



## **Integrating material flow analysis and life cycle assessment to optimise mechanical recycling of Polyethylene Terephthalate from some mineral water bottles in Douala-Cameroon: hotspots, circular benefits and low-cost scenario**

*Nkeng George Elambo <sup>[1]\*</sup> and Lele Christian <sup>[1]</sup>*

*[1] National Advanced School of Public Works, École Nationale Supérieure des Travaux Publics, BP 150, Environmental Engineering Department, Yaoundé city, Cameroon*

*\*Correspondence: [gnkeng@yahoo.fr](mailto:gnkeng@yahoo.fr); Tel.: +237 677700507*

### **Abstract**

The transition toward a circular economy for plastics in developing nations is frequently hindered by a critical lack of primary data regarding the operational and environmental performance of existing recycling infrastructures. This study evaluates and optimises the mechanical recycling of post-consumer polyethylene terephthalate (PET) bottles in Cameroon (Douala) using a synergistic framework combining Material Flow Analysis (MFA), gate-to-gate Life Cycle Assessment (LCA), and Multi-Criteria Decision Analysis (MCDA). To capture the cascading efficiency losses across the industrial line, a twofold Functional Unit (FU) was established: an intermediate (1,000 kg of clean PET flakes) and a final (1,000 kg of food-grade recycled PET pellets). Utilising primary industrial data, the baseline diagnostic reveals an overall material yield of 70.66% for the final pellets. The climate change impact is quantified at 112.25 kg CO<sub>2</sub>-eq per tonne of rPET pellets—substantially lower than virgin PET production, a finding validated by the Circular Footprint Formula (CFF) demonstrating a net climate benefit of -36.9%. However, the integrated MFA-LCA model identified critical system inefficiencies during the diagnostic phase: a high water intensity (714.46 L/tonne) and an 8.3% pure material loss stemming exclusively from the dimensional incompatibility of 10-litre water bottles with existing crushing equipment. To address these hotspots, two optimisation scenarios were engineered and evaluated using the ELECTRE I method. Results indicate that a low-capital intervention (semi-automatic bottle cutting) outperforms high-tech solutions (water ultrafiltration) by increasing the final yield to 83.45% with a three-month return on investment. These findings provide empirical evidence that targeted, context-appropriate technical interventions can significantly bridge the circularity gap in resource-constrained environments.

**Keywords:** Circular economy; Life Cycle Assessment; Material Flow Analysis; Polyethylene terephthalate; Mechanical recycling; Douala-Cameroon.

### **Résumé**

La transition vers une économie circulaire pour les plastiques dans les pays en développement est fréquemment entravée par un manque critique de données primaires concernant les performances opérationnelles et environnementales des infrastructures de recyclage existantes. Cette étude évalue et optimise le recyclage mécanique des bouteilles en polyéthylène téréphtalate (PET) post-consommation au Cameroun (Douala) à l'aide d'un cadre méthodologique synergique combinant l'Analyse des Flux de Matières (AFM), l'Analyse du Cycle de Vie (ACV) de la porte à la porte, et l'Analyse Décisionnelle Multi-Critères (ADMC). Afin de capter les pertes d'efficacité en cascade le long de la chaîne industrielle, une Unité Fonctionnelle (UF) double a été établie : une unité intermédiaire (1 000 kg de paillettes de PET propres) et une unité finale (1 000 kg de granulés de PET recyclé de qualité alimentaire). En s'appuyant sur des données industrielles primaires, le diagnostic de référence révèle un rendement matière global de 70,66 % pour les granulés finaux. L'impact sur le changement climatique est quantifié

**Nkeng et al.:** Integrating material flow analysis and life cycle assessment to optimise mechanical recycling of Polyethylene Terephthalate from some mineral water bottles in Douala-Cameroon: hotspots, circular benefits and low-cost scenario

à 112,25 kg éq. CO<sub>2</sub> par tonne métrique de granulés de rPET — sensiblement inférieur à la production de PET vierge — un résultat validé par la Formule d'Empreinte Circulaire (FEC) démontrant un bénéfice climatique net de -36,9 %. Toutefois, le modèle intégré AFM-ACV a identifié, lors de la phase diagnostique, des inefficacités systémiques critiques : une forte intensité hydrique (714,46 L/tonne) et une perte matière pure de 8,3 % découlant exclusivement de l'incompatibilité dimensionnelle des bouteilles d'eau de 10 litres avec les équipements de concassage existants. Pour résoudre ces points critiques, deux scénarios d'optimisation ont été conçus et évalués à l'aide de la méthode ELECTRE I. Les résultats indiquent qu'une intervention à faible capital (découpe semi-automatique des bouteilles) surpasse les solutions à haute technologie (ultrafiltration de l'eau) en portant le rendement final à 83,45 % avec un retour sur investissement de trois mois. Ces résultats apportent des preuves empiriques que des interventions techniques ciblées et adaptées au contexte peuvent combler de manière significative le déficit de circularité dans les environnements aux ressources limitées.

**Mots-clés :** Économie circulaire ; Analyse du Cycle de Vie ; Analyse des Flux de Matières ; Polyéthylène téréphthalate ; Recyclage mécanique ; Douala-Cameroun.

## I. Introduction

The unprecedented proliferation of plastic production and consumption constitutes one of the defining environmental challenges of the Anthropocene. Global plastic production has surged exponentially over recent decades, with an annual output surpassing 400 million tonnes, of which single-use packaging remains the dominant fraction (Geyer et al., 2017; PlasticsEurope, 2024). Among these polymers, Polyethylene Terephthalate (PET) is highly ubiquitous due to its exceptional mechanical strength, gas barrier properties, and optical clarity, making it the premier choice for beverage bottling. However, the linear "take-make-dispose" paradigm has led to catastrophic ecological consequences. Globally, less than 15% of post-consumer PET is successfully collected and recycled into secondary applications, with the remainder culminating in marine ecosystems, terrestrial landfills, or open-air incineration (MacArthur et al., 2020; Eriksen et al., 2020).

In Sub-Saharan Africa (SSA), the plastic pollution crisis is uniquely amplified by rapid urbanisation, exponential demographic growth, and chronically underfunded municipal solid waste management (MSWM) systems (Godfrey et al., 2022). In Cameroon, urban hubs such as Douala generate more than 600,000 tonnes of plastic waste annually, yet formal collection and municipal recycling rates consistently languish below 10% (MINEPDED, 2024; Jambeck et al., 2015). The institutional and structural deficit in municipal infrastructure forces a heavy reliance on a marginalised, informal network of waste pickers. Consequently, large volumes of post-consumer PET escape the formal value chain, causing severe urban drainage blockages, contributing to recurrent flooding, and driving localised open-burning practices that release persistent organic pollutants and greenhouse gases into the atmosphere (Nikiema & Asiedu, 2022).

Transitioning to a Circular Economy (CE) through industrial mechanical recycling represents the most mature and thermodynamically viable pathway to decouple plastic demand from fossil resource depletion (Rocha et al., 2022; Zheng & Suh,

2019). Mechanical reprocessing has been extensively proven to reduce carbon emissions by up to 60% compared to the synthesis of virgin PET resin (Shen et al., 2010). Nevertheless, the current body of literature on plastic recycling systems suffers from a profound geographical bias, as the vast majority of published Material Flow Analyses (MFA) and Life Cycle Assessments (LCA) rely disproportionately on secondary data or proxy operational averages derived from highly automated European and North American facilities (Faraca et al., 2019; Santomasini et al., 2024).

Applying global or Western baseline datasets to the African context introduces severe scientific distortions. Recycling plants in developing economies operate under radically different conditions, characterised by severe input contamination, fluctuating electricity grid stability, high volumetric water consumption, and a unique socio-technical landscape (Shamsuddin, A.S. et al., 2025). More importantly, recent systemic reviews note a critical lack of primary industrial data tracking how local packaging design features interact with processing machinery in developing markets (Liang et al., 2023; Khan et al., 2024). While Western researchers often evaluate advanced chemical degradation or multi-layer film separation as primary barriers to circularity, operators in SSA face fundamental, physical and dimensional incompatibilities between market-specific product designs and standard recycling infrastructures. Furthermore, traditional engineering methodologies frequently treat recycling plants as an aggregated "black box," masking the specific locations where material and environmental efficiencies diverge. By failing to separate the industrial facility into distinct subsystems the literature fails to accurately capture where the greatest circularity losses occur (Eriksen et al., 2019).

To bridge these critical empirical and methodological gaps, this study introduces a comprehensive, data-driven framework formulated around two core, testable research hypotheses. The first hypothesis posits that in resource-constrained developing economies, the primary operational and material bottlenecks restricting plastic circularity are

driven by physical, dimensional mismatches between local, market-specific product designs and standard processing infrastructures, rather than the chemical contamination barriers typical of advanced industrial economies. The second hypothesis suggests that under severe capital and infrastructure constraints, a low-cost, decentralised mechanical optimisation strategy will outrank highly automated, high-capital eco-efficiency retrofits across a multi-criteria techno-economic and environmental decision matrix.

The overarching objective of this study is to execute a rigorous gate-to-gate diagnostic and optimisation assessment of an operational, medium-scale PET mechanical recycling facility in Douala, Cameroon, using direct primary industrial inventories to systematically test these hypotheses. To achieve this comprehensive goal, the study first maps the physical economy of the processing facility using a Material Flow Analysis to isolate the exact nodes, structural features, and product dimensions responsible for material loss and processing inefficiencies. Subsequently, it conducts a life cycle impact assessment split into two distinct subsystems to pinpoint localised ecological hotspots.

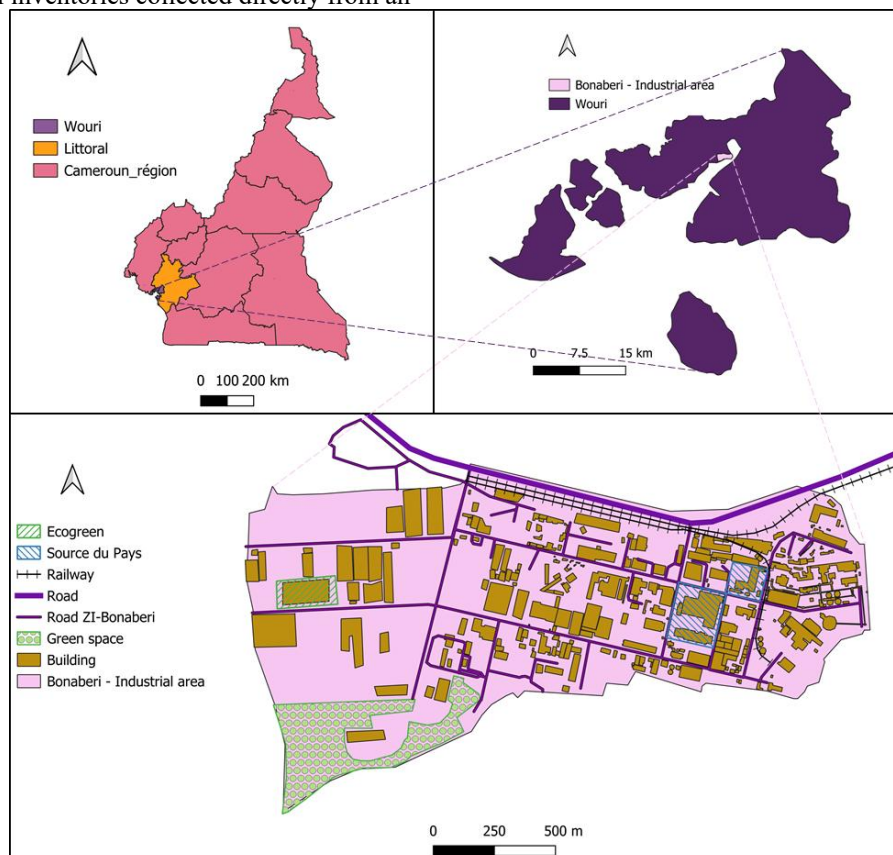
The novelty of this research rests on three core contributions: the reliance on primary gate-to-gate industrial inventories collected directly from an

operational line in Cameroon, the methodological granularity achieved by coupling MFA with LCA using dual functional units, and the application of context-driven optimisation via the ELECTRE I method to evaluate pragmatic, ex-post scenarios. By explicitly identifying how design mismatches in local product packaging drive mass destruction within specific subsystems, this study provides actionable insights. The resulting data offer a robust, transparent baseline for policymakers and industrial stakeholders designing and implementing Extended Producer Responsibility frameworks across developing nations.

## II. Materials and methods

### 2.1. Study area and system boundaries

The empirical foundation of this study relies on primary foreground data obtained from Ecogreen Sarl, a medium-scale industrial mechanical plastic recycling plant, located in Douala, Littoral Region, Wouri Department, Cameroon (Figure I). Douala, situated at 4°03'N, 9°42'E, constitutes the country's primary economic and industrial hub. It presents a critical case study for Sub-Saharan African (SSA) waste management due to its equatorial climate, high humidity, rapid unplanned urbanisation, and severe plastic-induced municipal drainage bottlenecks (GWP, 2023).



**Figure I.** Location of recycling plant in Douala, Cameroon

The field-sampling and data-monitoring campaigns were executed over a representative six-month operational period. This temporal window captured seasonal variations in feedstock quality, structural

**Nkeng et al.:** Integrating material flow analysis and life cycle assessment to optimise mechanical recycling of Polyethylene Terephthalate from some mineral water bottles in Douala-Cameroon: hotspots, circular benefits and low-cost scenario

contamination, and electricity grid reliability. The plant processes post-consumer PET bottles retrieved from formal and informal collection networks, dominantly composed of municipal beverage packaging from market-leading domestic brands (e.g., Opor and Supermont).

## 2.2. Functional unit and system boundaries

Mechanical recycling in data-scarce, resource-constrained regions involves highly volatile feedstock qualities and cascading material losses that distort a single unit analysis (Eriksen et al., 2019). Consequently, this study establishes a twofold Functional Unit (FU) framework to independently audit the efficiencies of the intermediate and final processing phases:

- **Intermediate functional unit:** The production of 1,000 kg of clean, sorted PET flakes at the exit of subsystem 1. This unit serves to isolate and quantify the environmental and material burdens of collection-bale conditioning, sorting, and primary mechanical processing;
- **Final functional unit:** The production of 1,000 kg of food-grade rPET pellets at the factory gate. This final reference point encapsulates the cumulative impacts of the entire system, highlighting the energy-intensive of pelletising and extrusion steps.

The system boundary is defined as gate-to-gate, focusing strictly on the Technosphere under direct industrial control. The operations are explicitly split into two interconnected subsystems aligned with the functional units: PET flake production (Bale-to-Flakes) and rPET resin production (Flakes-to-Pellets). Upstream processes (such as informal picking, municipal transport, and bale consolidation) and downstream processes (such as secondary blow-moulding and final consumer use) fall outside the scope of this industrial audit (Figure 2).

## 2.3. Material flow analysis modelling

To map the physical economy of the facility and mathematically model the transformation of waste into secondary resources, a Material Flow Analysis (MFA) was performed in strict accordance with the core methodology developed by Brunner and Rechberger (2016). Unlike conventional MFAs that rely on static, annual plant capacities, this model is directly coupled to the twofold Functional Unit. All mass flows ( $\dot{m}_i$ ), solid waste fractions, wastewater volumes, and process emissions are normalised dynamically using the mass conservation law:

$$\sum \dot{m}_{inputs} = \sum \dot{m}_{outputs} + \Delta \dot{m}_{storage} \quad (1)$$

Where  $\Delta \dot{m}_{storage}$  is assumed to be zero under continuous, steady-state industrial operations.

Primary data collection on rigorous physical tracking. Raw input bales, sorted non-PET fractions (caps, paper labels), rejected bottles, and fine polymer dust fractions were systematically weighted utilising calibrated platform scales ( $\pm 0.5$  kg). Mass differences across the thermal drying and extrusion stages were monitored to quantify water vapour loss and volatile organic compound (VOC) emissions. The balanced mass network, including transfer coefficients for individual processing nodes, was modelled using STAN (Substance Flow Analysis) v2.0 software. This computational setup enabled data reconciliation and the calculation of statistical uncertainties, ensuring a rigorous, audited closure of the material balances before transferring the parameters to the life cycle inventory.

The Sankey diagram was constructed to provide a clear, proportional visual representation of all material flows within the recycling system. Reconciled and balanced output values are exported from STAN v2.0 into SankeyMATIC, a web-based platform facilitating creation of high-resolution Sankey diagrams.

## 2.4. Life cycle assessment framework

The environmental impacts of the mechanical recycling process were evaluated following the ISO 14040/14044 standards.

### 2.4.1. Life cycle inventory and data quality

The Life Cycle Inventory (LCI) was populated utilising a strict data hierarchy, prioritising high-quality primary foreground data collected directly from the plant's operational logs, utility metres, and material invoices over the six-month observation window. Background data, encompassing the upstream production of processing chemicals (such as sodium hydroxide and surfactants), diesel fuel production, and waste disposal infrastructure, were extracted from the ecoinvent v3.10 database (Wernet et al., 2016).

A critical regional modification was performed on the background electricity dataset. The standard global or regional proxy grids fail to reflect local realities; therefore, a country-specific electricity mix was synthesised to reflect Cameroon's national grid profile, which is highly decarbonised and structurally dominated by hydroelectricity (approximately 70% hydro, with the remaining 30% split between heavy fuel oil and natural gas thermal plants) (ENEO, 2024)

Foreground consumption parameters (water, fuel, electricity, and chemicals) were systematically allocated and scaled across both the intermediate and final functional units, accounting for the cumulative downstream drag caused by the mass rejections identified in the MFA phase.

### 2.4.2. Life cycle impact assessment and circular footprint formula

The environmental profiles were computed using openLCA v2.2 software. Impact characterisation was performed using the European Commission’s Environmental Footprint (EF) 3.1 method, focusing on mid-point indicators highly sensitive to recycling systems: Global Warming Potential (GWP<sub>100</sub>), Water depletion, Freshwater eutrophication and Particulate matter formation. Results was normalised relatively to the European citizen (European Commission, 2021).

To rigorously allocate the environmental burdens and credits of the secondary material across its cascading life cycles, the standard Circular Footprint Formula (CFF) mandated by the European Product Environmental Footprint (PEF) guide (European Commission, 2019) was mathematically integrated into the model. The CFF parameters were calibrated as follows:

$$E = (1 - R_1)E_v + R_1 \left[ AE_R + (1 - A)E_v \frac{Q_{sin}}{Q_p} \right] + (1 - A)R_2 \left[ E_R - E_v \frac{Q_{sout}}{Q_p} \right] + (1 - R_2)E_D \quad (2)$$

Where:

- **A (Allocation factor):** Set at **0.8** for PET packaging, allocating 80% of the recycling credit to the recyclers to reflect market-driven circular supply (Santomasi et al., 2024);
- **R<sub>1</sub> and R<sub>2</sub> (Recycled content and recycling rate):** Adjusted based on empirical plant efficiencies and local market sourcing data;
- **Q<sub>sin</sub>/Q<sub>p</sub> and Q<sub>sout</sub>/Q<sub>sin</sub> (Quality ratios):** Calibrated to **0.90** to account for minor polymer degradation between virgin and secondary food-grade resin (Eriksen et al., 2022);
- **E<sub>v</sub> and E<sub>R</sub> (Environmental Impact):** respectively of virgin and recycled material production.

To handle operational data volatility, parameter uncertainties were systematically evaluated through a stochastic Monte Carlo simulation running 10,000.

### 2.5. Multi-criteria decision analysis

To evaluate process optimisations without resorting to arbitrary assumptions, two scenarios were structurally engineered ex-post, targeting the primary hotspots uncovered during the diagnostic MFA-LCA phases:

- **Scenario 1 (Mechanical Optimisation):** Integration of an upstream, low-cost, semi-automatic cutting machine designed to pre-slice 10L bulk water packaging, directly resolving the mass rejection hotspot within Subsystem 1.
- **Scenario 2 (Eco-Efficiency Optimisation):** Retrofitting Subsystem 1 with an automated closed-loop ultrafiltration and clarification system to handle the high volumetric water footprint and effluent toxicity.

To select the most viable pathway within a resource-constrained industrial ecosystem, the non-compensatory ELECTRE I method was deployed (Roy, 1968). This multi-criteria framework ensures that excellent performance in environmental categories cannot simply offset severe economic barriers (Table I).

**Table I.** Thresholds per criterion in the multi-criteria decision analysis

C <sub>r</sub>	Criterion	Scaling reference	Veto threshold (v)	Weight
1	GWP reduction (%)	Per final FU	3 %	3
2	Water scarcity reduction (%)	Per final FU	1 %	3
3	Other impacts categories	Per final FU	1 %	3
4	Circular footprint reduction (%)	Average reduction per final FU	2 %	3
5	Technical feasibility	Qualitative (1-5)	2.0 (veto if ≤2)	2
6	Economic feasibility (10×ROI)	Financial Log	2	2
7	Policy alignment (number)	Direct alignments accounting	1 (veto if < 1)	1

or every pair of scenarios \$(a, b)\$, the concordance index \$C(a, b)\$ and the discordance index \$D(a, b)\$ are defined by the following equations:

$$C(a, b) = \frac{1}{K} \sum_{\forall i, g_i(a) \geq g_i(b)} k_i \quad (2)$$

$$D(a, b) = \frac{1}{\delta} \max_i (g_i(b) - g_i(a)) \quad (3)$$

\$K\$ is the sum of \$k\_i\$ and \$\delta\$ is the maximal difference between two scenarios in the same criterion. Finally, scenario \$a\$ outranks scenario \$b\$ only if the \$C(a, b) \geq c\$ and the discordance index \$D(a, b) \leq d\$.

### III. Results

#### 3.1. Material flow analysis and mass balance

By establishing a mass balance closure of 99.8%, the model successfully eliminated data reconciliation anomalies and isolated the exact nodes responsible for material degradation.

##### 3.1.1. Subsystem 1: Post-consumer bottles to clean PET flakes

Subsystem 1 acts as the primary material loss hotspot (Table II). To produce the Intermediate Functional Unit of 1,000 kg of clean PET flakes, the system requires a baseline input of 1,258.95 kg of post-consumer bottles and 129.93 kg of PET preforms, representing an initial mass reduction of 28%. The primary cause is an 8.3% (equivalent to 104.59 kg per final functional unit) structural occurring during the initial sorting and feeding sequence. This loss is caused entirely by the dimensional incompatibility of 10-litre bulk water packaging. Because these oversized bottles exceed the physical throat geometry of standard industrial crushers, they are manually culled and rejected to prevent mechanical jams.

Table II. Major material loss categories in the recycling subsystem 1

Loss Category	Mass (kg)	% of Input	Primary Stage
10 L PET bottles	104.59	8.3	Feeding & sorting
Labels, caps & non-PET	86.00	6.8	Pre-washing/grinding
Dust & fines	41.30	3.3	Grinding & drying
Optical rejects & sieve	27.70	2.2	Final separation
<b>Total losses</b>	<b>388.87</b>	<b>28.0</b>	PET flakes production

Subsystem 1 also exhibits high resource intensity, requiring 714.46 litres of water per tonne of flakes due to the continuous open-loop design of the friction washing units.

##### 3.1.2. Subsystem 2: Clean PET flakes to food-grade pellets

In contrast, Subsystem 2 exhibits high mass stability. The transformation operates at a high internal material yield of 98.5%. The remaining 1.5% deficit is accounted for by Volatile Organic Compounds (VOCs) and moisture desorption (0.9%) and melt filtration scrap (0.6%). However, Subsystem 2 functions as the facility's primary energy sink, consuming 84% of the total plant electricity.

##### 3.1.3. Sankey diagram

The diagram generated directly from the measured one-day inventory and subsequently normalised to precisely 1,000 kg of PET flakes then 1,000 kg recycled PET resins, are illustrated by the Figure III.

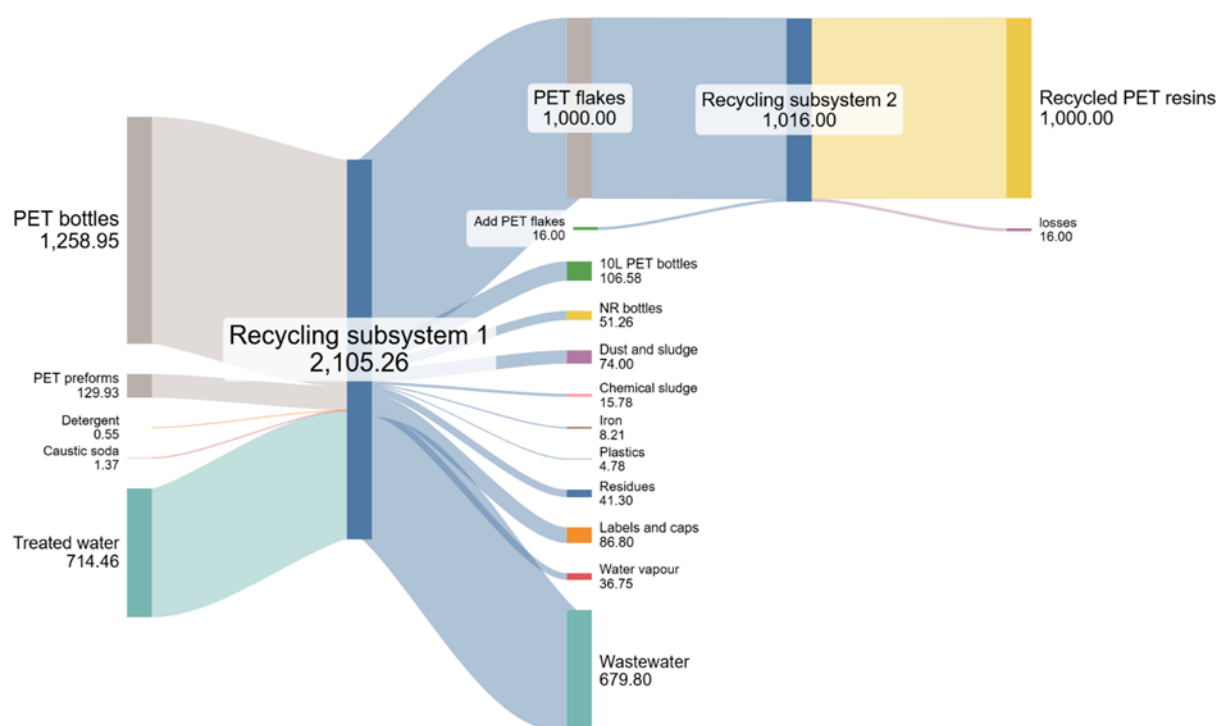


Figure II. Sankey diagram of material flows across the mechanical recycling chain

### 3.2. Environmental impact profile

Evaluating the facility's inventory across both functional units highlights how upstream mass rejections amplify downstream environmental burdens (Table III).

**Table III.** Life cycle impact assessment results per final functional unit

Impact Category	Reference Unit	Mean	Std Dev	Minimum	Maximum	Median
<b>Acidification</b>	mol H <sup>+</sup> eq	<b>0.1545</b>	0.1207	0.0573	2.0905	0.1218
<b>Cancer human toxicity</b>	CTUh	4.10E-07	7.60E-07	4.00E-08	1.74E-05	<b>2.10E-07</b>
<b>Climate change</b>	kg CO <sub>2</sub> eq	<b>112.25</b>	43.02	61.60	765.71	103.28
<b>Ecotoxicity, freshwater</b>	CTUe	1,542.82	2,849.02	127.25	64,864.06	<b>772.31</b>
<b>Eutrophication, freshwater</b>	kg P eq	0.0622	0.1152	0.0053	2.6440	<b>0.0311</b>
<b>Eutrophication, marine</b>	kg N eq	0.1034	0.1460	0.0217	3.2116	<b>0.0634</b>
<b>Eutrophication, terrestrial</b>	mol N eq	<b>0.4103</b>	0.2864	0.1665	4.8714	0.3344
<b>Ionising radiation, HH</b>	kBq U-235 eq	2.50	2.88	0.76	53.41	<b>1.69</b>
<b>Non-cancer human toxicity</b>	CTUh	2.34E-06	4.33E-06	2.00E-07	9.92E-05	<b>1.17E-06</b>
<b>Ozone depletion</b>	kg CFC-11 eq	2.00E-06	2.00E-06	0.00E+00	3.40E-05	<b>1.00E-06</b>
<b>Particulate matter formation</b>	disease inc.	<b>1.00E-06</b>	1.00E-06	0.00E+00	1.40E-05	1.00E-06
<b>Photochemical ozone formation</b>	kg NMVOC eq	<b>0.0956</b>	0.0523	0.0435	0.8535	0.0826
<b>Resource use, minerals &amp; metals</b>	kg Sb eq	<b>4.10E-05</b>	1.80E-05	2.20E-05	3.53E-04	3.70E-05
<b>Water scarcity</b>	m <sup>3</sup> deprived	95.81	121.67	25.26	2,257.85	<b>61.70</b>

The baseline LCA indicates a cumulative carbon footprint of 112.25 kg CO<sub>2</sub>-eq per tonne of food-grade rPET pellets, notably lower than standard European baselines. However, Subsystem 1 drives localised ecological damage, generating 93.5% of the total system impact for Water Scarcity and 85.7% for Freshwater Eutrophication due to untreated wash water discharge.

The environmental profile balanced by normalisation (mandatory in PEF) is illustrated by the Figure III.

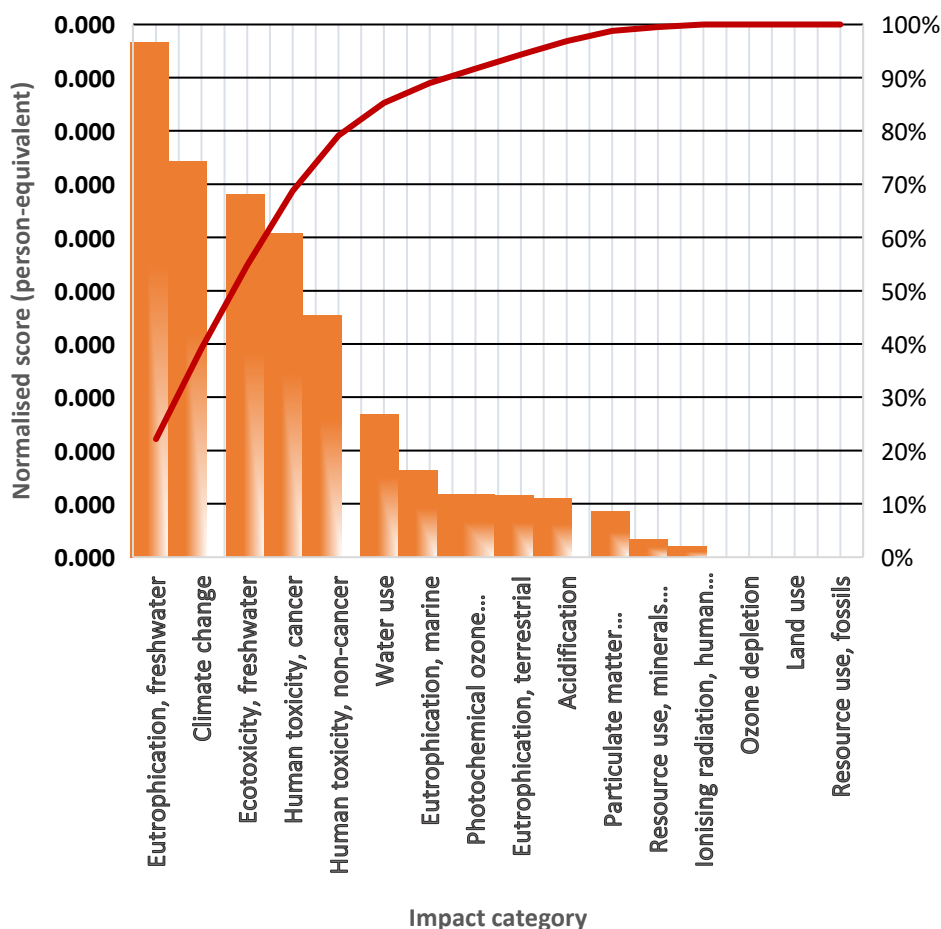


Figure III. Normalised environmental impacts of the recycling process

Applying the European Commission's Circular Footprint Formula (CFF) confirms that despite the material losses occurring in Subsystem 1, the total mechanical line yields a net climate benefit of 36.9% when compared directly against the manufacturing baseline of virgin PET resin, and an average circular benefit of 32.55% in all categories.

### 3.3. Evaluation of optimisation scenarios

#### 3.3.1. Techno-Economic and environmental performance of optimisation scenarios

To resolve the key inefficiencies identified during the diagnostic phase, the performance of the two targeted optimisation scenarios was compiled (Table IV) and evaluated.

Table IV. Performance evaluation matrix for ELECTRE I analysis

Criterion	Optimisation Goal	Baseline Profile	Scenario 1 (Mechanical Cutter)	Scenario 2 (Ultrafiltration)
Carbon Footprint	Minimise	112.25 kg CO <sub>2</sub> -eq	102 kg CO <sub>2</sub> -eq	104.12 kg CO <sub>2</sub> -eq
Water Scarcity	Minimise	61.7 m <sup>3</sup> deprived	62.8 m <sup>3</sup> deprived	40.1 m <sup>3</sup> deprived
Eutrophication freshwater	Minimise	0.0622 kg P eq	0.0425 kg P eq	0.026 kg P eq
Circular footprint benefits	Maximise	32.55%	36.93%	35.15%
Return on Investment	Maximise	0%	400% (3 Months)	16.6% (6 Years)
Technical Feasibility	Maximise	5.0 / 5.0	4.5 / 5.0	2.0 / 5.0
Policy alignment	Maximise	5	2	4

Scenario 1 (Mechanical Cutter) successfully re-integrated the 10L bulk water packaging into the processing line, shifting the overall plant material yield from 70.66% to 83.45%. This produced a cascading benefit, including a 15.2% reduction in GWP per final functional unit. Scenario 2 (Ultrafiltration) reduced Subsystem 1's water consumption by 90%, but increased electricity demand by 4.2%.

### **3.3.2. ELECTRE I outranking relation**

Applying the concordance and discordance thresholds, the final outranking kernel established that Scenario 1 strongly outranks Scenario 2 with  $C(a, b) = 0.8$ ,  $C(b, a) = 0.2$ ,  $D(b, a) = 1$ . The long amortisation period (6+ years) and high technical complexity of Scenario 2 created a substantial barrier, making it unviable for an independent local SME.

## **IV. Discussion**

### **4.1. The methodological value of twofold functional units**

This study challenges standard global LCA assumptions by decoupling environmental and material audits through two distinct functional units: an Intermediate Functional Unit of 1,000 kg of clean PET flakes, and a Final Functional Unit of 1,000 kg of food-grade rPET pellets. Conventional recycling models often treat industrial lines as a single "black box", which attributes most environmental and operational burdens to the energy-intensive thermal extrusion and pelletisation phases of Subsystem 2.

In contrast, this granular approach shows that in developing nations the main barrier to circularity lies upstream in Subsystem 1, Bale-to-Flakes. While Subsystem 2 consumes 84% of total plant electricity, its material yield remains stable at 98.5%. Subsystem 1, however, functions as a major material sink with a 28% mass reduction and accounts for 93.5% of the system's localised water scarcity impact. By isolating these parameters, the study demonstrates that the success of plastic circularity in resource-constrained areas is determined before polymer pelletisation. It is won or lost during the initial sorting, crushing, and washing stages of Subsystem 1.

### **4.2. Upstream eco-design mismatches in Sub-Saharan Africa**

The 8.3% material loss caused solely by the dimensional incompatibility of 10-litre bulk water packaging reveals a critical disconnect between product design and local recycling realities. In advanced economies, barriers to circularity usually involve multi-layer films, complex colourants, or polymer degradation during solid-state polycondensation. In Sub-Saharan Africa, however, operators face a more fundamental barrier: physical packaging dimensions that exceed the intake thresholds of standard machinery.

This mismatch demonstrates the risk of applying Western "Design for Recycling" guidelines without adapting them to local processing capacities. Large beverage manufacturers in Cameroon optimise large-format containers for transport stability and retail volume, which transfers the processing burden to underfunded local recycling facilities. Without updated national engineering standards or mandatory dimensional limits within

local Extended Producer Responsibility frameworks, these design mismatches will continue to cause significant material loss in early recycling stages.

### **4.3. The water-energy nexus and localised ecological trade-offs**

A key finding of this study is the unique profile of Cameroon's national electricity grid, which reshapes traditional life cycle impact dynamics. In standard European or North American LCAs, the carbon footprint of mechanical recycling is dominated by fossil-fuel-based electricity used to power heavy machinery. Cameroon presents the opposite case: approximately 70% of electricity comes from hydropower, creating a highly decarbonised grid. This structural advantage keeps the carbon footprint of food-grade rPET pellets remarkably low at 112.25 kg CO<sub>2</sub>-eq/tonne, delivering a net climate benefit of -36.9% compared to virgin PET production.

However, this climate benefit masks severe localised ecological damage. The open-loop friction washing units in Subsystem 1 require 714.46 litres of water per tonne of flakes, and because this water is discharged without adequate treatment, Subsystem 1 accounts for 85.7% of the system's total impact on freshwater eutrophication, 0.0622 kg P eq. Carbon mitigation is therefore achieved at the expense of local aquatic ecosystems, revealing a stark trade-off between global climate goals and regional environmental

### **4.4. Pragmatic low-tech interventions for high-impact circularity**

The outranking of Scenario 1, the semi-automatic mechanical cutter, over Scenario 2, the automated ultrafiltration system, using the ELECTRE I framework provides a key insight for industrial development in developing economies. From a purely environmental perspective, Scenario 2 is superior: it reduces the facility's water scarcity footprint by 90% and addresses critical ecotoxicity concerns. However, the non-compensatory logic of ELECTRE I prevents these environmental gains from offsetting severe financial liabilities.

This financial constraint is decisive for local independent recycling SMEs. These firms operate in a difficult economic environment marked by high interest rates, volatile feedstock supply, and an absence of municipal subsidies. For such businesses, investing in an automated ultrafiltration system with

a six-year return on investment is economically unviable.

Scenario 1 offers a more viable alternative by targeting the structural bottleneck identified in Subsystem 1. A low-cost, localised mechanical pre-cutting tool enables the facility to process 10L bottles and increases overall plant material yield from 70.66% to 83.45%. With full amortisation achieved within three months, the cascading economic benefit demonstrates that small, context-appropriate modifications are far more effective at bridging the circularity gap in resource-constrained markets than capital-intensive technological overhauls.

#### 4.5. Limitations of the study

The primary limitation of this study lies in its gate-to-gate system boundary. By excluding the collection and transportation phases, the LCA does not account for the environmental burdens generated by the highly fragmented, informal waste-picking sector that supplies the facility. Future research should adopt a comprehensive cradle-to-gate approach to quantify the logistical carbon footprint inherent to African supply chains and to assess the social life-cycle impacts of informal collection.

#### V. Conclusion

This study successfully implemented an integrated MFA-LCA-MCDA framework to diagnose and optimise the mechanical recycling of post-consumer PET bottles in Douala, Cameroon. By using primary industrial data and establishing a twofold functional unit, the research validated both core hypotheses. The findings reveal two main insights. First, vulnerabilities in developing plastic value chains are concentrated in the pre-treatment stage, Subsystem 1, due to structural design mismatches, rather than in the thermal reprocessing phase, Subsystem 2. Second, the application of the ELECTRE I method showed that context-appropriate, low-capital technical adjustments outperform advanced eco-efficiency retrofits. These low-cost solutions resolve operational bottlenecks while remaining financially viable for local businesses.

To accelerate the transition toward a resilient circular plastic economy in Sub-Saharan Africa, three targeted interventions are proposed based on actor roles. Packaging Manufacturers and Bottlers must address dimensional constraints through corporate eco-design. Large-format containers such as 10L bottles should be redesigned to include pre-melded structural failure lines that allow manual collapsing. Alternatively, companies can fund the deployment of compatible crushing components at regional recycling centres. Recycling Plant Operators in resource-constrained environments should prioritise low-cost, phased mechanical adjustments over high-capital automated equipment. Investing in tools such as semi-automatic pre-cutting

machines can resolve material bottlenecks, increase processing yields, and generate short-term cash flow. This revenue can then fund future environmental upgrades such as water treatment systems. Policymakers and Environmental Regulatory Bodies, including MINEPDED, should ground National Extended Producer Responsibility frameworks in subsystem-specific field data rather than generic international templates. Regulatory incentives must reflect actual processing yields, and a portion of plastic environmental taxes should be allocated to low-interest loan programmes that help local recycling SMEs overcome initial capital barriers

. While this study provides a clear gate-to-gate perspective, it also identifies key directions for future research. First, the system boundary should be expanded from gate-to-gate to a comprehensive cradle-to-gate framework. This broader scope would enable mathematical modelling of the carbon footprint of informal collection logistics and allow assessment of the social life-cycle impacts on marginalised networks of informal waste pickers. Second, future studies should examine operational variables and end-of-life options. Specifically, they should investigate how seasonal weather variations affect input contamination and sorting efficiency. They should also explore the chemical upcycling potential of heavily degraded polymer fractions that are currently rejected during mechanical processing.

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**Nkeng et al.:** Integrating material flow analysis and life cycle assessment to optimise mechanical recycling of Polyethylene Terephthalate from some mineral water bottles in Douala-Cameroon: hotspots, circular benefits and low-cost scenario

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