



JEERESD

Journal Home page: www.jeeresd.online

eISSN: 3078-2112



Quantifying the Net Environmental Benefits of Food-Grade Recycled PET in Cameroon: Application of the Circular Footprint Formula to Mid-Scale Mechanical Recycling

Lele Christian^{1*}, Ajeegah Gideon Aghaindum², Nkeng George Elambo¹

1. National Advanced School of Public Works (ENSTP), BP 510, Department of Environmental Engineering, Yaoundé, Cameroon
2. University of Yaoundé I, BP 812, Faculty of Sciences, Plant Biology and Physiology Department, Laboratory of Hydrology and Environment, Yaoundé, Cameroon

ARTICLE INFO

Keywords:

Circular Footprint Formula;
life cycle assessment;
material flow analysis;
recycled PET;
food-grade recycling;
circular economy;
Sub-Saharan Africa

ABSTRACT

Introduction: Mechanical recycling is often assumed, rather than demonstrated, to deliver a net environmental benefit relative to virgin plastic production, particularly in Sub-Saharan African contexts where primary process data are scarce. **Methods:** This study quantifies that benefit for food-grade recycled polyethylene terephthalate (rPET) produced at mid-scale in Cameroon, using the European Commission's Circular Footprint Formula (CFF) applied to a gate-to-gate life cycle assessment of the Opur and Supermont mineral-water bottle streams processed at Ecogreen Sarl, Douala.

Results: Applying the CFF with allocation factor $A = 0.5$ yielded an effective climate-change footprint of approximately 1,600 kg CO₂-eq per tonne. This corresponds to an avoided impact of 27.2% relative to a linear baseline of virgin production plus landfilling. Across the sixteen EF 3.1 categories, the median avoided impact was 28.6%; human-toxicity indicators showed a modest net increase.

*Corresponding author

Email: christianlele1@outlook.com

Affiliation address: 1National Advanced School of Public Works (ENSTP), BP 510, Department of Environmental Engineering, Yaoundé, Cameroon

- Phone number: +237 659 19 35 96
- ORCID: <https://orcid.org/0009-0006-4238-679>

DOI: 10.68305/jeeresd.v4i4.006

Received: 17 July 2026 | **Revised:** 09 August 2026 | **Accepted:** 24 September 2026 | **Published:** 01 October 2026

© 2026 The Authors. Published by EcoClean Environment Company on behalf of JEERESD. This article is distributed under the terms of the [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation and reproduction, provided that appropriate credit is given to the original authors and source.



Material flow analysis identified oversized 10-litre bottles as the single largest loss pathway (8.3 % of input mass), a design-process mismatch rather than a contamination problem.

Conclusion: The results demonstrate that the CFF, correctly parameterised with primary data, provides a robust, policy-relevant quantification of circularity benefits even where recycling operates below the collection and technology standards of mature economies, and that recycled-content rate is the single strongest lever available to policymakers and manufacturers seeking to maximise the environmental return of food-grade PET recycling in Cameroon.

What this study adds?

1. Quantifies the gate-to-gate environmental performance of food-grade recycled PET (rPET) production from post-consumer PET bottles, based on primary process data from a mid-scale facility in Cameroon, through the combined application of Material Flow Analysis (MFA) and Life Cycle Assessment (LCA).
2. Quantifies the net environmental benefit of rPET substitution over virgin PET through the application of the Product Environmental Footprint Circular Footprint Formula (CFF), yielding a CFF-derived effective footprint (E) comparable to the linear benchmark ($E_v + E_d$).
3. Identifies the process-level hotspots driving the environmental profile of food-grade rPET production.
4. Assesses, via *ceteris paribus* sensitivity analysis, the contribution of key CFF parameters to the environmental improvement potential of rPET.

1. Introduction

Global plastic production now exceeds 400 million tonnes per year, and single-use packaging - polyethylene terephthalate (PET) bottles foremost among it - accounts for a large and growing share of that total (Geyer *et al.*, 2017). Bottles designed for weeks of use persist in the environment for centuries, fragmenting into microplastics that enter food chains and freshwater and marine ecosystems (Crawford & Quinn, 2017). The crisis is most acute where waste-management infrastructure has not kept pace with urbanisation and plastic consumption: across Africa, mismanagement rates for plastic waste commonly exceed 80-90 % (Godfrey *et al.*, 2019; Yeboah *et al.*, 2025), and Sub-Saharan economies face the additional constraints of informal collection systems, weak regulatory enforcement and negligible formal recycling capacity.

Cameroon exemplifies these constraints. The country generates approximately 600,000 tonnes of plastic waste annually, yet formal recycling rates remain below 10 % (MINEPDED, 2024). PET bottles for mineral water - led by the Opur and Supermont brands, which together held a 61.7 % market share in 2017 (Business in Cameroon, 2017) - constitute a highly visible fraction of this stream, most of which ends in open dumps, waterways or uncontrolled burning. In response, national policy has begun to embrace the circular-economy paradigm, most notably through the 2024 National Strategy to Combat Plastic Pollution and an emerging extended-producer-responsibility (EPR) framework (MINEPDED, 2024). A formal manufacturer-

recycler partnership between Source du Pays S.A. (producer of Opor and Supermont) and Ecogreen Sarl, a mid-scale recycling facility in the Bonabéri industrial zone of Douala, represents an early, empirically observable instance of this transition proving that bottle-to-bottle mechanical recycling technologies have emerged as a primary pathway to close the loop in beverage packaging by converting post-consumer PET back into food-grade resins (Benyathiar *et al.*, 2022).

Whether such partnerships deliver a genuine net environmental benefit, however, is an empirical question that circularity rhetoric alone cannot answer. Recycling is not axiomatically superior to virgin production: energy-intensive reprocessing, water-intensive washing, and diesel-fuelled thermal drying can each erode the credit that recycled content is assumed to generate (Corona *et al.*, 2019; Haupt & Hellweg, 2019). Quantifying the net benefit requires an accounting framework capable of apportioning burdens and credits between virgin and recycled material streams in a transparent, comparable manner. The Circular Footprint Formula (CFF), developed by the European Commission for the Product Environmental Footprint (PEF) initiative, was designed for exactly this purpose: it combines the impact of virgin material displaced, the impact of the recycling process itself, and the quality of the recycled output relative to the primary material, weighted by an allocation factor A that apportions burdens and credits between the supplier and the user of recycled content (Allacker *et al.*, 2017; European Commission, 2013).

The CFF has been applied extensively to European PET recycling systems operating within mature, largely electrified, high-collection-rate infrastructures (Eriksen *et al.*, 2020; Jeswani *et al.*, 2021; Rigamonti *et al.*, 2014). Its application to a mid-scale, primary-data-verified recycling operation in Sub-Saharan Africa, where the counterfactual (open dumping, uncontrolled burning, or virgin substitution under a hydropower-dominated grid) differs structurally from the European case, has not, to the authors' knowledge, previously been reported with comparable methodological rigour. This gap matters because policy instruments (recycled-content mandates, EPR fee structures, eco-labelling) increasingly rely on CFF-type metrics, yet their local calibration in low- and middle-income countries remains largely untested.

This article addresses that gap. Building on a gate-to-gate life cycle assessment (LCA) and material flow analysis (MFA) of the mechanical PET recycling line in Cameroon, it pursues three objectives specific to the quantification of circularity benefit: (i) to characterise, with primary industrial data, the gate-to-gate environmental profile of food-grade rPET production at mid-scale in Cameroon; (ii) to apply the Circular Footprint Formula, with an allocation factor $A = 0.5$ consistent with European Commission guidance, to convert that process-level profile into an effective, credit-adjusted footprint directly comparable with virgin PET; and (iii) to quantify, through a parametric sensitivity analysis of the CFF itself, the maximum net environmental benefit achievable by varying the recycled-content rate, independently of any change in recycling-process technology. In doing so, the study provides one of the first primary-data-based CFF applications for mechanical plastics recycling in Sub-Saharan Africa identified by the authors, based on the literature reviewed in this manuscript, and a transferable template for similarly resourced facilities across the region.

To guide the evaluation of the environmental performance and circularity benefits of food-grade mechanical PET recycling in Cameroon, this study addresses three primary research questions: first, (RQ1) what is the gate-to-gate environmental profile of food-grade rPET pellet production at a mid-scale Cameroonian facility when characterised using primary process data?; second, (RQ2) how does this gate-to-gate profile translate, via the Circular Footprint Formula (CFF), into an effective credit-adjusted footprint, and what net environmental benefits are achieved relative to a linear baseline of virgin production and landfilling across EF 3.1 impact categories?; and third, (RQ3) how sensitive is the CFF-derived net environmental benefit to variations across key system parameters, and which parameters emerge as the dominant drivers of output uncertainty? Throughout this study, 'net benefit' is defined as the percentage difference between the effective environmental footprint calculated via the Circular Footprint Formula and a linear baseline system comprising primary virgin production plus end-of-life landfilling. Evaluated across each Environmental Footprint 3.1 impact category, this value serves as an internal accounting metric within the Circular Footprint Formula framework rather than a direct empirical comparison against unmodelled end-of-life counterfactuals, such as open dumping or uncontrolled burning.

2. Materials and Methods

2.1 Case study and system boundaries

The case study follows an embedded single-case design (Yin, 2018) encompassing the Opur and Supermont mineral-water bottles as an integrated production-recycling system. Both brands are mono-material PET bottles with HDPE screw caps and pigmented blue resin, each already incorporating at least 25 % recycled content (see Table 1). This figure is a manufacturer-stated lower-bound specification rather than a directly measured process parameter for the specific production campaign studied here; throughout this manuscript it is treated as an assumed input recycled-content rate ($R1 = 25\%$) for CFF purposes (§2.6), and this assumption is identified explicitly as a limitation (§4.5) pending confirmation from production records. Their combined share of the blue-bale fraction entering the recycling facility reached $88.8 \pm 9.5\%$, confirming that they are representative of the dominant post-consumer PET feedstock rather than an atypical subset.

Table 1. Key characteristics of Opur and Supermont mineral water bottles

Specific information	Opur	Supermont
Polymer type	Polyethylene Terephthalate (PET)	Polyethylene Terephthalate (PET)
Additive presence	Pigment	Pigment
Recycled content	At least 25%	At least 25%
Typical volumes	0.35 L, 0.5L, 1.5L, 10L, 20L	0.1L, 0.35 L, 0.5 L, 1 L, 1.5 L, 10L
Average mass	18–35 g (depending on volume)	15–30 g (depending on volume)
Colour	Blue	Blue

Cap and seal system	HDPE screw and detachable caps	HDPE screw and detachable caps
Overall shape	Blow-moulded, embossed markings	Blow-moulded, embossed markings
Reuse design	Reusable bottle	Reusable bottle

This study adopts a gate-to-gate system boundary, covering only the operations under the direct control of the mechanical recycling plant: from reception of post-consumer PET bales to rPET production. Post-consumer collection is excluded from primary boundary (Figure 1). The absence of official and structured dataset for the collection stage, is not specific to the present study: it is a structural feature of solid waste management in Sub-Saharan Africa, where recycling activity and the associated material flows are largely undocumented at household and informal-sector level (Morais *et al.*, 2022; Ogutu & Kathambi, 2022). The gate-to-gate boundary chosen is consistent with ISO 14044 (§4.2.3.3) and the Joint Research Centre reports that underpin default datasets used in the European Product Environmental Footprint (PEF) framework for plastics define their functional unit from a tonne of already sorted plastic waste, treating collection and sorting as distinct upstream stage requiring its own dataset (García-Gutiérrez *et al.*, 2023; Tonini *et al.*, 2021).

2.2 Functional units

Two nested functional units were defined, following the dual-functional-unit approach recommended by Tonini *et al.* (2021) for multi-stage recycling systems (Figure 1). The functional units are mass-based, as the primary function is waste management (ISO 14044, 2006). In accordance with the PEFCR for PET bottles (European Commission, 2018) and García-Gutiérrez *et al.* (2023), 1,000 kg of clean, colour-sorted PET flakes was defined as the intermediate functional unit, isolating the upstream stages most exposed to sorting and contamination losses, and 1,000 kg of food-grade rPET pellets was defined as the final functional unit, encompassing the full recycling value chain and serving as the reference flow for the Circular Footprint Formula and its recycled-content sensitivity analysis.

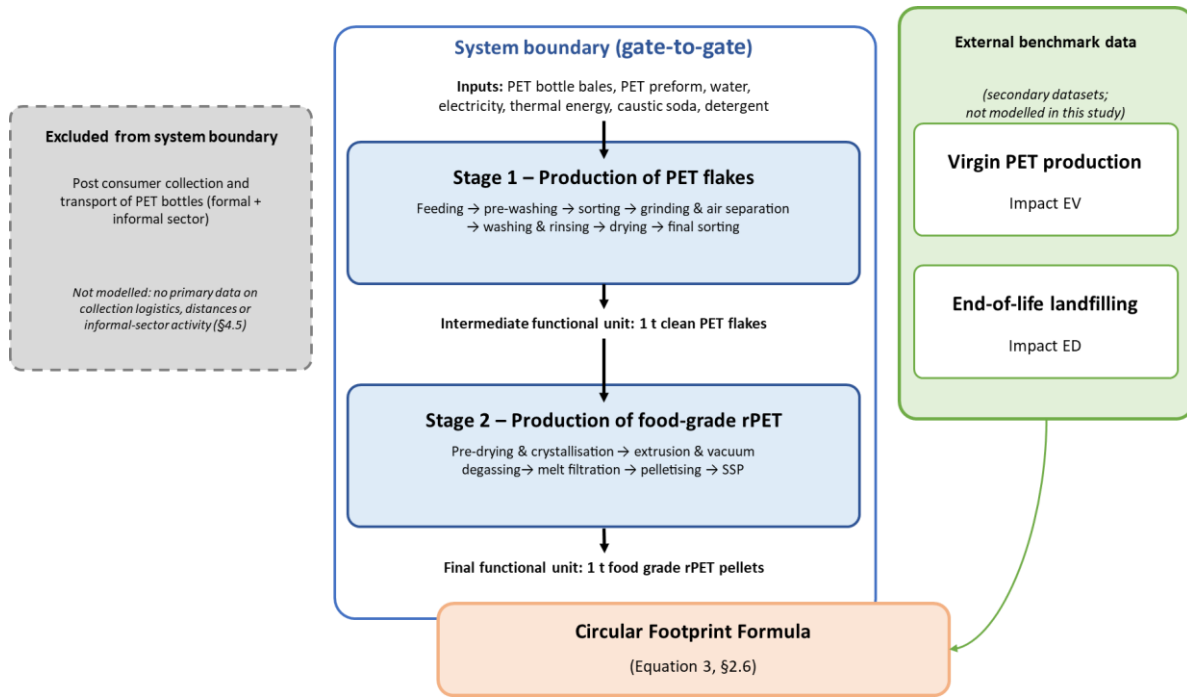


Figure 1. System boundary and functional units of the study

2.3 Data collection and quality assurance

Foreground (primary) data were collected daily over 90 days spanning the rainy-to-dry transition in Douala (April to July), building upon the primary operational dataset established in Lele (2025), to cover seasonal variability in feedstock contamination specific to the coastal humid zone. This satisfies the 3-month minimum at stable capacity (Garcia-Gutierrez et al., 2023, JRC132067, p.33) during a representative multi-day of three-shift production campaign using calibrated industrial platform scales (± 0.5 kg precision), in-line electromagnetic water flow meters, and shift-level electricity metering. Every foreground and background flow was scored against the pedigree matrix (Table 2; Weidema et al., 2013) for reliability, completeness, temporal, geographical and technological correlation, in accordance with ISO 14044:2006 §4.3. Diesel-derived thermal energy and nitrogen were quantified based on primary data from direct measurements. Background data were sourced from ecoinvent v3.10, allocation cut-off by classification model (Wernet et al., 2016), with the national electricity grid mix adapted to Cameroon's predominantly hydroelectric generation profile: 69.48% hydroelectricity, 18.5% Fuel based electricity, 6.39% from natural gas, 2% solar energy (ARSEL, 2026)

As environmental exchanges in ecoinvent follow a lognormal distribution (Weidema et al., 2013; Ciroth et al., 2016), the arithmetic dispersion was converted to geometric standard deviation as:

$$\sigma_{geo,basic} = \exp \left[\frac{1}{2} \times \log \left(\left(\frac{\sigma}{\mu} \right)^2 + 1 \right) \right] \quad (1)$$

This geometric standard deviation was combined with additional uncertainty from the pedigree matrix

$$\sigma_{geo} = \exp \left[\sqrt{\log(\sigma_{geo,basic})^2 + \log(\sigma_{geo,pedigree})^2} \right] \quad (2)$$

Table 2. Pedigree matrix for data quality assessment

Criterion	Score 1	Score 2	Score 3	Score 4	Score 5
Reliability	Verified data based on measurement	Verified data partly based on	Non-verified data partly based on	Qualified estimate	Non-qualified estimate
Completeness	Representative data from all sites over an adequate	Representative data from most sites and/or	Representative data from some sites and/or	Representative data from a smaller sample	Unknown representativeness
Temporal Correlation	Data from period of interest	Data from within 3 years of period of	Data from more than 3 years but less	Data more than 10 years old	Unknown age
Geographical Correlation	Data from area under study	Data from area with similar production	Data from area with slightly similar	Data from area with different production	Unknown origin
Technological Correlation	Data from enterprises producing under same technology	Data from enterprises with slightly different technology	Data from enterprises with different technology	Data from enterprises with no similarity	Unknown technology

2.4 Material flow analysis

Material flow analysis, based exclusively on the primary life cycle inventory (no secondary data), quantified inputs, outputs, residues and process-specific recycling efficiency at each unit-process stage, targeting a mass-balance closure exceeding the 95 % benchmark for high-confidence flow quantification identified by Brunner and Rechberger (2016).

MFA focused primarily on Subsystem 1 (PET flakes production) because this stage constitutes the critical interface between the post-consumer waste collection and sorting system and the subsequent manufacturing of secondary raw material. By concentrating the detailed MFA on Subsystem 1, the study captures the key points of material loss and transformation that determine the overall recycling efficiency and the quality of the resulting rPET. Downstream stages (pelletising) are more standardised and less variable across facilities. This focused approach is consistent with established MFA practice in plastic-recycling systems, which prioritises the stages with the greatest influence on circularity metrics and environmental performance (Haupt & Hellweg, 2019).

Sankey diagrams, constructed in STAN 2.0 (ifu Hamburg) and rendered in SankeyMATIC, visualised flow paths and loss points across the recycling chain, providing the physical backbone subsequently transferred into the life cycle inventory to ensure full MFA-LCA consistency. This is consistent with combined material flow and life cycle modelling frameworks applied to PET packaging streams (Barkhausen et al., 2023; Chaudhari et al., 2022; Lavers Westin et al., 2019).

2.5 Life cycle impact assessment

The life cycle impact assessment was performed in openLCA (v2.3.1) using the Environmental Footprint (EF) 3.1 characterisation method (European Commission, 2021), which builds on

established midpoint characterisation frameworks (Jolliet et al., 2004) to provide harmonised characterisation factors across sixteen impact categories (Table 3). Normalisation and weighting was performed using normalisation factors (global impact per person) and weighting factors provided Andreasi Bassi et al. (2023). Uncertainty was propagated through 10,000-iteration Monte-Carlo simulation using pedigree-derived geometric standard deviations. For impact categories exhibiting a coefficient of variation greater than 1.0, the median rather than the arithmetic mean was reported as the central estimate, following the statistical guidance of Igos et al. (2019) and Rousselet and Wilcox (2020) for strongly right-skewed distributions. Following PEFCR guidance, most relevant impact are identified as those cumulatively contributing to at least 80% of the single overall weighted score. Most relevant processes were then identified as those collectively contributing at least 80% of the most relevant impact categories.

Table 3. EF 3.1 Impact categories, characterisation indicators, and reference units

EF Impact category	Impact category indicator	Unit
Acidification	Accumulated Exceedance (AE)	mol H ⁺ _{eq}
Climate change, total	Radiative forcing as global warming potential (GWP100)	kgCO ₂ -eq
Ozone depletion	Ozone Depletion Potential (ODP)	kgCFC-11 _{eq}
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU _h)	CTU _h
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU _h)	CTU _h
Particulate matter	Human health effect associated with exposure to PM _{2.5}	Disease incidence
Ionising radiation, human health	Human exposure efficiency relative to U ²³⁵	kBqU ²³⁵
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kgNMVOC _{eq}
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N _{eq}
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	mol P _{eq}
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	mol N _{eq}
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU _e)	CTU _e
Land use	- Soil quality index - Biotic production - Erosion resistance - Mechanical filtration - Groundwater replenishment	- Dimensionless (pt) - Kg biotic production - Kg soil - m³ water
Water use	User deprivation potential (deprivation-weighted consumption)	m ³ -depriv water

Resource use, minerals and metals	Abiotic resource depletion (ADP kgSB _{eq} ultimate reserves)
Resource use, fossils	Abiotic resource depletion – fossil fuels MJ (ADP-fossil)

2.6 Circular Footprint Formula

To quantify the net environmental impacts and benefits associated with secondary material use and end-of-life recycling, the European Commission's Product Environmental Footprint (PEF) Circular Footprint Formula (CFF) was applied stochastically. The total environmental burden (E) per functional unit is structured into three dedicated modules representing material input and production, energy recovery, and final disposal:

$$(1 - R_1)E_V + R_1 \left[AE_R + (1 - A)E_V \frac{Q_{sin}}{Q_p} \right] + (1 - A)R_2 \left[E_R - E_V^* \frac{Q_{sout}}{Q_p} \right] + (1 - B)R_3(E_{ER} - LHV \times X_{ER,heat} \times E_{SE,heat} - LHV \times X_{ER,elec} \times E_{SE,elec}) + (1 - R_2 - R_3)E_D \quad (3)$$

A Monte Carlo simulation (n=10,000 iterations) was used to propagate the literature variability of virgin material production (E_V) and end-of-life disposal (E_D), the parameter uncertainty of the recycling process (E_R), and the operational variability of recycled-content (R_1) and recyclability (R_2). The CFF baseline is defined as the CFF value obtained at the baseline parameter values, together with the baseline values (mean or median) of E_V , E_R , E_D reported in Table 4. This deterministic baseline is the reference point against which parametric sensitivity analysis below are reported.

E_V and E_D were taken from established PEF/EF-compatible datasets, primarily Franklin Associates (2020), supplemented by EF 3.1 default characterisation factors for the remaining impact categories (European Commission, 2021). Following European Commission PEF guidance for packaging materials and consistent with the mid-point position of a system in which recycled content displaces but does not fully substitute virgin PET across all downstream applications, the allocation factor A was set at 0.5 (within the PEF-mandated range $0.2 \leq A \leq 0.80$). Operational plant utilises advanced decontamination and super-cleaning extruders producing food-contact grade rPET pellets with intrinsic viscosity (≥ 0.8 dL/g). The Product Environmental Footprint Category Rules (PEFCR) for PET bottles explicitly allow quality ratios (Q_{sin}/Q_p and Q_{sout}/Q_p) = 1 when the recycled material meets virgin specifications in a closed-loop system. A baseline value of $R_1 = 0.25$ was adopted, corresponding to the minimum recycled-content level already declared by the studied brands. In the absence of standardised municipal collection data and reliable, brand-specific or even national collection rate for post-consumer PET, the overall end-of-life recycling rate (R_2) was decomposed into the product of the municipal/regional post-consumer collection rate ($R_{collection}$) and the internal technical yield of the recycling plant ($\eta_{recycling}$):

$$R_2 = R_{collection} \times \eta_{recycling} \quad (4)$$

Based on empirical field studies on plastic waste streams in Central Africa (Ellen MacArthur Foundation & UNEP, 2021; Ngnikam et al., 2017), $R_{collection}$ for rigid PET bottles in major urban centres (Douala, Yaoundé) ranges between 15% and 35%. Consequently, 15% was taken as baseline value, to not overestimate recyclability.

Independently of this joint Monte Carlo uncertainty analysis, a one-at-a-time parametric sensitivity analysis was conducted using the CFF baseline as the reference point, in which each of R_1 and $R_{\text{collection}}$ was, in turn, swept across its full mathematically admissible range (0 to 1), while all other parameters were held fixed at their baseline values. This full-range sweep explores the theoretical envelope of the CFF's response to each parameter under a ceteris-paribus assumption. It is presented as a mathematical scenario analysis and should not be read as evidence that values outside the empirically supported Monte Carlo ranges above are operationally observed or currently achievable at the case-study facility.

Applying the CFF with a strictly gate-to-gate E_R (collection excluded) therefore risks under-declaring the impact of the recycling pathway and overstating its net environmental benefit. Where primary data are unavailable, the PEF guide explicitly permits the use of secondary or generic datasets and proxies. In line with this provision, a literature-derived extrapolation factor, F , was constructed to estimate the order of magnitude of the impact of the informal collection stage relative to the plant-level impact, and applied to E_R as a sensitivity test. On this basis, the factor was set, for climate change indicator only, at $F \in [1.1; 1.3]$, with central value $F = 1.3$. The factor was not extended to other impact categories, for which no comparably robust literature basis for extrapolation was identified.

Table 4. Circular Footprint Formula parameterisation

Parameter	Definition	Baseline value	Range tested	Source / basis
A	The allocation factor of burdens and credits between supplier and user of recycled materials.	0.5	0.2 / 0.5 / 0.8 (deterministic)	European Commission PEF/CFF guidance; mid-point for packaging (European Commission, 2013)
B	The allocation factor of energy recovery processes	0	/	European Commission PEF/CFF guidance
R_1	Proportion of recycled material in the input feedstock	0.25	Monte Carlo: 0.25–1; full-range sweep: 0–1	Brand declaration
$\eta_{\text{recycling}}$	Recycling process yield	$\eta_{\text{recycling}}$	/	Derived from the material flow analysis (§3.1)
$R_{\text{collection}}$	Collection rate	0.15	Monte Carlo: 0.15–0.30; full-range sweep: 0–1	Ellen MacArthur Foundation & UNEP (2021); Ngnikam et al. (2017)
R_2	The proportion of the material in the product that will be recycled in a subsequent system	0.106	Recomputed each iteration	$R_2 = R_{\text{collection}} \times \eta_{\text{recycling}}$
R_3	The proportion of the material in the product that is used for energy recovery at EoL	0	/	No energy recovery infrastructure (Business in Cameroon, 2026)

E_R	Impact of the recycling process itself (per EF 3.1 category)	Table 7	Monte Carlo (pedigree-derived)	Derived from life cycle impact assessment (§3.2)
E_v	Impact of virgin material production (per category)	Not tabulated separately; see §2.6	Monte Carlo (literature variability)	Franklin Associates (2020); NAPCOR (2025); EF 3.1 default characterisation factors
E_{v^*}	Impact of virgin material displaced by the recycled output	Assumed equal to E_v	/	Not separately reported in the source datasets
E_{ER}	Specific emissions and resources consumed arising from the energy recovery process	/	/	No energy recovery infrastructures
$E_{SE,heat}$ and $E_{SE,elec}$	Specific emissions and resources consumed that would have arisen from the specific substituted energy source, heat and electricity respectively	/	/	No energy recovery infrastructures
E_d	Impact of end-of-life landfilling	Not tabulated separately; see §2.6	Monte Carlo (literature variability)	Franklin Associates (2020)
$X_{ER,heat}$ and $X_{ER,elec}$	the efficiency of the energy recovery process for both heat and electricity	/	/	No energy recovery infrastructures
Q_{sin}/Q_p	Quality of the recycled input relative to primary material	1	/	In accordance with the PEFRC for bottled water
Q_{sout}/Q_p	Quality of the recycled output relative to primary material		/	

3. Results

3.1 Material flow analysis and process yield

The mass balance closed, reconciling 1,388.87 kg of incoming bottles (1,258.95 kg) and preforms (129.93 kg) against 1,000.00 kg of clean PET flakes plus 388.87 kg of documented losses per functional unit. Overall bottle-to-pellet yield reached 70.66 % (72.0 % from bales to clean flakes, 98.45 % from flakes to pellets), so the flake-production stage carries a 28.0 % mass shortfall relative to total incoming mass (1,388.87 kg). Four loss categories were separately quantified within this shortfall: oversized 10-litre bottles rejected at feeding and sorting (104.59 kg, 8.3 % of the PET bottle feed at that stage - the single largest category), labels, caps and non-PET contaminants (86.00 kg), dust and fines from feeding, grinding and drying (70.19 kg), non-recyclable bottles from feeding and sorting (51.26 kg). These four major categories are together equivalent to 22.4 % of total incoming mass (1,388.87 kg) with the remaining 5.6% attributed

to the other diversified sources. The Sankey diagram (Figure 2) visualises these flows across the full processing chain.

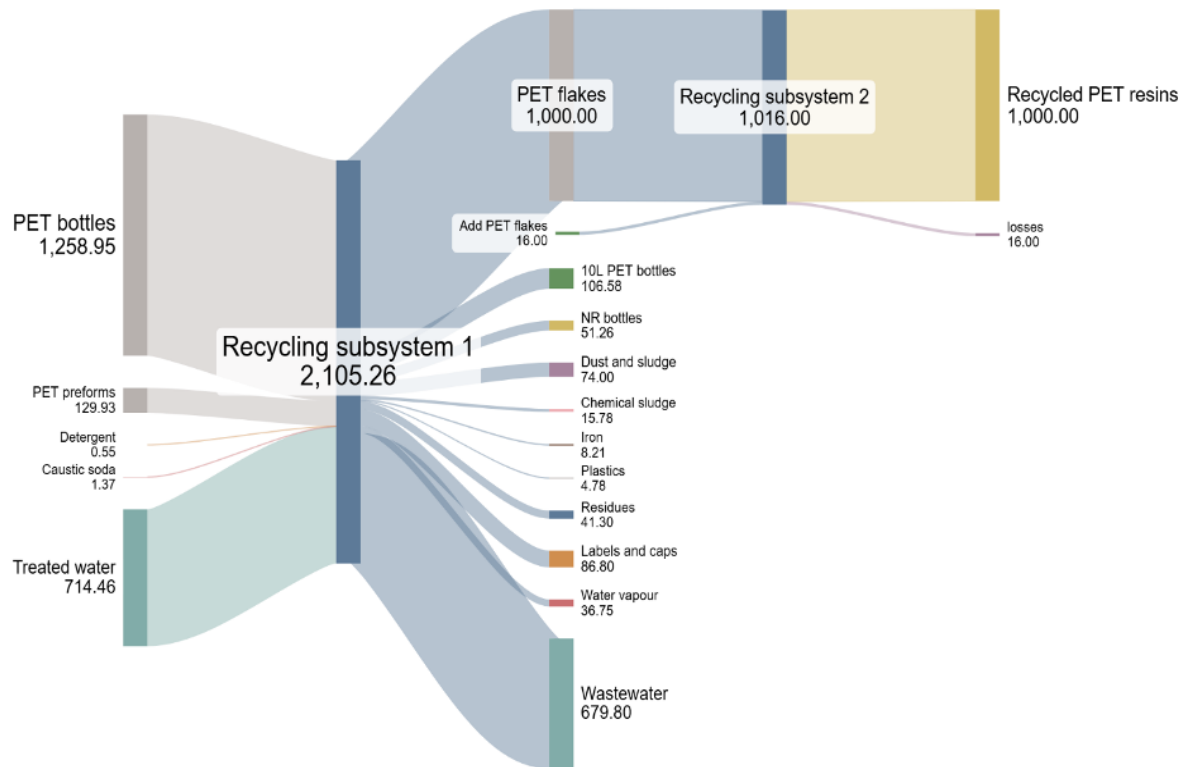


Figure 2. Sankey diagram of material flows across the mechanical recycling process (in kg)

The complete gate-to-gate inventory, presented in two parts (Table 5 and Table 6) corresponding to the intermediate (PET flakes) and final (food-grade rPET pellets) functional units

Table 5. Life cycle inventory for the intermediate functional unit

Process	Inputs	Quantity	Pedigree score	Unit	Outputs & emissions	Quantity	Pedigree score	Unit
Feeding	PET bottle	1,258.95	1.2	kg	PET bottles	1,078.71	1.2	kg
					Non-recyclable	180.24	1.2	kg
Pre-washing	Filtrated water	101.07	1.4	L	Wastewater, sludge, Reject	265.57	1.2	kg
Sorting						46.09	1.2	kg
Grinding & air separation	PET preforms	129.93	1.2	kg	Label flakes, dust,	26.75	1.4	kg
Washing & rinsing	Filtrated	613.40	1.4	L	Wastewater	501.68	1.4	kg
	Thermal	13.69	1.6	MJ	Chemical	15.78	1.4	kg
	Hot air	27.37	1.6	m ³	Waste heat	27.37	1.6	kg
	Caustic	1.37	1.2	kg				
	Detergen	0.55	1.2	kg	Water	6.07	1.6	kg
Centrifugation & Drying	Thermal energy	42.18	1.6	MJ	Water vapour,	40.86	1.6	kg

	Hot air	38.32	1.6	m ³				
Final separation & Stockage (total plant)					Residues PET flakes	27.7 1,000	1.6	kg kg
	Electricit	342.42	1.2	kW	Overall	72.0		%
	Water	714.46	1.4	L	Wastewater	679.8	4.0	kg

Table 6. Life cycle inventory for the final functional unit

Process	Inputs	Quantit y	Pedigre e score	Uni t	Outputs & emissions	Quantit y	Pedigre e score	Uni t
Starting material	Clean, sorted	1,016	1.2	kg				
Pre-drying & crystallisation	Electricit	52	1.4	kW	Residual	0.8	1.6	kg
	Thermal	145	1.6	MJ	CO ₂ from	10.7	1.8	kg
Extrusion & vacuum	Electricit	259.77	1.4	kW	Oligomers , VOCs	4.0	1.8	kg
Melt filtration	Electricit	17	1.4	kW	Filter cake	10	1.6	kg
Underwater pelletising	Electricit	16	1.4	kW	Wastewater	566.6	1.4	kg
	Process	3769.2	1.4	L	Hot water	3624.2	1.4	L
Centrifuge & vibration drying	Electricit	23	1.4	kW	Water vapour,	143	1.6	kg
Solid-State Polycondensation	Thermal	150	1.6	MJ	Water vapour	23	1.6	kg
	Electricit	105	1.4	kW				
	Nitrogen	8	1.6	kg				
Silo + big-bag filling	Electricit	1	1.4	kW	Food-grade	1,000		kg

3.2 Baseline gate-to-gate environmental profile

The characterised impact profile of the baseline process, per tonne of food-grade rPET pellets, is reported in Table 7. Mean climate-change impact was 186 kg CO₂-eq, and water scarcity at 25.3 m³ deprived.

Table 7. Characterised environmental impacts of the baseline scenario

Impact category	Reference unit		Mean	Standard deviation	5% Percentile	Median	95% Percentile
Acidification	mol eq	H+	4.57E-01	7.07E-02	3.55E-01	4.50E-01	5.84E-01
Climate change	kg eq	CO2	1.86E+02	2.74E+01	1.46E+02	1.83E+02	2.35E+02
Climate change - biogenic	kg eq	CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Climate change - fossil	kg eq	CO2	1.86E+02	2.74E+01	1.46E+02	1.83E+02	2.35E+02
Climate change - land use and transform.	kg eq	CO2	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ecotoxicity freshwater	CTUe		7.55E+02	1.58E+02	5.28E+02	7.38E+02	1.04E+03

Eutrophication freshwater	kg P eq	2.99E-02	6.44E-03	2.07E-02	2.93E-02	4.16E-02
Eutrophication marine	kg N eq	1.25E-01	2.00E-02	9.69E-02	1.23E-01	1.61E-01
Eutrophication terrestrial	mol N eq	1.03E+00	1.86E-01	7.76E-01	1.00E+00	1.37E+00
Human toxicity, cancer	CTUh	1.99E-07	4.25E-08	1.38E-07	1.94E-07	2.76E-07
Human toxicity, non-cancer	CTUh	1.13E-06	2.42E-07	7.83E-07	1.10E-06	1.57E-06
Ionising radiation, human health	kBq U-235 eq	1.97E+00	2.72E-01	1.57E+00	1.95E+00	2.45E+00
Land use	Pt	5.99E-01	2.61E-01	2.98E-01	5.42E-01	1.09E+00
Ozone depletion	kg CFC11 eq	1.14E-06	1.59E-07	9.07E-07	1.13E-06	1.42E-06
Particulate matter	disease inc.	3.40E-06	5.34E-07	2.63E-06	3.34E-06	4.37E-06
Photochemical ozone formation, human health	kg NMVOC eq	3.80E-01	6.12E-02	2.93E-01	3.73E-01	4.90E-01
Resource use, fossils	MJ	1.64E+03	2.91E+02	1.24E+03	1.60E+03	2.17E+03
Resource use, mineral and metals	kg Sb eq	3.60E-05	5.23E-06	2.82E-05	3.56E-05	4.52E-05
Water use	m3 depriv.	6.93E+00	6.78E+00	-3.98E+00	6.81E+00	1.84E+01

The normalised and weighted results (Figure 3) revealed climate change, fossil resource use, freshwater eutrophication and acidification as the four dominant categories.

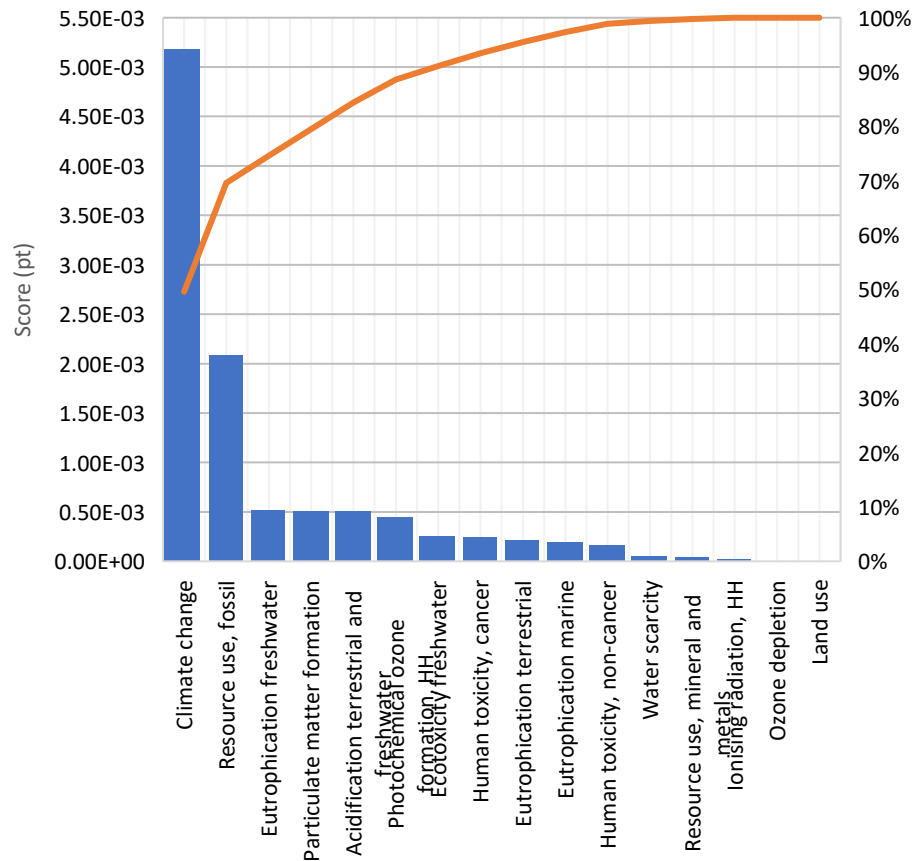


Figure 3. Normalised and weighted environmental impacts of the recycling process
Contribution analysis attributed climate change, fossil resource use, particulate matter and acidification primarily to electricity (Table 8).

Table 8. Most relevant processes

Impact category	Impact value	Main process contributors	Contribution (%)
Climate change	186 kgCO ₂ -eq	Electricity production	67.6
		Thermal energy production	20.5
Resource use, fossils	1640 MJ	Electricity production	68
		Thermal energy production	31.1
Eutrophication freshwater	0.03 kg P eq	Wastewater treatment	99.8
Particulate matter	0.0000034 disease inc.	Electricity production	83.4
Acidification	0.457 mol H ⁺ eq	Electricity production	70.8
		Thermal energy production	22.3

3.3 Circular Footprint Formula: net benefits of food-grade rPET

Application of the CFF (Equation 3, $A = 0.5$, $R1 = 0.25$, $R2 = 0.106$) using Monte Carlo simulation converted the gate-to-gate process impact E_R into an effective, credit-adjusted footprint E directly comparable to virgin PET production for each of the sixteen EF 3.1 categories (Table 9).

Table 9. Results of Circular Footprint Formula application

Impact category			Unit	Mean	Standard deviation	5% percentile	Median	95% percentile
Acidification freshwater	terrestrial and		mol H+ eq	6.15E+00	1.38E+00	3.91E+00	6.12E+00	8.43E+00
Climate change			kg CO2 eq	1.60E+03	3.45E+02	1.04E+03	1.60E+03	2.18E+03
Climate change - biogenic			kg CO2 eq	2.86E+00	6.75E-01	1.76E+00	2.86E+00	3.98E+00
Climate change - fossil			kg CO2 eq	1.60E+03	3.46E+02	1.04E+03	1.59E+03	2.18E+03
Climate change - land use and transform.			kg CO2 eq	2.86E+00	6.76E-01	1.75E+00	2.86E+00	3.99E+00
Ecotoxicity freshwater			CTUe	1.41E+04	3.13E+03	9.03E+03	1.41E+04	1.93E+04
Eutrophication freshwater			kg P eq	1.03E-01	3.89E-02	6.41E-02	9.72E-02	1.58E-01
Eutrophication marine			kg N eq	1.43E+00	3.08E-01	9.33E-01	1.43E+00	1.95E+00
Eutrophication terrestrial			mol N eq	1.56E+01	3.43E+00	1.00E+01	1.55E+01	2.13E+01
Human toxicity, cancer			CTUh	4.56E-07	2.72E-07	2.60E-07	4.02E-07	8.06E-07
Human toxicity, non-cancer			CTUh	2.04E-06	1.35E-06	1.09E-06	1.70E-06	4.11E-06
Ionising radiation, human health			kBq U-235 eq	5.94E+01	1.36E+01	3.71E+01	5.93E+01	8.22E+01
Land use			Pt	5.97E+02	1.37E+03	3.72E+03	5.97E+02	8.23E+02
Ozone depletion			kg CFC11 eq	1.30E-04	3.11E-05	7.94E-05	1.30E-04	1.82E-04
Particulate matter			disease inc.	2.79E-05	6.26E-06	1.78E-05	2.78E-05	3.84E-05
Photochemical ozone formation, human health			kg NMVOC	3.82E+00	8.46E-01	2.44E+00	3.81E+00	5.23E+00
Resource use, fossils			MJ	4.83E+04	1.14E+04	2.99E+04	4.82E+04	6.75E+04
Resource use, mineral and metals			kg Sb eq	1.04E-03	2.42E-04	6.50E-04	1.04E-03	1.45E-03
Water scarcity			m3 depriv.	3.51E+02	7.86E+01	2.26E+02	3.48E+02	4.81E+02

According to Figure 4, for climate change, an avoided impact of 27.20 % relative to linear baseline (virgin production + landfilling). Comparable net benefits were obtained across the impact suite: -26.98 % for particulate matter, 28.44 % for acidification, and 29.78 % for fossil resource use, with impact augmentation recorded for human toxicity non-cancer (-21.21%) and human toxicity cancer (-5.8 %). As a descriptive summary only, the median of the net benefit across all sixteen categories was 28.63 %; because this statistic averages percentages expressed in different units and with different policy significance across categories, it should not be read

as a formally weighted or aggregated environmental indicator, and the category-specific benefits reported above and in Table 9 constitute the primary results.

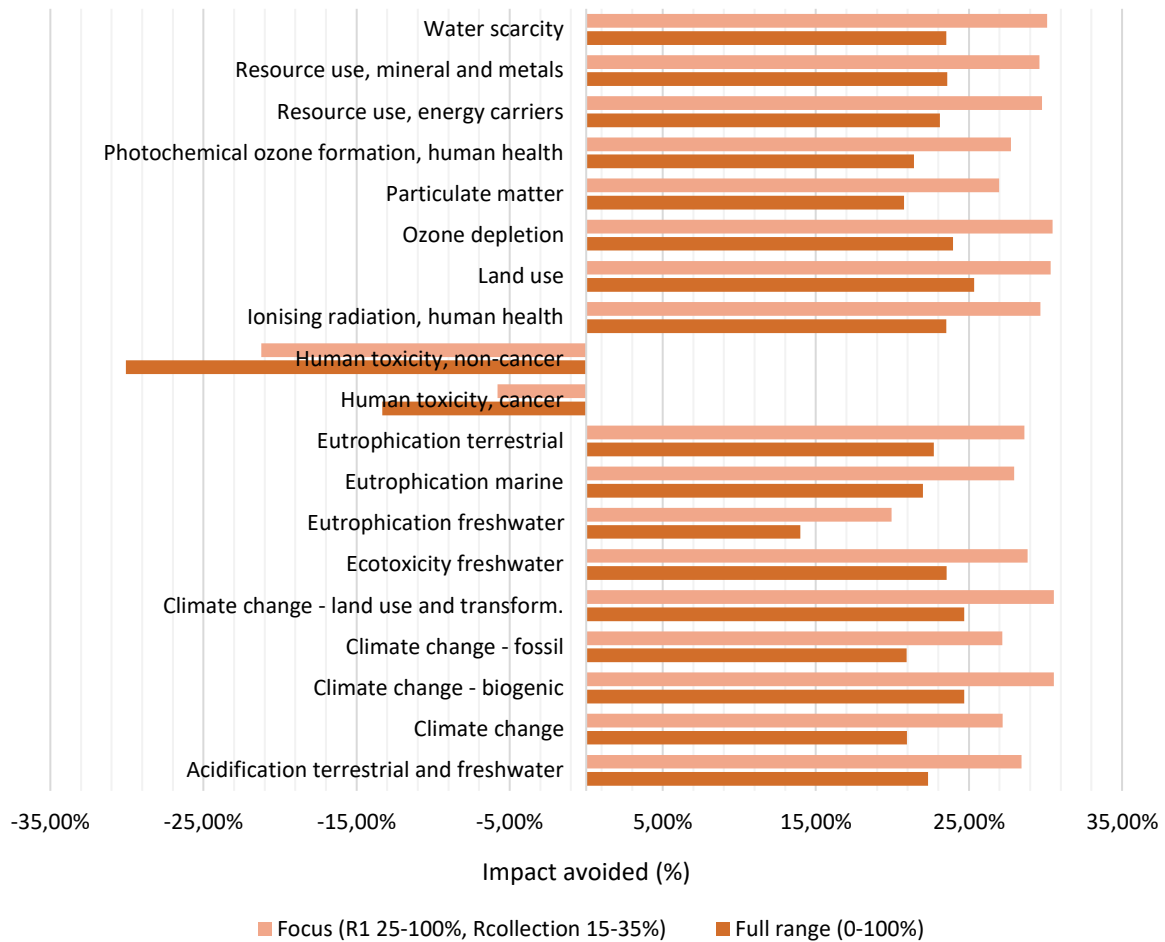


Figure 4. Environmental benefits of circularity

3.4 Sensitivity analysis

Sensitivity analyses were performed on two key system parameters: the recycled content (Figure 5) of the final product and the collection rate of post-consumer PET (Figure 6), across key impact categories.

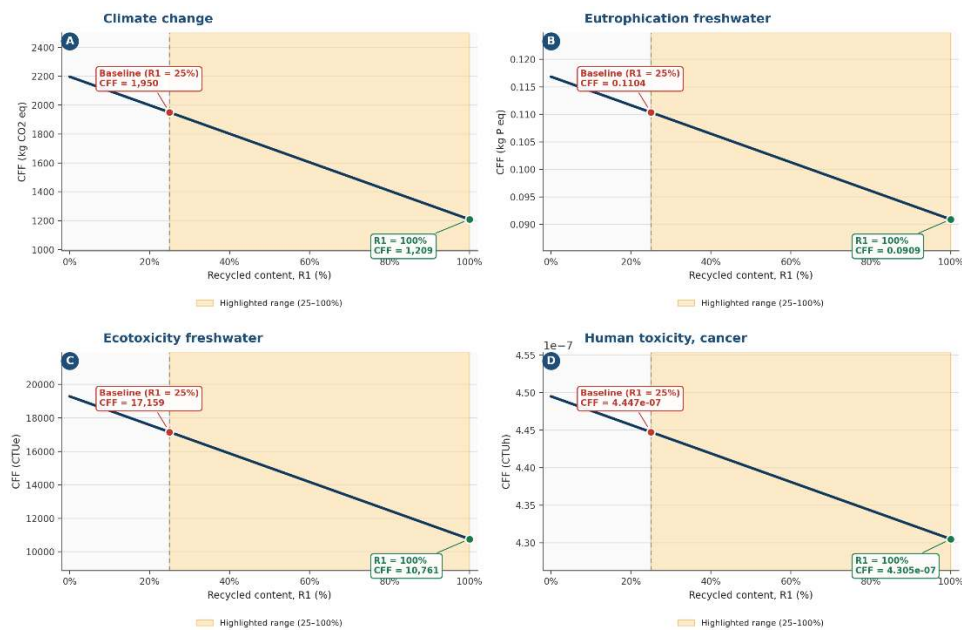


Figure 5. CFF sensitivity to recycled content

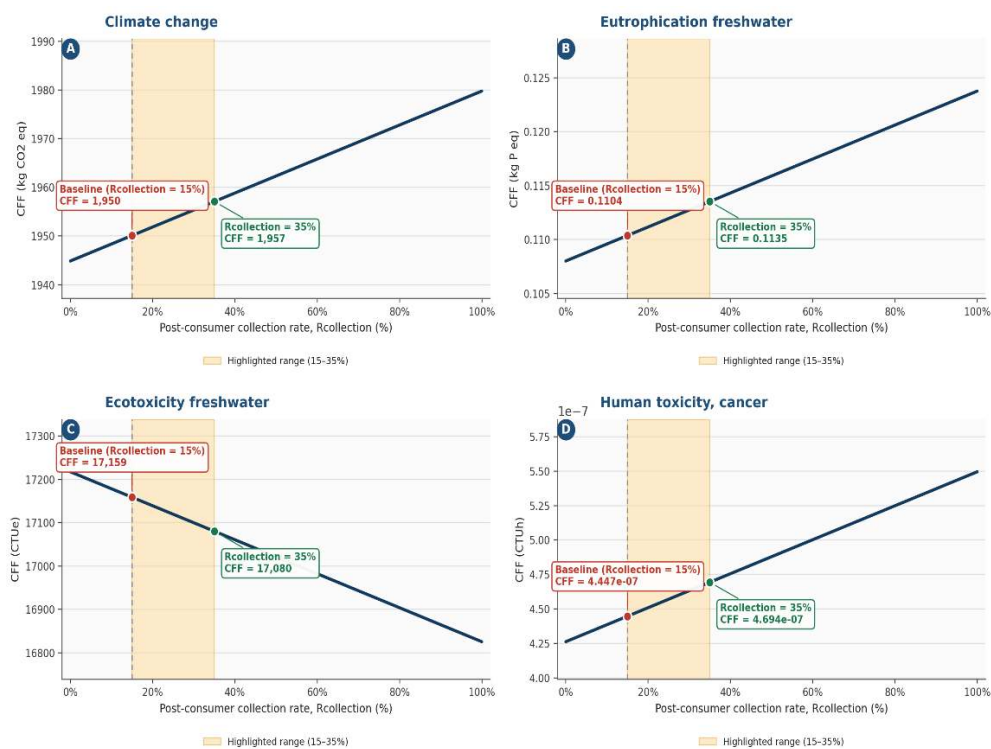


Figure 6. CFF sensitivity to collection rate

Drivers of CFF output uncertainty was determined through spearman rank correlation. Figure 7 presents drivers of climate change category.

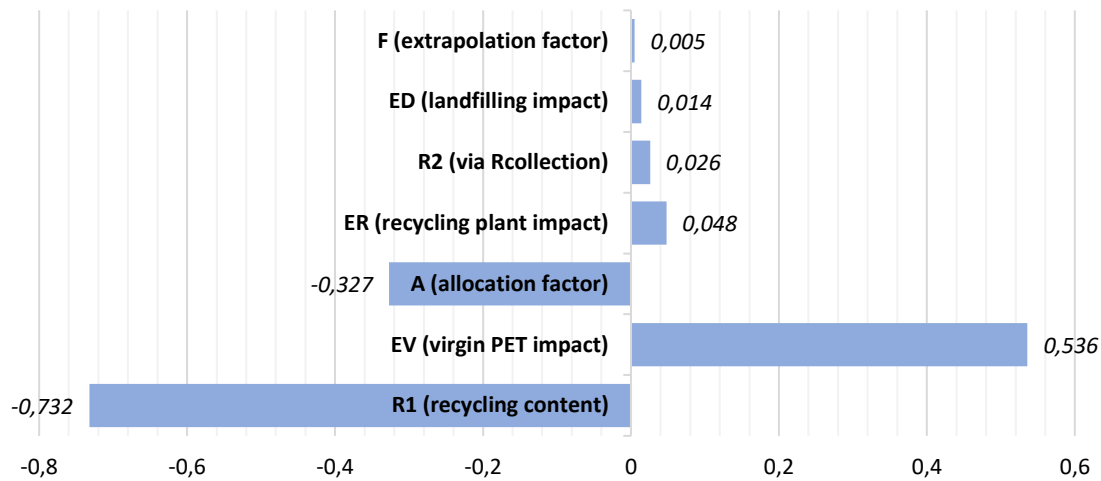


Figure 7. Sensitivity drivers of climate change

4. Discussion

4.1 Gate-to-gate performance

Primary data yield a gate-to-gate climate-change impact of 186 kg CO₂-eq per tonne of food-grade rPET pellets (Table 7). This is an order of magnitude lower than the cradle-to-gate impact of virgin PET resin, for which independent inventories consistently report 2,000–2,800 kg CO₂-eq/t (Franklin Associates, 2020; PlasticsEurope, 2022). The result is also situated at the lower end of the literature for mechanical PET recycling itself. In Europe and North America, gate-to-gate and process-level estimates for mechanically recycled PET typically range from 280 to 1,500 kg CO₂-eq/t, with variation driven by system boundary definition, electricity grid intensity, and whether upstream baling, sorting and transport are included (Shen et al., 2010; Uekert et al., 2023; reporting 0.28–0.53 kg CO₂-eq/kg). Two inventory features explain this low process burden. First, the facility operates on Cameroon's low-carbon electricity mix, which is approximately 70% hydroelectric, resulting in a markedly lower scope 2 emission factor than the UCTE or US average mixes used in most European and North American LCA studies. Second, the boundary is strictly gate-to-gate: post-consumer collection, municipal sorting, bale transport to the plant, and downstream distribution of rPET pellets are deliberately excluded, as specified in Section 2.3. Consequently, direct comparison with cradle-to-gate or cradle-to-grave values is limited and is presented here only to contextualise the magnitude of process-level savings achievable under a low-carbon energy mix.

4.2 CFF-derived net benefit

Application of the Circular Footprint Formula converts the gate-to-gate process impact into a credit-adjusted footprint of 1,600 kg CO₂-eq/t for climate change (Table 9). Relative to the linear baseline defined as virgin PET production plus landfilling, this corresponds to an avoided impact of 27.2%. Across the remaining EF 3.1 categories, the same calculation yields avoided impacts of 27.0% for particulate matter, 28.4% for acidification, and 29.8% for fossil resource use. The opposite sign is observed for human toxicity: –5.8% for cancer effects and –21.2% for non-cancer effects, indicating a modest net increase relative to the linear baseline, attributable

to ancillary chemical and energy inputs in the recycling inventory as well as chemical additives present in post-consumer plastic feedstocks (Hahladakis *et al.*, 2018). The median avoided impact across all sixteen EF 3.1 categories is 28.6%. These figures are direct numerical outputs of the Monte-Carlo CFF runs reported in Section 3.3 and do not include additional uncertainty from choice of allocation. The magnitude of the climate benefit (27.2% avoided) lies toward the lower end of the range reported in the benchmark LCA for open-loop PET bottle-to-fibre recycling. Shen *et al.* (2010) reported, depending on the allocation method applied (cut-off, waste-valuation, system expansion, Non-Renewable Energy Use savings of 40–85% and Global Warming Potential savings of 25–75% for recycled PET fibre versus virgin PET fibre. The present result is consistent with the lower-bound estimates obtained for mechanical recycling under conservative allocation in a developing-country context. Bataineh (2020) found that mechanically recycled PET flake provided a net GHG benefit of sensibly equal to 1.8 kg CO₂-eq per kg of rPET versus virgin production in Jordan, but highlighted that energy consumption during processing and transport dominated the footprint, with recycled PET consuming only 14% less energy than virgin PET in that system. In this study, the use of $A = 0.5$, the mid-point default recommended in the PEF guidance for PET packaging, rather than a 0:100 end-of-life (100% credit to recycled material) approach, explains the more moderate credit relative to studies assigning the full avoided virgin burden to the recycled stream. The choice of A therefore dominates the final credit magnitude, as also stressed by Shen *et al.* (2010).

4.3 Hotspots behind the residual footprint

Contribution analysis (Table 8) isolates two persistent clusters. Electricity production accounts for 67.6 % of climate change, 68 % of fossil-resource use, 83.4 % of particulate-matter formation and 70.8 % of acidification; thermal energy supplies most of the remainder of these categories. This energy dominance is a recurring pattern in mechanical PET recycling LCAs; recent process-level comparisons show electricity contributing 90–97 % of energy use and GHG emissions in many mechanical routes (Uekert *et al.*, 2023). Freshwater eutrophication is almost entirely (99.8 %) attributable to wastewater treatment arising from the caustic hot-wash and rinse stages. The same wastewater stream dominates freshwater ecotoxicity. Identical wastewater-driven eutrophication and toxicity signatures have been reported for mechanical PET systems in Jordan (Bataineh, 2020) and in broader contribution analyses of caustic washing lines, confirming that the nutrient and toxic-load burden is a structural feature of the chemistry rather than a Cameroon-specific artefact. Material-flow analysis supplies a third, operationally actionable finding. The overall bottle-to-pellet yield is 70.66 %. Within the 28 % mass shortfall at the flake-production stage, oversized 10-litre bottles rejected at feeding and sorting constitute the single largest discrete loss (104.59 kg, or 8.3 % of the PET-bottle feed). Labels, caps and non-PET contaminants, dust and fines, and non-recyclable bottles make up the balance. Typical yield losses reported in the literature for mature facilities are attributed primarily to labels, adhesives, colour mixing, or residual contamination and impurities (Santomasi *et al.*, 2024). The 10-litre loss identified here has no direct parallel in the reviewed European or North-American studies and is therefore interpreted as a design–process mismatch: the feeding and sorting equipment was dimensioned for the dominant small- and

medium-format bottles, while the same brands are also sold in 10 L and 20 L formats. Because the loss occurs before energy- or chemical-intensive unit operations, it is both environmentally and economically costly and is, in principle, removable by modest equipment adaptation or by EPR design rules that align bottle formats with existing sorting infrastructure.

4.4 Sensitivity of the CFF result to recycled-content rate

Under the *ceteris-paribus* parametric scenario that holds E_R , R_2 , A and the quality ratios fixed, the CFF effective impact declines linearly with increasing R_1 (Figure 5). The climate-change benefit deepens from the baseline value of 27.20 % avoided impact at $R_1 = 0.25$ toward substantially larger savings at higher recycled-content rates. Collection-rate variation (Figure 6) exerts a weaker influence within the plausible 15–35 % range for urban Cameroon. Spearman rank correlation confirms that R_1 is the dominant driver of CFF output uncertainty for climate change ($\rho = -0.73$), followed by the virgin-PET benchmark E_V ($\rho = 0.54$). This linear response is a direct mathematical property of the CFF equation when process parameters are held constant. It aligns with the broader observation in PEF guidance and related applications that recycled-content rate is a high-leverage variable for packaging systems. Raising R_1 would of course require a corresponding increase in the volume and quality of post-consumer bales; any deterioration in bale quality would shift E_R and R_2 and could flatten the linear gain. Process-efficiency improvements that lower E_R remain complementary: they shift the entire sensitivity curve downward. The relative cost-effectiveness of the two levers cannot be ranked from the present data.

4.5 Policy implications

Three direct policy messages follow from the numbers reported in Section 3. First, the 27.20 % climate benefit already achieved at 25 % recycled content, together with the linear response of the CFF to further increases in R_1 , supports a phased regulatory pathway that raises the minimum recycled-content threshold for PET beverage bottles. Such a mandate would reinforce the emerging EPR framework and create a stable demand signal for food-grade rPET, consistent with the direction of EU Single-Use Plastics Directive targets and analogous African EPR developments. Second, the residual dominance of wastewater treatment in eutrophication and ecotoxicity indicates that discharge fees or scarcity pricing calibrated to the quantified burdens could strengthen the business case for closed-loop water circuits or advanced on-site treatment. Third, the EF 3.1-compliant inventory and CFF parameterisation constructed here provide a ready basis for Product Environmental Footprint declarations. Realising export-market opportunities will additionally require food-contact certification, traceability systems and a national PET quality protocol that standardises CFF reporting—none of which is established by the present study, but all of which become more feasible once primary process data of the quality reported in Tables 5–9 are available.

4.6 Limitations

Five limitations qualify the CFF results reported here. First, the gate-to-gate boundary excludes collection and transport, which contribute 15–35 % of the full system climate burden in comparable cradle-to-gate assessments (Shen *et al.*, 2010); a cradle-to-gate extension would raise both E_R and, to a lesser extent, E_V , narrowing but not eliminating the reported net benefit.

Second, the CFF benchmark values for virgin PET (E_v) and landfilling (E_d) were drawn from established international datasets (Franklin Associates, 2020) rather than measured locally, introducing a source of geographic uncertainty common to nearly all CFF applications outside the regions for which such benchmarks were originally developed. Third, the single-facility, multi-day campaign design, while methodologically rigorous within its scope, cannot capture inter-facility variability across Cameroon's broader (and substantially informal) recycling sector, nor seasonal variation in bale quality between Douala's dry and wet seasons. Fourth, the recycled-content sensitivity analysis (§3.3) holds E_R , R_2 and the quality ratios constant as R_1 varies; in practice, sourcing substantially higher volumes of post-consumer bales to raise R_1 toward 50-100 % could alter bale quality, sorting losses and therefore E_R and R_2 in ways this linear extrapolation does not capture, so the reported curve should be read as an upper-bound, process-technology-held-constant estimate rather than a guaranteed outcome of any specific content mandate. Fifth, the Monte-Carlo uncertainty propagation reported in §2.5/§3.2 characterises uncertainty in the recycling-process impact (E_R) and its underlying life cycle inventory only; uncertainty in R_1 , R_2 , A and the quality ratios (Q_{sin}/Q_p , Q_{out}/Q_p) was not propagated through the CFF itself, and the functional equivalence assumed between food-grade rPET and virgin PET was not independently verified. Consequently, the sign and approximate magnitude of the reported net benefit are consistent with the primary process data collected, but a formal claim that this result is robust to joint uncertainty in the CFF parameters has not yet been demonstrated and should be treated as a priority for the revised analysis rather than an established finding.

5. Conclusion

This study provides a primary-data-based application of the Circular Footprint Formula to mechanical PET recycling in Sub-Saharan Africa. Applied with an allocation factor ($A = 0.5$) consistent with the mid-point of European Commission PEF/CFF guidance to a gate-to-gate life cycle inventory with an end-of-life recycling rate ($R_2 = 10.6$ %) reconstructed as the product of an assumed regional collection rate and the measured plant yield rather than treated as a directly measured end-of-life recyclability parameter, the CFF converts a raw gate-to-gate process impact of 186 kg CO₂-eq per tonne into an effective, policy-comparable climate-change footprint of approximately 1,600 kg CO₂-eq per tonne, corresponding to an avoided impact of 27.2 % relative to a linear baseline of virgin PET production plus landfilling. Comparable avoided impacts were obtained for acidification, fossil resource use and particulate matter, while human toxicity indicators showed a modest net increase; the median avoided impact of 28.6 % across the sixteen EF 3.1 categories evaluated is reported as a descriptive statistic only and should not be read as a formally weighted circularity indicator (§3.3). A *ceteris-paribus* parametric sensitivity analysis, holding the recycling-process impact, end-of-life recycling rate, allocation factor and quality ratios fixed, shows that the credited climate benefit increases monotonically with the input recycled-content rate above the case-study baseline of 25 %; because this response is a mathematical property of the CFF equation under fixed process parameters rather than independent evidence of technical feasibility at higher recycled-

content rates, it is presented here as a policy-relevant scenario for discussion rather than a demonstrated outcome (§4.4). These results should be read alongside the methodological caveats identified in this manuscript: uncertainty was propagated through 10,000 Monte-Carlo iterations for the recycling-process inventory only, and uncertainty in R_1 , R_2 , A and the quality ratios (Q_{sin}/Q_p , Q_{out}/Q_p , both assumed equal to 1 on the basis of PEFCR guidance for closed-loop, food-contact systems) has not yet been propagated through the CFF itself; the gate-to-gate boundary excludes collection and transport, whose inclusion would narrow, but is not expected to eliminate, the reported benefit; and the single-facility campaign design cannot capture inter-facility or seasonal variability across Cameroon's broader recycling sector (§4.6). Subject to this further work, the findings indicate that the Circular Footprint Formula, parameterised with high-pedigree primary data, offers a policy-relevant, moderate but consistently positive, basis for quantifying and improving the circularity performance of plastics recycling in resource-constrained settings, and that recycled-content policy, alongside investment in process-level efficiency and wastewater management, is an influential lever for narrowing Cameroon's circularity gap.

Acknowledgements

The authors thank the management and staff of Ecogreen Sarl and Source du Pays S.A. for facility access and operational data, and the Department of Environmental Engineering, National Advanced School of Public Works (ENSTP), the Laboratory of Hydrology and Environment, University of Yaoundé I, Yaoundé, for institutional support.

Funding

This research received no specific funding.

Author Contributions (CRediT)

Lele Christian: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Writing – original draft; Supervision
Ajeagah Gideon Aghaindum: Validation; Writing – review & editing
Nkeng George Elambo: Writing – review & editing; Supervision.

Ethics Approval and Consent to Participate

Not applicable. This study involved no human participants or animals.

Competing Interests

The authors declare no competing interests.

Data Availability Statement

Supporting data are available from the corresponding author upon reasonable request.

Declaration of Generative AI Use

No generative AI use was declared.

Consent for Publication

All authors approved the final manuscript and consented to its publication.

References

Afrik21.africa. (2023, January 8). *Ecogreen, a new start-up for plastic waste recycling in Cameroon*. <https://www.expadd.org/en/cameroon-ecogreen-a-new-start-up-for-plastic-waste-recycling/>

- Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). *Updated characterisation and normalisation factors for the Environmental Footprint 3.1 method* (EUR 31414 EN, JRC130796). Publications Office of the European Union. <https://doi.org/10.2760/798894>
- ARSEL. (2026). *Rapport d'activité 2025*. Agence de la Régulation du Secteur de l'Électricité. <https://arsel-cm.org/rapports-annuels/>
- Allacker, K., Mathieux, F., Pennington, D., & Pant, R. (2017). The search for an appropriate end-of-life formula for the purpose of the European Commission Environmental Footprint initiative. *International Journal of Life Cycle Assessment*, 22(9), 1441-1458. <https://doi.org/10.1007/s11367-016-1244-0>
- Barkhausen, R., Rostek, L., Miao, Z. C., & Zeller, V. (2023). Combinations of material flow analysis and life cycle assessment and their applicability to assess circular economy requirements in EU product regulations. *Journal of Cleaner Production*, 407, Article 137017. <https://doi.org/10.1016/j.jclepro.2023.137017>
- Bataineh, K. M. (2020). Life-cycle assessment of recycling postconsumer high-density polyethylene and polyethylene terephthalate. *Advances in Civil Engineering*, 2020, 1-15. <https://doi.org/10.1155/2020/8905431>
- Benyathiar, P., Kumar, P., Carpenter, G., Brace, J., & Mishra, D. K. (2022). Polyethylene terephthalate (PET) bottle-to-bottle recycling for the beverage industry: A review. *Polymers*, 14(15), Article 2366. <https://doi.org/10.3390/polym14122366>
- Brunner, P. H., & Rechberger, H. (2016). *Handbook of material flow analysis: For environment, resource, and waste engineers* (2nd ed.). CRC Press. <https://doi.org/10.1201/9781315313450>
- Business in Cameroon. (2017). *Cameroon: source du pays captured 61.7% of mineral water market shares in 2017*. Business in Cameroon. <https://www.businessincameroon.com/agrobusiness/2808-8286-cameroon-source-du-pays-captured-61-7-of-mineral-water-market-shares-in-2017>
- Business in Cameroon. (2026). *Cameroon signs deals for \$1.4 billion waste-to-energy projects in douala and Yaoundé*. <https://www.businessincameroon.com/public-management/1603-15898-cameroon-signs-deals-for-1-4-billion-waste-to-energy-projects-in-douala-and-yaounde>
- Chaudhari, U. S., Johnson, A. T., Reck, B. K., Handler, R. M., Thompson, V. S., Hartley, S. H., Young, W., Watkins, D., & Shonnard, D. (2022). Material flow analysis and life cycle assessment of polyethylene terephthalate and polyolefin plastics supply chains in the United States. *ACS Sustainable Chemistry and Engineering*, 10(39), 13145-13155. <https://doi.org/10.1021/acssuschemeng.2c04004>
- Ciroth, A., Muller, S., Weidema, B. P., & Lesage, P. (2016). Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *International Journal of Life Cycle Assessment*, 21(9), 1338-1348. <https://doi.org/10.1007/s11367-013-0670-5>
- Corona, B., Shen, L., Reike, D., & Blok, K. (2019). Towards sustainable development through the circular economy - A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, 151, Article 104498. <https://doi.org/10.1016/j.resconrec.2019.104498>
- Crawford, C. B., & Quinn, B. (2017). *Microplastic pollutants* (1st ed.). Elsevier Science.

- Ellen MacArthur Foundation & United Nations Environment Programme. (2021). *The Global Commitment 2021 Progress Report*.
<https://content.ellenmacarthurfoundation.org/m/4e0229983b5d1ecd/original/The-Global-Commitment-2021-Progress-Report.pdf>
- Eriksen, M. K., Pivnenko, K., Faraca, G., Boldrin, A., & Astrup, T. F. (2020). Dynamic material flow analysis of PET, PE, and PP flows in Europe: Evaluation of the potential for circular economy. *Environmental Science & Technology*, 54(24), 16166-16175.
<https://doi.org/10.1021/acs.est.0c03435>
- European Commission. (2013). *Product Environmental Footprint (PEF) guide*. Joint Research Centre. N 070307/2009/552517.
- European Commission. (2018). *Product Environmental Footprint Category Rules Guidance, Version 6.3*. Joint Research Centre.
- European Commission. (2021). *Environmental Footprint 3.1 method*. Joint Research Centre.
- Franklin Associates. (2020). Cradle-to-resin life cycle analysis of polyethylene terephthalate resin. National Association for PET Container Resources. <https://napcor.com/sustainability/life-cycle-analysis/>
- García-Gutiérrez, P., Amadei, A. M., Klenert, D., Nessi, S., Tonini, D., Tosches, D., Ardente, F., & Saveyn, H. (2023). *Environmental and economic assessment of plastic waste recycling: A comparison of mechanical, physical, chemical recycling and energy recovery of plastic waste* (EUR 31423 EN, JRC132067). Publications Office of the European Union. <https://doi.org/10.2760/0472>
- Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, 3(7), Article e1700782. <https://doi.org/10.1126/sciadv.1700782>
- Godfrey, L., Ahmed, M. T., Gebremedhin, K. G., Katima, J. H. Y., Oelofse, S., Osibanjo, O., Richter, U. H., & Yonli, A. H. (2019). Solid waste management in Africa: Governance failure or development opportunity? In H. Edomah (Ed.), *Regional development in Africa* (pp. 235-247). IntechOpen. <https://doi.org/10.5772/intechopen.86974>
- Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics. *Journal of Hazardous Materials*, 344, 179-199.
<https://doi.org/10.1016/j.jhazmat.2017.10.014>
- Haupt, M., & Hellweg, S. (2019). Measuring the environmental sustainability of a circular economy. *Environmental and Sustainability Indicators*, 1-2, Article 100005.
<https://doi.org/10.1016/j.indic.2019.100005>.
- Igos, E., Benetto, E., Meyer, R., Baustert, P., & Othoniel, B. (2019). How to treat uncertainties in life cycle assessment studies?. *Journal of Cleaner Production*, 24, 794-807.
<https://doi.org/10.1007/s11367-018-1477-1>
- International Organization for Standardization. (2006a). ISO 14040: *Environmental management - Life cycle assessment - Principles and framework*.
- International Organization for Standardization. (2006b). ISO 14044: *Environmental management - Life cycle assessment - Requirements and guidelines*.
- Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in

- comparison with mechanical recycling and energy recovery. *Science of The Total Environment*, 769, Article 144483. <https://doi.org/10.1016/j.scitotenv.2020.144483>
- Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., Itsubo, N., Peña, C., Pennington, D., Potting, J., Rebitzer, G., Stewart, M., De Haes, H. A. U., & Weidema, B. (2004). The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. *International Journal of Life Cycle Assessment*, 9(6), 394-404. <https://doi.org/10.1065/lca2004.09.175>
- Lavers Westin, A., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R., & Rydberg, T. (2019). Combining material flow analysis with life cycle assessment to identify hotspots of urban consumption. *Journal of Cleaner Production*, 226, 526-539. <https://doi.org/10.1016/j.jclepro.2019.04.036>.
- Lele, C. (2025). *Optimising environmental performance of the recycling of polyethylene terephthalate bottles in the context of circular economy: Case of mineral water (Opur and Supermont) bottles [Master's thesis]*. National Advanced School of Public Works, Yaoundé.
- MINEPDED. (2024). *National Strategy to Combat Plastic Pollution*. Ministry of Environment, Protection of Nature and Sustainable Development, Cameroon. <https://minepded.gov.cm/wp-content/uploads/2024/01/NATIONAL-STRATEGY-TO-COMBAT-PLASTIC-POLLUTION.pdf>
- Morais, J., Glen, C., Golev, A., Lawson, L., & Ali, S. (2022). Global review of human waste-picking and its contribution to poverty alleviation and a circular economy. *Environmental Research Letters*, 17(6). Article 063002. <https://doi.org/10.1088/1748-9326/ac6b49>
- NAPCOR. (2025). *2024 PET Recycling Report*. National Association for PET Container Resources. <https://napcor.com/reports-resources/>
- Ngnikam, E., Naquin, P., Oumbe, R., & Djietcheu, K. (2017). Evolution des caractéristiques des déchets solides ménagers dans la ville de Yaoundé au Cameroun (1995-2015). *Déchets, sciences et techniques*, 74, Article 7778. <https://doi.org/10.4267/dechets-sciences-techniques.3654>
- Ogut, F. A., & Kathambi, B. (2022). Recycling gap, Africa's perspective for sustainable waste management. In H. M. Saleh & A. I. Hassan (Eds.), *Recycling strategy and challenges associated with waste management towards sustaining the world* (Chap. 5). IntechOpen. <https://doi.org/10.5772/intechopen.108582>
- PlasticsEurope. (2022). *Eco-profiles and environmental product declarations of the European plastics manufacturers: Polyethylene Terephthalate (PET)*.
- Rigamonti, L., Grosso, M., Moller, J., Martinez Sanchez, V., Magnani, S., & Christensen, T.H. (2014). Environmental evaluation of plastic waste management scenarios. *Resources, Conservation and Recycling*, 85, 12-53. <https://doi.org/10.1016/j.resconrec.2013.12.012>
- Rousselet, G. A., & Wilcox, R. R. (2020). Reaction times and other skewed distributions: Problems with the mean and the median. *Meta-Psychology*, 4, Article 1630. <https://doi.org/10.15626/MP.2019.1630>
- Santomasi, G., Todaro, F., Petrella, A., Notarnicola, M., & Thoden van Velzen, E. U. (2024). Mechanical recycling of PET multi-layer post-consumer packaging: Effects of impurity content. *Recycling*, 9(5), Article 93. <https://doi.org/10.3390/recycling9050093>.

- Shen, L., Worrell, E., & Patel, M. K. (2010). Environmental impact assessment of mechanical and feedstock recycling. *Resources, Conservation and Recycling*, 55(1), 34-52. <https://doi.org/10.1016/j.resconrec.2010.06.014>
- Tonini, D., Garcia-Gutierrez, P., & Nessi, S. (2021). *Environmental effects of plastic waste recycling* (EUR 30668 EN, JRC122455). Publications Office of the European Union. <https://doi.org/10.2760/955772>
- Uekert, T., Singh, A., DesVeaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., Afzal, S., Walzberg, J., Knauer, K.M., Nicholson, S.R., Beckham, G.T., & Carpenter, A.C. (2023). *Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics*. *ACS Sustainable Chemistry & Engineering*, 11(3), 965–978. <https://doi.org/10.1021/acssuschemeng.2c05497>
- Weidema, B. P., Bauer, C., Hischer, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O., & Wernet, G. (2013). *Overview and methodology: Data quality guideline for the ecoinvent database version 3* (Ecoinvent Report No. 1). Swiss Centre for Life Cycle Inventories.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, 21(9), 1218-1230. <https://doi.org/10.1007/s11367-016-1087-8>
- Yeboah, C., Tetteh, E. K., Chollom, M. N., & Rathilal, S. (2025). Sustainable solutions for plastic waste mitigation in Sub-Saharan Africa. *Polymers*, 17(11), 1521. <https://doi.org/10.3390/polym17111521>
- Yin, R. K. (2018). *Case study research: Design and methods* (6th ed.). SAGE Publications.