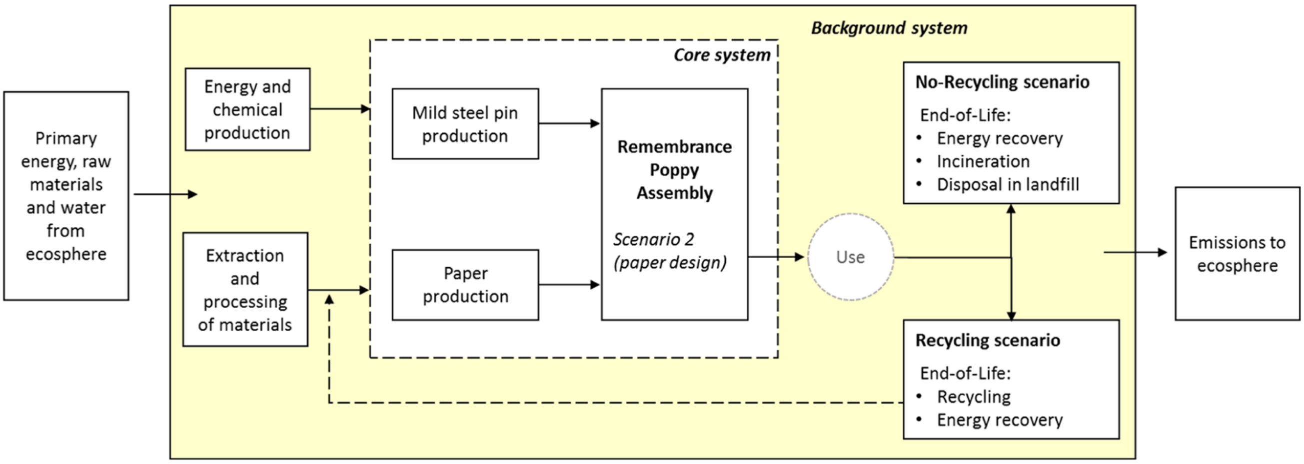

Fig. 3 Schematic of the "cradle-to-grave" system boundaries considered for scenario 2 (S2) design. *Incineration refers to the option without energy recovery.

Table 2 Normalisation and weighting factors

| Impact categories EF 2.0 | Units | Normalisation factors, per year/capita | Weighting factors |
|---|---|---|---|
| Acidification | Mole of H$^+$ equivalent | $1.45 \times 10^{2}$ | 5.44 |
| Climate change | kg $CO_2$ equivalent | $9.85 \times 10^{2}$ | 17.76 |
| Ecotoxicity freshwater | CTU$_e$[a] | $1.90 \times 10^{4}$ | 4.21 |
| Eutrophication, freshwater | kg P equivalent | $8.40 \times 10^{-1}$ | 3.51 |
| Eutrophication, marine | kg N equivalent | $2.90 \times 10^{1}$ | 3.24 |
| Eutrophication, terrestrial | Mole of N equivalent | $8.87 \times 10^{2}$ | 3.25 |
| Human toxicity, cancer effects | CTU$_h$ | $1.39 \times 10^{-4}$ | 4.68 |
| Human toxicity, non-cancer effects | CTU$_h$ | $5.93 \times 10^{-4}$ | 4.05 |
| Ionizing radiation | kBq U235 equivalent | $7.62 \times 10^{4}$ | 6.28 |
| Ozone depletion | kg CFC-11 equivalent | $7.49 \times 10^{-5}$ | 7.68 |
| Particulate matter | Disease incidences | $5.88 \times 10^{1}$ | 7.56 |
| Photochemical ozone formation | kg NMVOC equivalent[b] | $3.24 \times 10^{4}$ | 5.24 |
| Resource use, fossils | MJ | $3.17 \times 10^{-2}$ | 6.09 |
| Resource use, mineral and metals | kg Sb equivalent | $2.63 \times 10^{4}$ | 5.52 |
| Water use | m$^3$ world equivalent | $9.85 \times 10^{2}$ | 8.01 |

[a] Comparative toxic unit [b] Non-methane volatile organic compounds

material composition (although S1 uses recycled materials) and therefore the same weight (~1.12 g). Scenario 2 is based on a paper design, which results in lower overall weight (~0.48 g). We made several assumptions on the components' upstream manufacturing processes. For plastic parts (stem and black pistil), we assumed that they were produced from LDPE granulates *via* moulding using inventory data provided in the Sphera database. Note that since the moulding process typically generate negligible losses (<3%) we did not consider the disposal of the manufacturing waste. We also assumed that plastic recyclates are obtained *via* mechanical recycling of post-consumer waste, using Sphera inventory data that includes transportation as well as washing, separation, granulation and pelletization.

For the other parts, we only considered the production process related to the material (*e.g.* paper) and not further processes to manufacture the required shape. The production of paper from virgin pulp was assumed to occur *via* a chemi-thermomechanical process based on data from the ecoinvent database, whilst that for recycled pulp from clean coffee cups (post-industrial waste) was based on the process developed by James Cropper; the underlying inventory data cannot be reported due to confidentiality reasons. Unlike for the plastic-based design, the paper design generates significant amount of

Table 3 Bill of materials for one Poppy

| Component | Baseline & S1 | S2 |
|---|---|---|
| Stem | 0.5 g | 0.33 g |
| Black pistil | 0.3 g | |
| Leaves | 0.17 g | |
| Petal | 0.14 g | 0.14 g |
| Pin | 0.0077 g | 0.0077 g |
| Total weight | 1.12 g | 0.48 g |

waste paper during the manufacture of the poppy, specifically from cutting the paper strips; this waste amounts to 0.51 g of paper per Poppy (which is comparable with the overall weight of the Poppy; see Table 3). We assumed that this wastepaper is fully recycled. In the ESI† we also report the Bill of Materials (and a picture) of the Poppyscotland version, which differ for two aspects: the absence of the leaves and a slightly heavier petal (0.16 g); the Poppyscotland Poppy is lighter than RBL's version with a total weight of 0.96 g.

Secondary data from LCA databases – Sphera[19] and ecoinvent v3.7, cut-off system[20] – were used for modelling production of energy and remaining materials, and end-of-life treatments, using as geographical reference the UK, where available. In the ESI† we report all datasets used in the LCA model. The production of ink was not considered, for two reasons: lack of data related to the process of ink production, and low contribution to the overall environmental impacts, as reported in a study by Ecomatters.[25] We also did not consider the transportation of raw materials and waste and the production of plastics additives due to lack of data.

For the end-of-life of the plastic-based Poppy and no-recycling scenario of the paper-based version, we assumed that the Poppy is disposed of as general waste; in 2020 in the UK around 46% of this waste is incinerated with energy recovery, 18% without energy recovery and 34% is disposed of in landfill.[1] For the recycling scenario of the paper-based Poppy, it was assumed a 100% collection efficiency and an 81% recycling efficiency based on data provided by James Cropper. Note that we did not explicitly consider the potential effects of additives on the recycling efficiency of plastics; however, this is partly accounted for by the quality parameter in the Circular Footprint Formula (see Section 2.4).

### 2.4 Allocation approach for recycled content and recycling

With the exception of the baseline, all designs considered envisage either or both the use of recycled materials and the recycling at the end-of-life. Recycling activities convert a waste into a new product; their environmental impacts occur therefore at the boundaries between the product system generating the waste and the product system using the recycled material. To allocate the environmental impacts of recycled materials and end-of-life recycling between different product systems, we employed the Circular Footprint Formula developed in the context of the Product Environmental Footprint by the Joint Research Center of the European Commission.[21] This formula accounts for the share of recycled materials and the proportion of materials that are recycled or incinerated for energy recovery at the end-of-life. It assumes that using recycled materials and recycling avoids production of virgin materials, taking into account the quality of the recycled materials based on their price compared to virgin alternatives. For incineration, it assumes that the generated electricity and heat displaces an equivalent amount that is generated from the electricity grid mix or the conventional source of heat (*i.e.* natural gas).

Table SI 3† reports the formula's parameter values that we used in modelling of both the plastic and paper-based Poppy designs. The parameter $A$ is of particular importance and represents how the burdens of credits of recycled materials are shared between suppliers and users. In this work, we adopted a balance approach using an $A$ factor equal to 0.5 for both materials, even though the current availability of recycled paper may warrant a lower $A$ factor (0.2) as suggested by the JRC.§ For the quality of the recycled materials (which is expressed *via* their price), we followed the recommendations of the JRC whereby the price of plastic recyclates correspond to 75% of that of virgin plastic, whilst the price for virgin and recycled paper is equal.[1]

## 3 Results and discussions

In Section 3.1, we provide a hot-spot analysis highlighting the key processes dominating the environmental impacts, whilst in Section 3.2 we compare the environmental performance of the different designs and scenarios considered. Section 3.3 aims at identifying the most environment-friendly product design based on normalisation and weighting. Numerical LCA results are reported in Table SI 4.†

### 3.1 Hot-spot analysis

Fig. 4 presents an analysis of the key contributors to the environmental impacts of the baseline design of the Poppy. The chart in Fig. 4 shows that the production of virgin paper and virgin LDPE generate the vast majority of environmental impacts. The contributions of paper production range from ∼25% of fossils resource use up to ∼98% in the categories ozone depletion and freshwater eutrophication, whilst those associated with virgin LDPE vary from ∼1% and up to ∼84% in the category resource use, fossils. The metal pin has negligible contributions across all impact categories. The disposal of the Poppy generates non-negligible contributions in few environmental categories, including climate change and water use, whilst providing credits (*i.e.* negative contributions) to a number of categories including ionising radiations, fossils resource use and particulate matter. In the baseline scenario the Poppy is assumed to be disposed of as general waste, which is treated by a combination of incineration with and without energy recovery and disposal in landfills. The climate change impacts are driven by emissions from incineration and landfills, whilst the credits are associated with the generation of electricity from incineration that displaces in part electricity from nuclear energy. The hot-spot analysis for S1 (recycled content design, reported in Fig. SI 1†) shows a similar trend but with slightly lower contributions from the production of paper and LDPE due to the use of recycled materials.

The environmental impacts of the paper-based design are dominated by the production of paper, which is expected given the mono-material nature of this design and the results of the contribution analysis presented above (baseline and S1). To provide a better understanding of the sources of environmental impacts, we distinguish between the impacts of virgin and

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§ EF reference package 3.1 (transition phase) available here: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

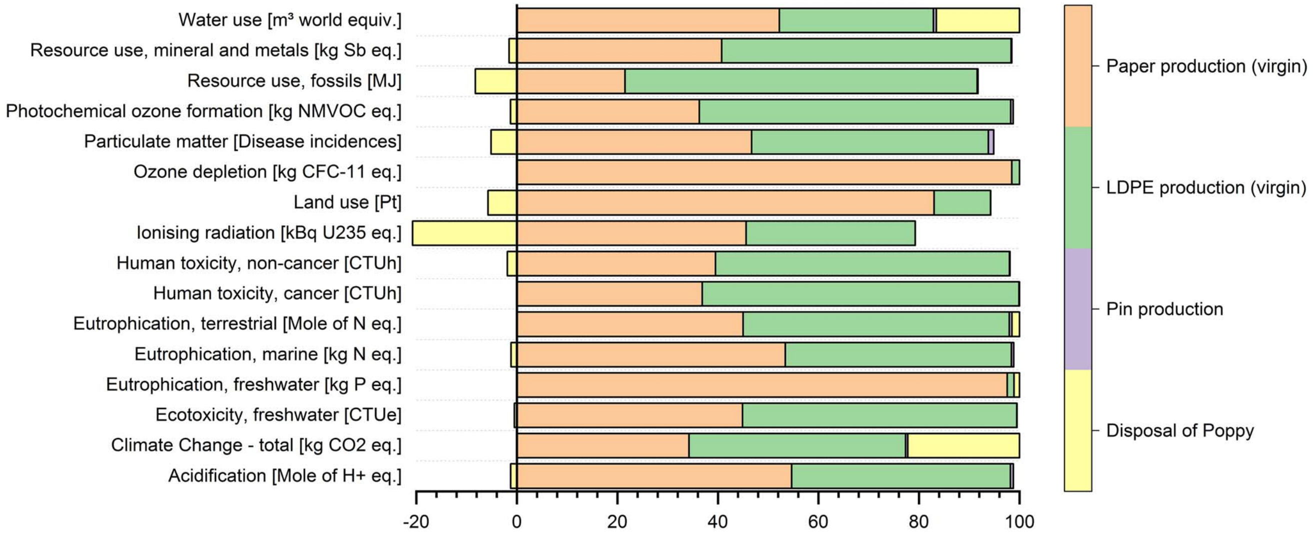

Fig. 4 Hot-spot analysis of the baseline scenario (virgin LDPE and virgin paper). Impacts associated with "Paper production-materials" include the environmental burdens of chemicals and additives, whilst those due to the energy demands are displayed separately as "Paper production-electricity".

recycled pulp and the paper manufacturing process. Under a no-recycling scenario (Fig. SI 2†), the production of virgin pulp represents the largest contributor to most environmental impacts, with contributions ranging from 34% to 69% of the absolute impact scores. The paper manufacturing process is the largest contributor to climate change impacts (50%) and the second-largest in the most remaining categories. The environmental impacts of this process originate from the consumption of electricity and of additives. The process of reclaiming pulp fibres from clean coffee cups shows meagre contributions; the only exception to this trend is for the category water use, where reclaiming fibres generate the second-highest contributions, with contributions amounting to ~25%. The end-of-life of the Poppy (which is assumed to be disposed of as general waste) has minor contributions to the environmental impacts. However, the end-of-life of the other wastes – primarily the paper cut-off strips (see Section 2.2) which are assumed to be recycled – contributes to lowering the environmental burdens in all categories except climate change and water use by 10–30% of the absolute impact scores.

The environmental impacts of the paper-based design are significantly reduced when the Poppy is recycled at its end of life (EoL): Fig. 4 shows that the credits assumed for displacing virgin pulp are comparable to those for the other EoL recycling activities, whose combined effect is in the order of 10–50% of the absolute impact scores. The scenarios with increasing recycled content of paper (S2-75 and S2-100) present a similar trend to that of S2-50 described above but with decreasing contributions from virgin pulp production and increasing contributions from the process of reclaiming fibres. The environmental impacts of the remaining activities are unchanged.

Overall, the hot-spot analysis clearly indicates that to obtain significant improvements in the environmental performance of the paper-based design, efforts should be focused on (i) identifying eco-efficient virgin pulp suppliers and (ii) reducing electricity requirements of the paper manufacturing process and/or switching to low-impact energy sources.

### 3.2 Comparative analysis

The results of the comparative analysis show the environmental performances of the alternative designs relative to the baseline, calculated according to eqn (1).

$$\text{relative change}[\%] = \frac{\text{scenario } x - \text{baseline}}{\text{baseline}} \times 100 \qquad (1)$$

Fig. 6 focuses on the recycled content (S1) and paper-based (S2-50) designs, including recycling and no-recycling scenarios. The chart shows how both S1 and S2-50 scenarios outperform the baseline across all impact categories with the exception of water use in scenario 2 (paper-based design) under a no-recycling. The lowest environmental impacts are associated with the paper-based design (S2) when the Poppy is recycled at the end of its life, with net benefits compared to the baseline ranging from 25% in the category water use up to 110% in the category eutrophication freshwater. When the Poppy is not recycled the paper-based design yields significantly lower benefits, thus demonstrating the key role played by credits associated with EoL recycling; in this case, the benefits range from 6% in the category resource use, fossils and up to an increase in impacts of 17% in the category water use. The latter is because the life-cycle water use of the paper-based design is driven by production of virgin pulp and reclaimed fibres (Fig. 5), which are more water-intensive than LDPE production. The recycling of the Poppy and other materials at the end of life partially offset the increase in water use, which explains why under a recycling scenario the paper-based design yields benefits compared to the baseline also in this category. Overall, the benefits of the paper-based design are not to be exclusively attributed to the use of paper in place of LDPE or to the recycling at the end of life; a key

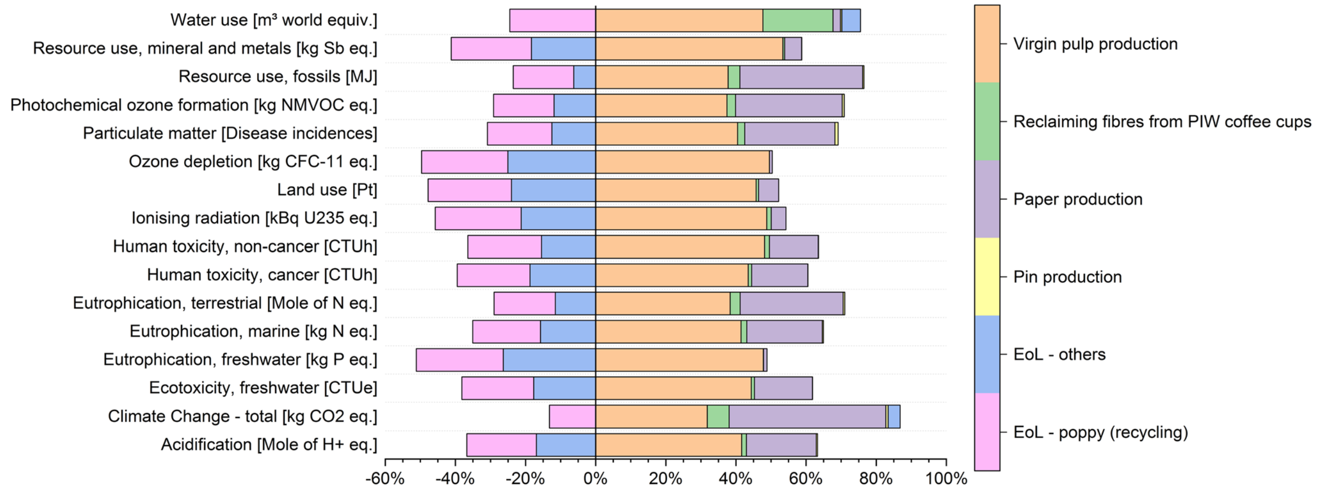

Fig. 5 Hot-spot analysis for S2-50 (scenario 2, paper-based with 50% recycled content) when the Poppy is recycled at its end-of-life. PIW: Post-Industrial Waste.

factor in determining the environmental performance is the overall material intensity of the Poppy, which is significantly lighter (<50%, see Table 3) than its plastic counterpart. Given the similarities between RBL and Poppyscotland versions (see Section 1.3 and ESI†), we expect that the application of LCA would lead to a similar trend for the Poppyscotland Poppy, although the numerical impacts and differences amongst scenarios may vary. Notably, Poppyscotland version is lighter, thus the benefits of reducing the material intensity are reduced.

The environmental benefits of partially replacing virgin (as in the baseline) with recycled content LDPE and paper (S1) range between 1% for the category water use and up to 41% for the category ozone depletion. This is expected as recycled materials generally carry lower environmental impacts, partly

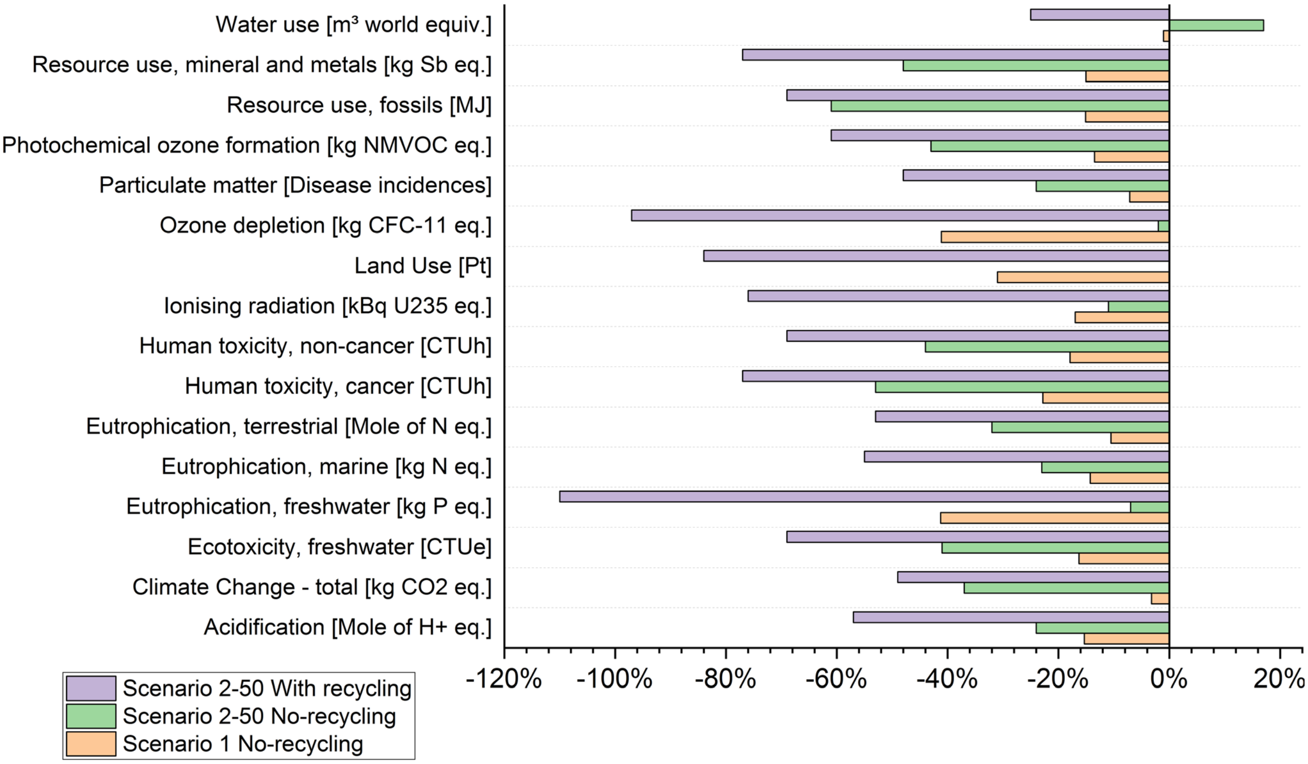

Fig. 6 Environmental performance of S1 (recycled-content plastic design) and S2-50 (paper design, 50% recycled content) including recycling and no-recycling scenarios, compared to the baseline. The origin of the *x*-axis represents the baseline scenario. Bars with a positive value indicate higher environmental impacts compared with the baseline; instead bars with negative values represent lower environmental impacts.

because of how environmental impacts are allocated (Section 2.4). Under a no-recycling scenario, the paper-based design does not outperform the recycled-content plastic design (S1) across all impact categories; specifically, in this case S1 outperforms S2 in four categories concerning freshwater eutrophication, ozone depletion, land use and human impacts from ionising radiations. As described in Section 3.1, the underlying reason is that these categories are particularly affected by virgin pulp production. To identify which of these designs is environmentally preferable, in Section 3.3 we normalise and weigh the environmental impact scores to generate a ranking of options.

The results discussed in this Section showcase the significant environmental importance of using recycled materials and recycling at the end of life. However, it must be noted that the allocation approach that we used (Section 2.4) – although being one of the most commonly adopted – is one amongst many that have been proposed in the literature, and different approaches may lead to different results.[26] A similar effect is given by the "A Factor" in the Circular Footprint Formula (see Table SI 3†) which controls how burdens and benefits are allocated between suppliers and users of recycled materials; this is further discussed in Section 3.4.

Fig. 7 and SI 3† investigate the effects of increasing ratios of recycled content in the paper-based design (S2), focusing on recycling and no-recycling scenarios respectively. The charts confirm the results found for S1 in demonstrating that increasing the use of recycled paper leads to lower environmental impacts. For example, the environmental benefits of a 100% recycled-content paper-based design (S2-100) increase significantly with respect to S2-50, ranging between 52% and 175% under a recycling scenario and between 39% and 72% under a no-recycling scenario. The only exception to this trend is the category water use where increasing the recycled content leads to higher environmental impacts. The underlying reason is that the production of reclaimed fibres from coffee cups is more water intensive that the production of virgin pulp. In the no-recycling scenario, the increase in recycled content makes the paper-based design less water efficient, with impacts compared to the baseline that increase from 17% to 23%. On the other hand, in the recycling scenario the increase in water use due to reclaimed pulp is offset by the credits associated with the recycling at the end-of-life, resulting in net lower impacts compared to the baseline even when using 100% recycled content.

### 3.3 Supporting decision-making: normalisation and weighting results

Interpreting LCA results is not straightforward, especially when different design options are compared *via* an extensive set of environmental indicators as we did in this work. Impact categories cannot in fact be compared amongst themselves because they relate to different environmental issues and are expressed in different units. To aid decision-making we normalised and weighted LCA results. Tables SI 4 and SI 5† report the normalised and weighted numerical results which are colour-ranked, from dark red (higher impacts) to dark green (lower impacts).

The categories with the highest normalised impacts include climate change and fossils resource use, especially for the

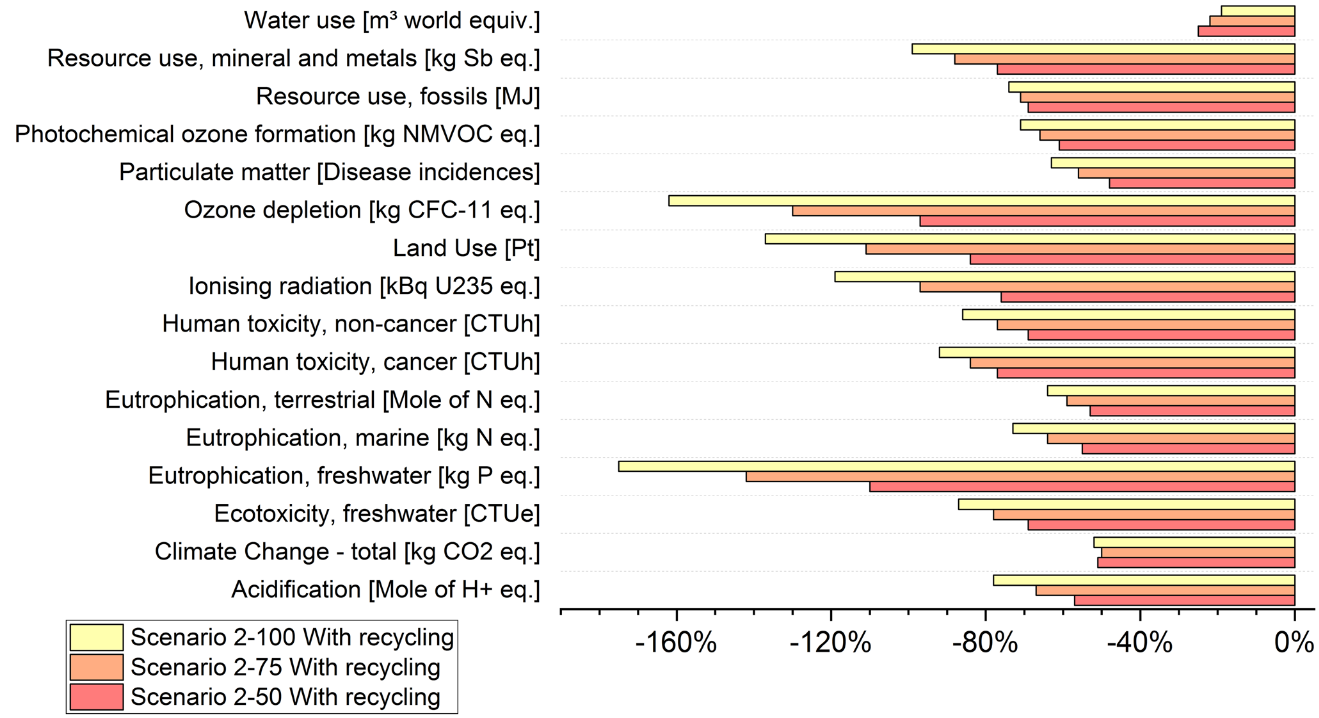

Fig. 7 Environmental performance of the paper-based design with increasing recycled content (from 50% to 100%), under a recycling scenario. The origin of the *x*-axis represents the baseline scenario. Bars with a positive value indicate higher environmental impacts when compared with the baseline. Instead, bars with negative values represent lower environmental impacts.

Table 4 Single score obtained after aggregating weighted and normalisation results. The scores are colour ranked from lower impact in green to higher impact in red

| Scenario | Final score | Ranking | Relative change from baseline |
|---|---|---|---|
| Baseline | $1.0 \times 10^{-4}$ | 8 | — |
| S1 | $8.9 \times 10^{-5}$ | 7 | −11% |
| S2-50 – no-recycling | $6.1 \times 10^{-5}$ | 6 | −39% |
| S2-75 – no-recycling | $5.1 \times 10^{-5}$ | 5 | −42% |
| S2-100 – no-recycling | $5.5 \times 10^{-5}$ | 4 | −45% |
| S2-50 – recycling | $4.6 \times 10^{-5}$ | 3 | −54% |
| S2-75 – recycling | $4.4 \times 10^{-5}$ | 2 | −57% |
| S2-100 – recycling | $4.0 \times 10^{-5}$ | 1 | −59% |

baseline and scenario 1; as noted above, these categories are driven by the consumption of electricity from fossil resources, the use of fossil resources for LDPE production, and the disposal of the Poppy when this is not recycled. On the other hand, freshwater eutrophication is the category with the lowest normalised impacts and that which benefits the most from switching from a plastic to a paper-based design; this is because virgin paper dominates freshwater eutrophication impacts in all designs (see Fig. 4, 5, SI 1 and SI 2†), and therefore the use of reclaimed fibres and the recycling of paper at the end-of-life that avoids production of virgin pulp provides significant impact reductions.

The results from the weighting step confirm the analysis from the normalised impact. Table 4 reports the aggregated weighted results into a single environmental score for each design option and recycling scenario, and the relative change from the baseline. The Table shows that the 100% recycled paper-based design (S2-100) under a recycling scenario represents the overall best option from an environmental perspective, yielding overall environmental savings compared to the baseline design that amount to 50%. Regardless of the EoL scenario, the paper-based design outperforms the recycled content design (S1) by a substantial margin: the environmental benefits for the paper-based design are in the range of 39–59%, compared to only 11% for the recycled content design. However, we note that all alternative scenarios that we considered in this study present an improvement with respect to the current design. We also note that a similar ranking of options is likely to be applicable to Poppyscotland version.

The weighted results also indicate that it is environmentally preferable to recycle the Poppy at the end of its life rather than increasing the recycled content from 50% to 100%. In fact, the S2-50 design under a recycling scenario is environmentally preferable to the S2-100 under a no-recycling scenario by a margin of 9%. We note that the recycling of Poppy falls within the behaviour of individuals whilst the use of recycled paper is within the sphere of decision of RBL. Therefore, a campaign focusing on the recyclability aspect of the RP may be as important as increasing the recycled content. Note however that the preference of recycling over recycled content is heavily dependent on A Factor in the Circular Footprint Formula, which is discussed in Section 3.4.

### 3.4 Limitations

The LCA results are significantly dependent on the credits for recycling and recycled content and therefore on the parameters used in the circular footprint formula, particularly the *A* factor and the quality parameter for the recycled materials. For the *A* factor, we adopted a balanced approach choosing a value equal to 0.5 for both plastic and paper, thereby allocating equally the benefits of recycling and using recycled content to suppliers and users of recycled materials. However, according to the JRC current market conditions may require a lower *A* factor for paper because the offer for recycled paper is lower than its demand. A lower *A* factor reduces the environmental advantages of recycling and increase those of using recycled paper, leading lower to a smaller difference between the environmental performance of recycling and no-recycling scenarios for the paper-based design and between that of S1 and the paper-based recycling scenario. However, a lower *A* factor would not affect the ranking between baseline, S1 and S2.

For the quality of recyclates, we did not explicitly model the recycling process nor did we test the potential quality of the plastic and paper recyclates. Rather, we relied on average data recommended by the JRC for the circular footprint formula whereby the quality of the recyclates is inferred from their prices. Based on this data, recyclates have lower quality that virgin for plastics, whilst the quality of virgin and recycled paper is similar. In the circular footprint formula, the use of low quality recyclates (as recycled content) reduces the environmental impacts of the products, whilst the generation of low quality recyclates at EoL increases impacts; the underlying rationale is to promote uptake of low-quality recycles and discourage the production of low-quality recyclates. This entails that the environmental impacts of S1 would diminish if plastic recyclates are of lower quality than what we assumed. For the paper-based design (S2), the environmental impacts would depend on the relative quality of paper recyclates from post-industrial coffee cups and that of the recyclates obtained from the recycling of the Poppy.

The single score aggregated LCA results are heavily dependent on the choice of normalisation and weighting factors. The latter are particularly important in that they inherently reflect value-based choices. The weighting factors that we used represent a good balance of expert and public perspective whilst covering a number of aspects (see Section 2.2); nevertheless, different weighting factors may yield significantly different results.

Finally, we note that we excluded a number of activities in our LCA model – primarily due to lack of data – including production of ink and plastic additives, manufacturing process of paper-based Poppy and transportation of materials and wastes. Although these activities affect the investigated designs in different ways, most are unlikely to significantly change the LCA results, including the options ranking. Ink was found to have negligible environmental impacts in a case study on printing.[25] Transportation of wastes is similar across the scenarios investigated, whilst that for raw materials favours the paper-based design and potentially also the plastic-based, recycled content design based on the availability of recycled materials in the UK. The environmental impacts of plastic additives are poorly investigated in the literature. They make up a minuscule fraction of total weight, but their environmental impacts may not be negligible, particularly in the categories concerning toxicity; this aspect should be subject to future research efforts.

## 4 Conclusions

This article presented a Life Cycle Assessment (LCA) study of the Royal British Legion's Remembrance Poppy aimed at supporting eco-design by assessing the environmental performance of different options and identifying those most environmentally preferable. The current design (the baseline) is multi-material, comprising LDPE, paper and metal; for this reason, it rarely recycled in the UK and thus considered within the realm of single-use plastics. The alternative designs considered include (i) a variation to the baseline design (known as S1) that uses recycled LDPE (30%) and paper (50%), and (ii) a new design (S2) entirely made of paper, with a percentage of recycled pulp obtained from clean coffee cups, post-industrial waste. For the latter, we varied the percentage of recycled paper from 50% (which is representative of an existing product in the UK) to 100%, with the objective of investigating the effects of the recycled content on the overall environmental performance of the Poppy. Unlike the baseline and S1 designs, the paper-based design (S2) can be recycled; for this reason and for completeness, we modelled both the case that the Poppy is and is not recycled at the end of its life. The LCA study considers the full life cycle of one Poppy from "cradle to grave". The inventory is based on primary data provided by the Royal British Legion and by James Cropper, and complemented by data from Sphera and Ecoinvent databases. The LCA results are obtained using the Environmental Footprint (EF) 2.0 method, and translated into a single impact score *via* normalisation and weighting.

The comparative analysis shows that the paper-based design (50% recycled content) outperforms the baseline designs across the full spectrum of categories, even when the Poppy is not recycled. This design also outperforms the recycled-content plastic-design (S1) but only when the Poppy is assumed to be recycled; otherwise, our study identifies some environmental trade-offs. The hot-spot analysis identifies LDPE and paper production as key hot-spots for the baseline and scenario 1, whilst the impacts of the paper-based design are dominated by the production of virgin pulp and the paper manufacturing process. The LCA results also demonstrate that increasing the recycled content of paper increases the environmental performance of the Poppy. After normalisation and weighting, the LCA results indicate overall environmental benefits ranging from 39% to 59% for the paper-based design compared to the baseline, with the recycled-content plastic-design providing significantly lower benefits (11%). The results of this LCA study highlight the importance of using increasing percentages of recycled content, as well as that of designing product that are recyclable at the end of their life – both are key principles of the Circular Economy.

## Author contributions

Andrea Paulillo and Martina Pucciarelli contributed equally to the manuscript. Andrea Paulillo: conceptualization, methodology, investigation, formal analysis, writing – original draft, writing – review & editing, project administration. Martina Pucciarelli: conceptualization, methodology, investigation, software, visualisation, formal analysis, writing – original draft, visualization, writing – review & editing. Phil Prior: resources, writing – review & editing. Paola Lettieri: project administration, funding acquisition, writing – review & editing.

## Conflicts of interest

There are no conflicts of interest to declare.

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