Electronic Supplementary Material (ESI) for RSC Sustainability.

Eco-design of Remembrance Poppy: a Life Cycle Assessment study.

Andrea Paulillo[1**], Martina Pucciarelli[1**], Phil Prior[2], Paola Lettieri[1*]

[1]Department of Chemical Engineering, University College London
[2]Royal British Legion, UK

*Corresponding author: Paola Lettieri, p.lettieri@ucl.ac.uk
** Co-first Authors

ANNEX I: LCA datasets

Table SI 1 Datasets employed for LCA modelling. The Table reports selected dataset, its geographical reference, and the underlying database.

Geographical reference	Dataset name	Database
GB	Diesel mix at filling station	Sphera
GLO	Bulk waste truck, Euro 6, 20-26t gross weight/10t playload capacity (urban area)	Sphera
GB	Electricity grid mix 1kV-60kV	Sphera
RER	Chemi-thermochemical pulp production	Ecoinvent 3.7.1
GLO	Truck-trailer, Euro 6, 28 - 34t gross weight / 22t payload capacity	Sphera
EU-28	Container ship ocean incl. fuel, 27,500 dwt payload capacity, ocean going	Sphera
US	Citric acid (from starch)	Sphera
EU-28	Sodium hydroxide (caustic soda) mix (100%)	Sphera
EU-28	Tap water from groundwater	Sphera
GB	Electricity from photovoltaic	Sphera
GB	Electricity from hydro power	Sphera
GB	Electricity grid mix	Sphera
EU-28	Thermal energy from natural gas	Sphera
EU-28	Thermal energy from light fuel oil (LFO)	Sphera
EU-28	Municipal waste water treatment (mix)	Sphera
GB	PE in waste incineration plant	Sphera
GLO	Electricity credit Sphera <u-so>	Sphera
GLO	Credit Thermal Energy Sphera <u-so>	Sphera
RER	EUR-flat pallet production	Ecoinvent 3.7.1
EU-28	Kraftliner (2018) - for use in cut-off EoL scenario cases	Sphera/FEFCO
DE	Polyethylene Film (PE-LD) without additives	Sphera
EU-28	Ferro metals on landfill	Sphera
GB	Ferro metals in waste incineration plant	Sphera
GB	Disposal of paper/cardboard (landfill/incineration)	Sphera
DE	Hydrogen peroxide (100%; H2O2) (Hydrogen from steam reforming)	Sphera
DE	Sodium hydroxide (caustic soda) mix (100%)	Sphera
DE	Adipic acid	Sphera
RER	Soap production	Ecoinvent 3.6
RER	Sodium dithionite production, anhydrous	Ecoinvent 3.7.1
RER	Sodium silicate production, spray powder, 80%	Ecoinvent 3.7.1
EU-28	Municipal waste water treatment (mix)	Sphera
US	Polyethylene low density granulate (LDPE/PE-LD) secondary	Sphera

ANNEX II: Circular Footprint Formula parameters.

Table SI 2 Parameters employed in the Circular Footprint Formula for modelling the environmental impacts associated with the usage of recycled materials and their recyclability at the end-of-life.

	Term of the Circular Footprint Formula (CFF) and Explanation	*Plastic & paper design*	*Paper-based design*		
		S1	**S2-50**	**S2-75**	**S2-1004**
PARAMETERS CONCERNING THE MATERIAL RECYCLING, REPROCESSING AND DISPOSAL	**R_1** - Proportion of material in the input to the production that has been recycled from a previous system. [Recycled content]	Plastic: 30% Paper: 50%	50%	75%	100%
	R_2- Proportion of material in the product that will be recycled (or reused) in a subsequent system. R_2 shall therefore take into account the inefficiencies in the collection and recycling (or reuse) processes. R_2 shall be measures at the output of the recycling plant. [Recyclability rate]	Plastic: 0 Paper: 0	Recycling scenario:: 81% No-recycling scenario: 0%		
	R_3- Proportion of the material in the product that is used for energy recovery at End of Life.	Plastic & Paper: 46%	Recycling scenario: 19% No-recycling scenario: 46%		
	E_v - Specific emissions and resources consumed (per functional unit) arising from the acquisition and pre-processing of virgin material.	Emissions per FU from the modelling.			
	E^*_v Environmental burdens arising from the acquisition and pre-processing of virgin material assumed to be substituted by recyclable materials.	Emissions per FU from the modelling.			
	$E_{recycled}$ Environmental burden of the recycling activities that supplied recycled material to the production process	Emissions per FU from the modelling.			
	$E_{recyclingEoL}$ Specific emissions and resources consumed (per functional unit) arising from the recycling process at EoL, including collection, sorting and transportation process.	Emissions per FU from the modelling.			
	E_D Specific emissions and resources consumed (per functional unit) arising from disposal of waste material at the EoL of the analysed product, landfill (L) and incineration without energy recovery (I) or other usable product output.	Emissions per FU from the modelling. 34% material to (L), 18% to (I)	Share of material to landfill and incineration. Optimistic case: 0% (L) and (I). Pessimistic case: 34% (L), 18% (I).		
	Q_{Sin}/Q_P Q_{Sin} = Quality of the ingoing secondary material, i.e. quality secondary material at the point of substitution. Q_P = Quality of the primary material, i.e. virgin material.	Plastic: 75% (JRC-PEF, annex C)	100%		
	Q_{Sout}/Q_P Q_{Sout} = Quality of the outgoing secondary material, i.e. quality secondary material at the point of substitution.	--	100%		
	A - Allocation factor of burdens and benefits (jointly: "credits") between supplier and user of recycled materials. If A=0, credits to recyclable materials at EoL. Closed loop approximation. If A=1, credits to recycled contents.	50%	50%	50%	50%
PARAMETERS CONCERNING THE ENERGY RECOVERY	**B -** Allocation factor of energy recovery processes. It applies both to burdens and benefits. If B=0 (default value), the electricity generated is used externally and credited to the producer and debited to the user of the secondary energy.	Default value equal to 0			
	E_{ER} - Specific emissions and resources consumed (per FU) arising from the energy recovery process (e.g. incineration with energy recovery, landfill with energy recovery, etc.)	Emissions per FU from the modelling.			
	$E_{SE,heat}$ & $E_{SE,elect}$. Specific emissions and resources consumed (per FU) that would have arisen from the specific substituted energy source, heat and electricity respectively	Emissions per FU from the modelling.			
	$X_{SE,heat}$ & $X_{SE,elect}$. -Efficiency of the energy recovery process for both heat and electricity.	Emissions per FU from the modelling.			
	LHV - Lower heating value of the material in the product that is used for energy recovery.	Emissions per FU from the modelling.			

ANNEX III: Life Cycle Impact Assessment results

Table SI 3 Numerical LCA results for the environmental categories and the scenarios considered.

Impact categories	**Baseline**	**S1**	**S2-50**		**S2-75**		**S2-100**	
			Recycling	No-recycling	Recycling	No-recycling	Recycling	No-recycling
Acidification; mole H+ eq.	7.70E-06	6.52E-06	3.29E-06	5.84E-06	2.51E-06	5.06E-06	1.73E-06	4.28E-06
Climate change; kg CO2 eq.	4.06E-03	3.93E-03	2.08E-03	2.56E-03	2.02E-03	2.50E-03	1.96E-03	2.44E-03
Ecotoxicity, freshwater; CTUe	8.65E-04	7.24E-04	2.71E-04	5.08E-04	1.92E-04	4.28E-04	1.12E-04	3.48E-04
Eutrophication, freshwater; kg P eq.	3.37E-07	1.98E-07	-3.25E-08	3.15E-07	-1.43E-07	2.04E-07	-2.53E-07	9.38E-08
Eutrophication, marine; kg N eq.	2.03E-06	1.74E-06	9.18E-07	1.56E-06	7.31E-07	1.37E-06	5.44E-07	1.18E-06
Eutrophication, terrestrial; mole of N eq.	1.90E-05	1.70E-05	8.90E-06	1.30E-05	7.84E-06	1.20E-05	6.78E-06	1.09E-05
Human toxicity, cancer; CTUh	3.64E-11	2.81E-11	8.52E-12	1.71E-11	5.76E-12	1.43E-11	3.00E-12	1.15E-11
Human toxicity, non-cancer; CTUh	3.24E-10	2.66E-10	1.01E-10	1.82E-10	7.35E-11	1.55E-10	4.60E-11	1.27E-10
Ionising radiation, human health; kBq U235 eq.	2.53E-04	2.10E-04	6.07E-05	2.26E-04	6.94E-06	1.72E-04	-4.69E-05	1.18E-04
Land use; Pt	3.16E-02	2.19E-02	4.94E-03	3.17E-02	-3.32E-03	2.34E-02	-1.16E-02	1.52E-02
Ozone depletion; kg CFC-11 eq.	3.21E-11	1.89E-11	8.11E-13	3.16E-11	-9.50E-12	2.13E-11	-1.98E-11	1.09E-11
Particulate matter; disease incidences	4.76E-11	4.42E-11	2.46E-11	3.64E-11	2.10E-11	3.28E-11	1.74E-11	2.92E-11
Photochemical ozone formation, kg NMVOC eq.	6.60E-06	5.71E-06	2.55E-06	3.76E-06	2.24E-06	3.45E-06	1.94E-06	3.14E-06
Resource use, fossils; MJ	7.68E-02	6.52E-02	2.39E-02	3.03E-02	2.19E-02	2.82E-02	1.98E-02	2.61E-02
Resource use, mineral and metals; kg Sb eq.	6.44E-09	5.47E-09	1.48E-09	3.38E-09	7.63E-10	2.66E-09	4.31E-11	1.94E-09
Water use; m3 world eq.	9.50E-04	9.40E-04	7.12E-04	1.11E-03	7.41E-04	1.14E-03	7.70E-04	1.17E-03

ANNEX IV: Hot-spot analysis

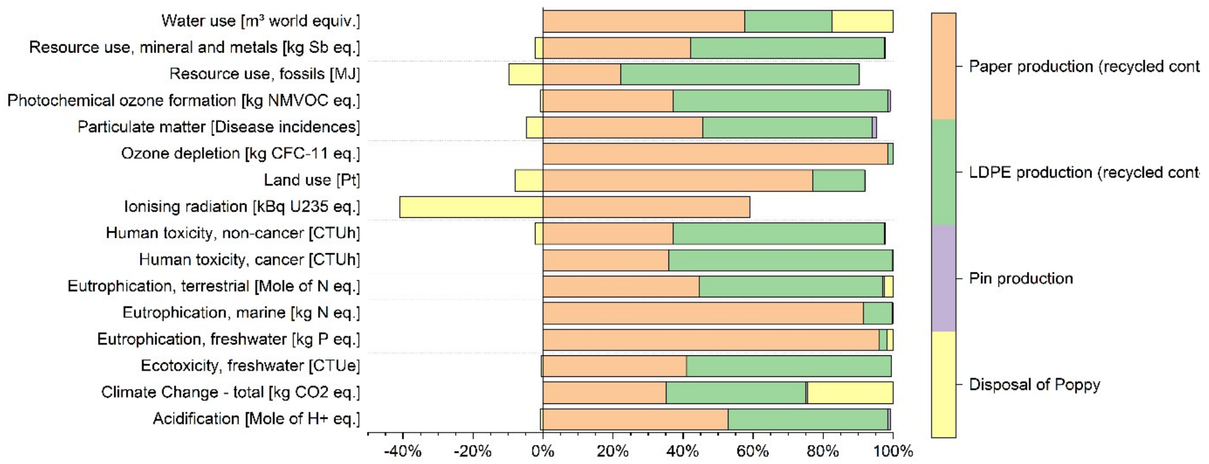

Figure SI 1 Hot-spot analysis of Scenario 1.

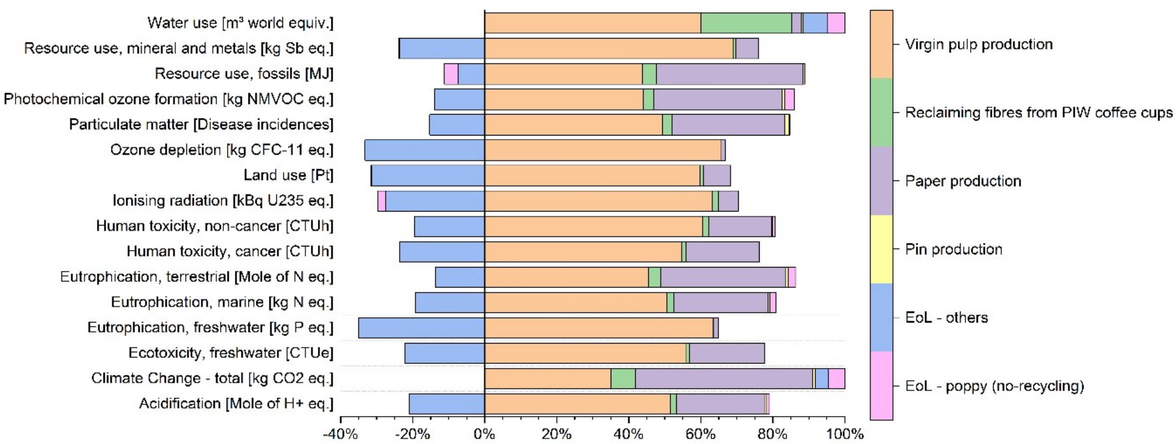

Figure SI 2 Hot-spot analysis of Scenario 2-50 (50% recycled content) under a no-recycling scenario.

ANNEX V: Comparative analysis

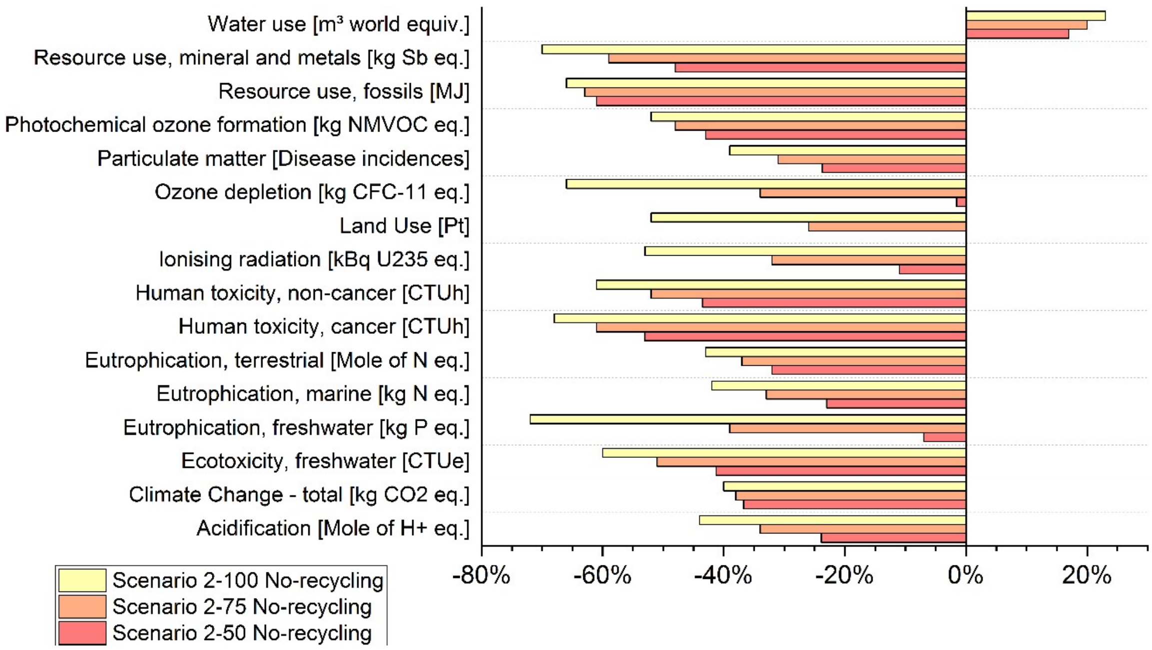

Figure SI 3 Comparison of paper designs: Scenario 2-50 (50% recycled content), Scenario 2-75 (75% recycled content) and Scenario 2-100 (100% recycled content), when the RP is not recycled at the EoL. The origin of the x-axis represents the baseline scenario. Bars with a positive value indicate higher environmental impacts when compared with the baseline. Instead, bars with negative values represent lower environmental impacts.

ANNEX V: Normalised and weighted results

Table SI 4 Normalised LCA results using the Joint Research Centre Planetary Boundaries-based normalisation factors. Results are colour-ranked scale from dark red (highest impacts) to dark green (lowest impacts).

Normalised results								
	Baseline	*S1*	*S2-50*		*S2-75*		*S2-100*	
			Recycling	*No-recycling*	*Recycling*	*No-recycling*	*Recycling*	*No-recycling*
Acidification	5.32E-08	4.26E-08	2.27E-08	4.03E-08	1.73E-08	3.49E-08	1.19E-08	2.96E-08
Climate change	4.12E-06	3.81E-06	2.11E-06	2.60E-06	2.05E-06	2.54E-06	1.99E-06	2.48E-06
Ecotoxicity, freshwater	4.55E-08	3.70E-08	1.43E-08	2.67E-08	1.01E-08	2.25E-08	5.89E-09	1.83E-08
Eutrophication, freshwater	4.01E-07	2.35E-07	-3.87E-08	3.75E-07	-1.70E-07	2.43E-07	-3.01E-07	1.12E-07
Eutrophication, marine	7.00E-08	5.67E-08	3.17E-08	5.38E-08	2.52E-08	4.72E-08	1.88E-08	4.07E-08
Eutrophication, terrestrial	2.14E-08	1.82E-08	1.00E-08	1.47E-08	8.84E-09	1.35E-08	7.64E-09	1.23E-08
Human toxicity, cancer	2.62E-07	1.99E-07	6.12E-08	1.23E-07	4.14E-08	1.03E-07	2.16E-08	8.27E-08
Human toxicity, non-cancer	5.47E-07	4.26E-07	1.70E-07	3.07E-07	1.24E-07	2.62E-07	7.76E-08	2.14E-07
Ionising radiation	3.32E-09	2.35E-09	7.97E-10	2.97E-09	9.11E-11	2.26E-09	-6.16E-10	1.55E-09
Land use	2.51E-08	1.66E-08	3.92E-09	2.52E-08	-2.64E-09	1.86E-08	-9.22E-09	1.21E-08
Ozone depletion	4.12E-10	2.42E-10	1.04E-11	4.05E-10	-1.22E-10	2.73E-10	-2.54E-10	1.40E-10
Particulate matter	6.36E-07	5.27E-07	3.28E-07	4.86E-07	2.80E-07	4.38E-07	2.32E-07	3.90E-07
Photochemical ozone formation	1.12E-07	9.25E-08	4.34E-08	6.39E-08	3.81E-08	5.87E-08	3.30E-08	5.34E-08
Resource use, fossils	2.37E-06	1.92E-06	7.38E-07	9.35E-07	6.76E-07	8.70E-07	6.11E-07	8.05E-07
Resource use, mineral and metals	2.03E-07	1.29E-07	4.66E-08	1.07E-07	2.40E-08	8.38E-08	1.36E-09	6.11E-08
Water use	3.61E-08	3.55E-08	2.71E-08	4.22E-08	2.82E-08	4.34E-08	2.93E-08	4.45E-08

Table SI 5 Weighted normalised results based on Joint Research Center weighting factors adapted by Chau et al. (2021). Results are colour-ranked scale from dark red (highest impacts) to dark green (lowest impacts).

Weighted results								
	Baseline	*S1*	*S2-50*		*S2-75*		*S2-100*	
			Recycling	*No-recycling*	*Recycling*	*No-recycling*	*Recycling*	*No-recycling*
Acidification	2.89E-07	2.32E-07	1.24E-07	2.19E-07	9.43E-08	1.90E-07	6.50E-08	1.61E-07
Climate change	7.32E-05	6.76E-05	3.75E-05	4.62E-05	3.64E-05	4.51E-05	3.53E-05	4.40E-05
Ecotoxicity, freshwater	1.92E-07	1.56E-07	6.01E-08	1.13E-07	4.26E-08	9.49E-08	2.48E-08	7.72E-08
Eutrophication, freshwater	1.41E-06	8.25E-07	-1.36E-07	1.32E-06	-5.98E-07	8.53E-07	-1.06E-06	3.92E-07
Eutrophication, marine	2.27E-07	1.84E-07	1.03E-07	1.74E-07	8.16E-08	1.53E-07	6.08E-08	1.32E-07
Eutrophication, terrestrial	6.96E-08	5.90E-08	3.26E-08	4.76E-08	2.87E-08	4.40E-08	2.48E-08	3.99E-08
Human toxicity, cancer	1.22E-06	9.31E-07	2.87E-07	5.75E-07	1.94E-07	4.81E-07	1.01E-07	3.87E-07
Human toxicity, non-cancer	2.21E-06	1.73E-06	6.90E-07	1.24E-06	5.02E-07	1.06E-06	3.14E-07	8.68E-07
Ionising radiation	2.09E-08	1.47E-08	5.00E-09	1.86E-08	5.72E-10	1.42E-08	-3.87E-09	9.72E-09
Land use	1.88E-07	1.24E-07	2.93E-08	1.88E-07	-1.97E-08	1.39E-07	-6.88E-08	9.02E-08
Ozone depletion	3.16E-09	1.86E-09	7.99E-11	3.11E-09	-9.36E-10	2.10E-09	-1.95E-09	1.07E-09
Particulate matter	4.81E-06	3.98E-06	2.48E-06	3.67E-06	2.12E-06	3.31E-06	1.76E-06	2.95E-06
Photochemical ozone formation	5.89E-07	4.85E-07	2.27E-07	3.35E-07	2.00E-07	3.08E-07	1.73E-07	2.80E-07
Resource use, fossils	1.44E-05	1.17E-05	4.49E-06	5.69E-06	4.11E-06	5.30E-06	3.72E-06	4.90E-06
Resource use, mineral and metals	1.12E-06	7.11E-07	2.57E-07	5.88E-07	1.33E-07	4.63E-07	7.50E-09	3.37E-07
Water use	2.89E-07	2.85E-07	2.17E-07	3.38E-07	2.26E-07	3.47E-07	2.35E-07	3.56E-07

ANNEX V: Poppyscotland Remembrance Poppy

Table SI 6 Bill of Materials for one Poppyscotland Poppy.

Component	Baseline
Stem	0.5g
Black pistil	0.3g
Petal	0.16g
Pin	0.0077g
Total weight	0.97g

Figure SI 4 Image of Poppyscotland Remembrance Poppy. Left: baseline design. Right: paper-based design