

Article

An Integrated Framework for Environmental and Social Life Cycle Assessments in PET Bottle Waste Management: A Case Study in Brazil

Eduardo J. P. Martin ¹, Deborah S. B. L. Oliveira ^{2,3}, Luiza S. B. L. Oliveira ^{2,4} and Barbara S. Bezerra ^{5,*}

¹ Department of Production Engineering, Sao Paulo State University—UNESP, Bauru 17033-360, Brazil; eduardo.martin@unesp.br

² Department of Chemical Engineering, Federal University of Sao Carlos—UFSCar, Sao Carlos 13565-905, Brazil; pmdsbl@leeds.ac.uk (D.S.B.L.O.); lstolteb@purdue.edu (L.S.B.L.O.)

³ School of Chemical and Process Engineering, University of Leeds, Leeds LS2 9JT, UK

⁴ Agricultural and Biological Engineering Department, Purdue University, West Lafayette, IN 47907, USA

⁵ Department of Civil and Environmental Engineering, Sao Paulo State University—UNESP, Bauru 17033-360, Brazil

* Correspondence: barbara.bezerra@unesp.br; Tel.: +55-14-31036112

Abstract: The improper disposal of PET bottle waste in Brazil jeopardizes the sustainability goals, impacting the social, economic, and environmental aspects. In order to tackle this issue, this study introduces a framework that was developed using a combination of environmental and social life cycle assessments (LCAs), along with a modified Analytic Hierarchy Process (AHP) methodology. Nine disposal scenarios were evaluated in Bauru, Brazil, including various combinations of landfills, sorting cooperatives, and incineration. Environmental (Env-LCA) and social (S-LCA) assessments followed the ISO 14040 standards, with the S-LCA incorporating the UNEP/SETAC guidelines. Scenario 9 was identified as the most sustainable option from the evaluated scenarios, with 100% of the waste sent to sorting cooperatives, with modified collection schemes. Conversely, Scenario 1, with a high landfill percentage, proved to be the least sustainable.

Keywords: PET bottle waste; S-LCA; LCA integration; modified AHP



Citation: Martin, E.J.P.; Oliveira, D.S.B.L.; Oliveira, L.S.B.L.; Bezerra, B.S. An Integrated Framework for Environmental and Social Life Cycle Assessments in PET Bottle Waste Management: A Case Study in Brazil. *Waste* **2023**, *1*, 724–739. <https://doi.org/10.3390/waste1030043>

Academic Editor: Giovanni De Feo

Received: 7 June 2023

Revised: 14 July 2023

Accepted: 15 August 2023

Published: 25 August 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Sustainable development (DS) is a means to protect current and future generations, where both the population and the Earth's resources are at the core of the system. Its success depends on robust changes to promote equality, inclusion, and resilience [1]. The term sustainable development is not new; it has been three decades since it was described in the Brundtland Commission report. Despite being a consolidated concept at global levels, putting it into practice is still a challenge [2].

One key aspect of achieving sustainability in products and services lies in measuring their impacts. A consolidated tool for assessing environmental sustainability and supporting decision-making is the integration of environmental and social life cycle assessments (Env-LCA and S-LCA, respectively) [3].

In addition, in parallel with the growing awareness of sustainability, important concepts such as extended product responsibility have emerged, which encourage producers to design green products and manage their waste in the post-consumption period. In Brazil, the National Solid Waste Policy (PNRS), which creates rules and objectives for solid waste management, stands out for its shared responsibility between producers, consumers, and municipalities [4]. However, PET bottle waste has additional legal limitations regarding its reuse in the Brazilian food chain. For instance, in the food sector, only 25% of PET bottle waste returns to its original chain. The remainder migrates to the following sectors:

textile (25.7%), resins (28.6%), laminates and composites (8.6%), handles (5.7%), and others (5.7%) [5].

Few studies have discussed the management of PET bottle waste encompassing both environmental and social impacts. In addition, the results of the review demonstrate the predominance of the use of the AHP method for the integration of LCAs; however, there has been recurring criticism regarding the weighting through a panel of specialists, due to the bias arising from individual perceptions. To work around this, an independent mathematical model created by a panel of experts was used, and a sensitivity analysis was carried out using different scenarios.

Thus, this study aims to establish a framework using this mathematical model to integrate the environmental and social impacts obtained in the Env-LCA and S-LCA for the Brazilian scenario. In order to test the framework, a case study was performed in the city of Bauru, Brazil. Nine scenarios were proposed: (1) the current scenario (base), where 96.4% of PET waste is sent to landfills and 3.6% to sorting cooperatives; (2) 50% to sorting cooperatives and 50% to landfills; (3) 50% to sorting cooperatives and 50% to incineration; (4) 50% to landfills and 50% to incineration; (5) 100% to sorting cooperatives (maintaining current collection practices); (6) 100% to landfills; (7) 100% to incineration; (8) 100% to sorting cooperatives (50% collected in Ecopoints and 50% by selective waste collection), (9) 100% to sorting cooperatives (75% collected in Ecopoints and 25% by selective waste collection). The framework can be used as a tool for municipalities to establish the relevant policies for PET bottle waste disposal in Latin American and developing countries.

In summary, this work aimed to establish a fundamental structure for the integration of Lifecycle Assessments (LCAs) through the modified methodology of the Analytic Hierarchy Process (AHP). This paper has five sections: Section 1 is this introduction; Section 2 presents a background of the LCA integration in the literature, highlighting the problem of using the AHP for this integration. Section 3 aims to demonstrate the multicriteria method that was adopted; that is, the AHP modified in five steps: 1—set objectives; 2—set and perform LCAs for each scenario; 3—define weights for the scenarios and the consistency ratio; 4—define the weights of the pillars and the consistency ratio; and 5—determine the final weight of each scenario. In step 4, a modification of the AHP method is presented, where the weighting of the environmental and social pillars takes place through the application of the eigenvector to the results obtained in the previous step of the assessments of the social and environmental lifecycle. In Section 4, the framework is applied to the city of Bauru, Brazil, for nine scenarios of PET bottle waste management. The case study conducted in Bauru revealed that recycling scenarios exhibited a more sustainable approach to PET bottle waste management, considering the socioenvironmental impacts. This was followed by incineration and landfills as alternative options. In Section 5, we present the conclusions of this paper, where we suggest that future research could expand on the framework to the three pillars of sustainability (environmental, social, and economic).

2. LCA Integration Background

The concept of sustainability is firmly established upon the core principles of the “Triple Bottom Line” approach, which encompasses the environmental, economic, and social dimensions. It is widely acknowledged that sustainability metrics must transcend the sole focus on the environmental aspect and also encompass social and economic considerations. In the pursuit of this comprehensive perspective on sustainability, a multitude of scholarly papers have presented invaluable insights and perspectives on the integration of these pillars within lifecycle assessment (LCA) methodologies. Notably, Ref. [6] has made significant contributions to the field with influential work on LCA integration. Furthermore, Refs. [7,8] have conducted thorough literature reviews, thereby further enriching our understanding of the integration of LCA approaches and shedding light on this pertinent topic.

Visentin et al. [8] elucidated the use of several tools that can be used in the integration of the sustainability pillars and highlighted that, in the analyzed studies, there was a predomi-

nance of multi-criteria methods, among which the AHP method stood out. The authors also mentioned that only 51% of the studies performed integrated life cycle assessments.

In 2009, UNEP's Life Cycle Initiative introduced the Guidelines for Social Life Cycle Assessment (S-LCA) [9], which have since been used by researchers and practitioners to assess the social and socio-economic impacts of products throughout their entire lifecycle. The practice of S-LCA has expanded beyond academia to involve industry, policymakers, and business professionals. Thus, in 2020, these guidelines were updated to provide more accessible information and tools for decision-making, bridging the gap between theory and practice [10]. The 2020 edition also explores the connection between a product's social impacts and an organization's influence across its lifecycle [10]. In addition, in 2021 [11], UNEP updated the inventory and data sources of its previous version [12].

The UNEP guidelines play a significant role in addressing certain questions that arise in the context of integrating sustainability pillars. Ref. [7] pointed out that the sustainable integration of the pillars of sustainability (Environmental, Economic and Social) is primarily ensured by first calculating the LCA for each pillar independently and then integrating the results through a multi-criteria analysis, where the AHP method emerged as the main method. The UNEP 2020 [10] guidelines offer valuable guidance on various aspects, including the determination of weights and aggregation methods, as well as the utilization of panel experts to establish a comprehensive list of performance indicators aligned with a reference scale.

Nevertheless, even with the progress made by these guidelines, certain challenges persist, particularly concerning the aggregation and weighting methods. Therefore, this paper adopts the approach suggested by [7,8], utilizing the Analytic Hierarchy Process (AHP) to integrate the results of both Env-LCA and S-LCA from previous studies [13,14]. The selection of AHP also enables comparisons with similar research endeavors found in the literature. Detailed explanations of the employed methods will be provided in the subsequent section.

The AHP methodology relies on a panel of experts who evaluate the relative importance of criteria through pair-wise comparisons. This process generates an answers matrix, from which a priority vector is derived, indicating the weights assigned to each criterion. However, it is crucial to acknowledge a potential challenge associated with this method, namely the representation of diverse hierarchies influenced by the selection and aggregation of criteria, as well as individual perceptions [15].

In order to overcome this problem, the papers of [16–18] suggested standardization, such as normalization of the criteria under analysis. In addition, Refs. [7,8] identified the use of normalization to aggregate the pillars of sustainability.

Nevertheless, Ref. [18] demonstrated that the selected normalization method has a greater influence on the general results than either the aggregation method or weighting factors.

With the purpose of reducing the influence of normalization, which depends on the value judgments of experts, and maintaining consistency, this work used additive aggregation and sensitivity analysis, as well as normalization, to obtain criteria weighting.

3. Materials and Methods

The method used in this work was the multi-criteria analysis recommended by [15,19–23].

Systematic literature review studies on life cycle assessment integration [7,8] have explored various multicriteria decision analysis methodologies, including Multi-Attributed Value Theory, Sustainability Ranking, Life Cycle Sustainability Dashboard, life cycle sustainability performance, Fuzzy method, Three-Dimensional Coordinate Diagram, Multiple Decision Making Interval, AHP, Technique for Order Preference by Similarity to Ideal Solution, and Preference Ranking Organization Method for Enriched Evaluation. Among these methodologies, the Analytic Hierarchy Process (AHP) stands out due to its distinctive advantages. Unlike other methods, such as Multi-Attribute Value Theory, Sustainability Ranking, Lifecycle Sustainability Dashboard, and Life Cycle Sustainability performance, AHP offers a structured approach that organizes complex problems into a hierarchical

structure of criteria and sub-criteria. This hierarchical representation allows for decision-makers (or an expert panel) to systematically assess and prioritize alternatives, considering the relative importance of different criteria. In contrast, methods such as the Fuzzy method, Three-Dimensional Coordinate Diagram, Multiple Decision Making Interval, Technique for Order Preference by Similarity to Ideal Solution, and Preference Ranking Organization Method for Enriched Evaluation may lack the structured framework and clarity provided by AHP. Moreover, AHP enables decision-makers to make pairwise comparisons and quantitatively evaluate the relative significance of criteria, fostering a more rigorous and transparent decision-making process. These qualities make AHP a powerful tool for decision-making, especially when tackling intricate and multifaceted problems.

The research conducted by [7] demonstrated that the choice of tools in life cycle assessment (LCA) integration depends on the systems integration path. Two approaches were identified:

- Approach 1 involved applying LCA separately with later integration, where the recommended tools were Analytic Hierarchy Process (AHP) or Multi-attribute Value Theory (MVT).
- Approach 2 focused on a joint assessment of sustainability aspects, predominantly using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method.

Considering the previous studies, this work, which focuses on PET bottle waste, chose to adopt Approach 1 to ensure comparability with similar research. Therefore, following the recommendations of [7,8], the AHP method was utilized to integrate the previously performed Env-LCA and S-LCA. Furthermore, the review results indicate a prevalent use of the AHP method for LCA integration. However, there has been recurring criticism regarding the weighting process using a panel of specialists in AHP, due to the potential bias arising from individual perceptions. To address this concern, a mathematical model independent of expert panels was employed in this study, aiming to mitigate biases. Additionally, a sensitivity analysis was conducted through scenario testing, allowing for a comprehensive examination of the results and their robustness.

Thus, this work establishes a framework for integrating Env-LCA and S-LCA based on the propositions outlined by [6]. The integration process follows an additive approach, considering the normalized results of each LCA, as shown in Equation (1).

$$I\text{-LCA} = \text{Env-LCA} + \text{Econ-LCA} + \text{S-LCA} \quad (1)$$

where:

Env-LCA—Environmental Life Cycle Assessment.

Econ-LCA—Economic Life Cycle Assessment (Life Cycle Cost Analysis).

S-LCA—Social Life Cycle Assessment.

I-LCA—Integrated Life Cycle Assessment.

For integration among the pillars, it is important that life cycle assessments have the same units of comparison: system boundaries, functional unit, and comparison scenarios.

In this work, we are focusing on the integration of the Env-LCA and S-LCA.

LCA integration was carried out using the modified Analytic Hierarchy Process (AHP) method, which has five steps. The nomenclature of each phase is given below:

1. Set objectives.
2. Set and perform LCAs for each scenario.
3. Define weights for the scenarios and consistency ratio.
4. Define the weights of the pillars and the consistency ratio.
5. Determining the final weight of each scenario.

In Step 4, the modified AHP method is introduced, which involves the weighting of the environmental and social pillars. This weighting is achieved by applying the Eigen Vector to the results obtained in the previous step, where the assessments of the social and

environmental life cycle were made. The subsequent subsections provide a more detailed description of the steps involved in the modified AHP method.

3.1. Set Objectives (Step 1)

The objective of the method was to find the most sustainable alternative scenario considering the chosen pillars.

3.2. Set and Perform LCAs for Each Scenario (Step 2)

Select the chosen pillars for integration (environmental and social, in this study) and the methodology for executing individual life cycle assessments. For the Env-LCA, the ISO 14040 standards were used:

- (a) NBR ISO 14040: environmental management—life cycle assessment—principles and structure [24].
- (b) NBR ISO 14044: environmental management—life cycle assessment—requirements and guidance [24].

For the S-LCA, the NBR ISO 14040 standard [24] and the guidelines of SETAC/UNEP were used:

- (a) Guidelines for evaluating the social life cycle of products [9,10].
- (b) The Methodological Forms for Subcategories in the Social Life Cycle Assessment [11,12].

3.3. Define Weights for the Scenarios and Consistency Ratio (Step 3)

At this stage, the results of life cycle assessments should be standardized from 0 to 1 for comparison. According to [16,18], external standardization should be used based on annual data, if available. Otherwise, internal normalization of the analyzed scenarios is used. The nature of the data should be observed to optimize normalization. This procedure is based on Equations (2) and (3), where the maximum and minimum reference values are used to normalize each criterion (impact category) within each alternative scenario [25]. Equation (2) is used to normalize positive values and Equation (3) for negative values.

$$N_{ij} = \frac{s_{ij}}{s_{i,max}} \quad (2)$$

where:

N_{ij} is the normalized value of criterion i for alternative j ;

s_{ij} is the value of criterion i for alternative j , before normalization;

$s_{i, max}$ is the maximum value of criterion i selected between the values of s_{ij} .

$$N_{ij} = \frac{s_{i,min}}{s_{ij}} \quad (3)$$

where:

$s_{i,min}$ is the minimum value of the criterion i selected between the values of s_{ij} .

If the results contain data with different behaviors, other normalization methods can be used, such as linear, vectorial, standard, sigmoidal, decimal [25], difference, minimum and ranking [18].

The results of the normalized matrix of LCA evaluations are aggregated into a preference (or priority) matrix to compare the scenarios (Table 1). Table 1 shows these for one criterion and three scenarios, as a simple example. To calculate the values of each cell of the preference matrix among scenarios in Table 1, the formula described in the table itself is used.

Table 1. Normalized criterion values (from 0 to 1) and preference matrix among scenarios.

Normalization (Using Equations (2) and (3))	Normalized Criterion Values		
	Scenario 1	Scenario 2	Scenario 3
	N_1	N_2	N_3
Preference Matrix among Scenarios	Scenario 1	Scenario 2	Scenario 3
Scenario 1	$\frac{N_1}{N_1}$	$\frac{N_1}{N_2}$	$\frac{N_1}{N_3}$
Scenario 2	$\frac{N_2}{N_1}$	$\frac{N_2}{N_2}$	$\frac{N_2}{N_3}$
Scenario 3	$\frac{N_3}{N_1}$	$\frac{N_3}{N_2}$	$\frac{N_3}{N_3}$

Matrix A (Equation (4)) is established from Table 1, where the priorities are calculated by the ‘Eigen Vector’, as listed in the work of [26].

$$A = \begin{bmatrix} \frac{N_1}{N_1} & \frac{N_1}{N_2} & \frac{N_1}{N_3} \\ \frac{N_2}{N_1} & \frac{N_2}{N_2} & \frac{N_2}{N_3} \\ \frac{N_3}{N_1} & \frac{N_3}{N_2} & \frac{N_3}{N_3} \end{bmatrix} \quad (4)$$

Matrix A is multiplied by itself, generating matrix $B = A^2$ (Equation (5)). The elements of this matrix are then used to calculate weight W_1 , as shown in Equation (6).

$$B = A^2 = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (5)$$

$$W_1 = \begin{bmatrix} S_1/S_T \\ S_2/S_T \\ S_3/S_T \end{bmatrix}, \text{ where } \begin{matrix} S_1 = A_{11} + A_{12} + A_{13} \\ S_2 = A_{21} + A_{22} + A_{23} \\ S_3 = A_{31} + A_{32} + A_{33} \end{matrix} \text{ and } S_T = S_1 + S_2 + S_3 \quad (6)$$

To verify the consistency ratio, the Eigen vector was used again by multiplying the $B = A^2$ matrix by itself (Equation (7)). Then, weight W_2 was calculated from Equation (8).

$$B^2 = [A^2]^2 = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \quad (7)$$

$$W_2 = \begin{bmatrix} R_1/R_T \\ R_2/R_T \\ R_3/R_T \end{bmatrix}, \text{ where } \begin{matrix} R_1 = B_{11} + B_{12} + B_{13} \\ R_2 = B_{21} + B_{22} + B_{23} \\ R_3 = B_{31} + B_{32} + B_{33} \end{matrix} \text{ and } R_T = R_1 + R_2 + R_3 \quad (8)$$

Finally, the last step of consistency calculation takes the difference between the W_1 and W_2 vectors (Equation (9)). The value must be close to zero to be valid for weighting.

$$\text{Difference} = W_1 - W_2 = \begin{bmatrix} S_1/S_T - R_1/R_T \\ S_2/S_T - R_2/R_T \\ S_3/S_T - R_3/R_T \end{bmatrix} \quad (9)$$

This is carried out for each sustainability pillar; that is, each scenario has a weight for each pillar.

3.4. Define the Weights of the Pillars and the Consistency Ratio (Step 4)

The same process as that applied in step 3 is performed to normalize each pillar and calculate its weight. The input data are the weights previously generated in step 3. It should be mentioned that, at this step, the rows and columns of the preference matrix are not the scenarios (as in step 3), but the pillars themselves.

3.5. Determining the Final Weight of Each Scenario (Step 5)

The weights of each scenario within a pillar are multiplied by the weight of the respective pillar, and these are aggregated for all pillars. Considering the integration between environmental and social pillars, the final weight for scenario i ($i = 1-9$), W_i , is expressed by Equation (10).

$$W_i = W_{i,social} \times W_{Social} + W_{i, environmental} \times W_{Environmental} \quad (10)$$

We would like to highlight step 4, as this is the main point of change in the AHP method used in this work. The original AHP method applied by [15,20,21,27] uses a panel of experts in step 4 to establish weights for the pillars. However, this work modified the AHP method in step 4 so that the weights were determined by the results of the socio-environmental impacts through the calculation of the Eigen Vector.

The weights calculated in step 3 for the scenarios in each pillar were used to compose the normalized values of each pillar according to Equation (2). Thus, these data can be used to generate the preference matrix between the pillars (Reference Table 1), and later, through the 'Eigen Vector', the priority matrix between them (Equations (4)–(8)).

This modification reduces subjectivity in decision-making, a gap pointed out by [15], and prioritizes objectivity in the weighting between the pillars (environmental and social).

4. Framework Application

This section aims to compare the sustainability of nine scenarios of the disposal of PET bottle waste through the social and environmental pillars using the proposed framework presented in Section 3. Life cycle assessments were conducted separately and then aggregated into a single sustainability indicator.

4.1. Goal and Scope

The established functional unit was 1 ton (t) of PET bottle waste. The total PET bottle waste collected in the city of Bauru in 2019 was used to measure the percentages of the reference flow rate per ton.

4.2. System Boundaries

The system boundary includes the collection and transportation of PET waste, its sorting or disposal, and the replacement of fossil-based PET granules (by esterification of ethylene glycol and terephthalic acid process), when applicable. System boundaries are depicted in Figure 1 for the base scenario (Scenario 1).

The area of application of this work was the city of Bauru, where 96,274 tons of recycled materials was collected in 2019 according to municipal agencies; more detailed information is presented in [13].

Waste collection is under the supervision of Secretariat of the Environment (SEMMA), where each type of waste to be collected is described as follows: (1) Conventional curb collection carried out by EMDURB (urban and rural development company of the city). This type of collection has a higher percentage of organic material; however, the existence of a large amount of recyclable material was verified during an in loco visit to the landfill. (2) Selective recyclable materials' curb (door-to-door) collection, also performed by EMDURB. (3) The selective collection of recyclable materials in door-to-door mode, performed by ASCAM. (4) The selective collection of recyclable materials in Ecopoints. In this type of collection, people voluntarily deposit recyclable waste without remuneration at eight points distributed throughout the city.

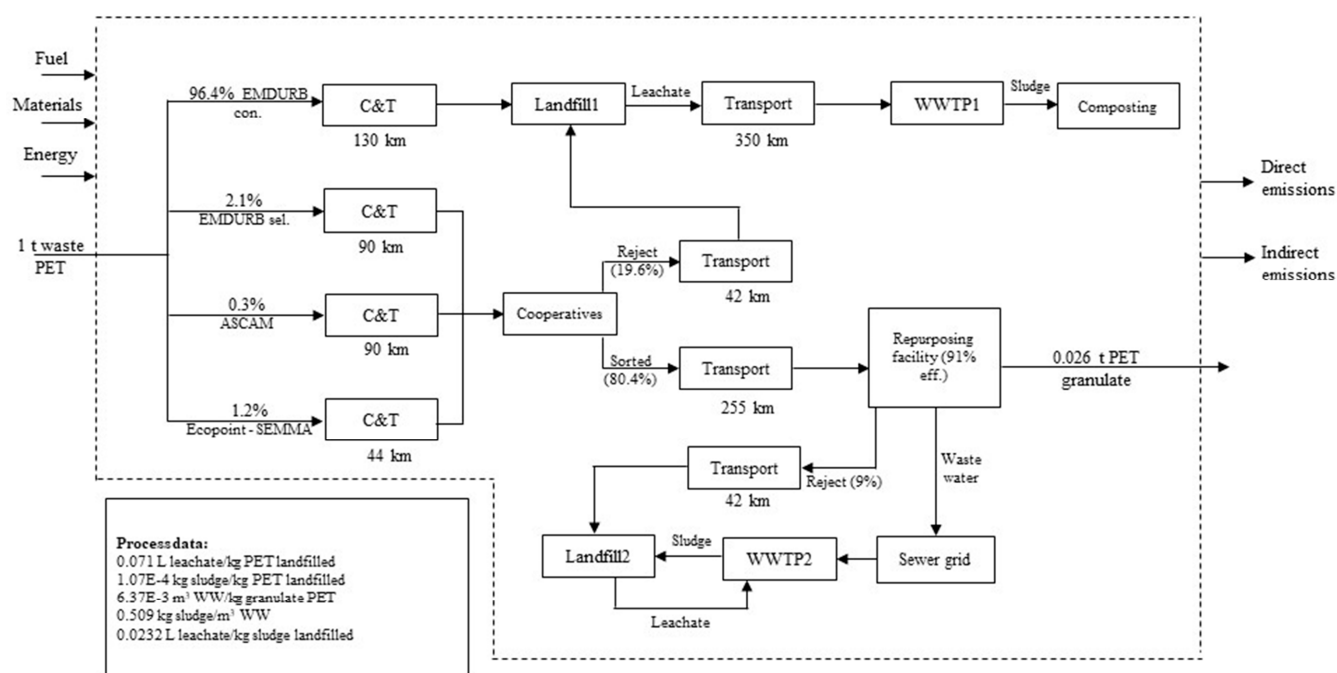


Figure 1. System boundary for base scenario. Source: Martin et al. [13].

Recyclable waste is taken to sorting cooperatives (Cootramat, Cooperbau and Coopeco). The final residue of sorting is taken to the landfill. The waste collected in the conventional way is directed to the landfill located in the city of Piratininga. This work included the insertion of an additional scenario (incineration) for comparison purposes using the data presented by Foolmaun; Ramjeawon (2013).

In this paper, nine PET bottle-waste final-disposition scenarios were analyzed, as presented in [13]:

- (1) Current (base) scenario (96.4% of the reference flow is sent to landfill, 3.6% is sent to screening cooperatives);
- (2) 50% for sorting cooperatives, 50% for landfill;
- (3) 50% for sorting cooperatives, 50% for incineration;
- (4) 50% for landfill, 50% for incineration;
- (5) 100% for sorting cooperatives (maintaining current collection distribution scheme);
- (6) 100% for landfill;
- (7) 100% for incineration;
- (8) 100% for sorting cooperatives (50% collected in Ecopoints, 50% collected by selective collection);
- (9) 100% for sorting cooperatives (75% collected in Ecopoints, 25% collected by selective collection).

4.3. Determining Weights for the Scenarios

Environmental and social pillars were considered. ISO 14040 standards were used for the Env-LCA, while for S-LCA, in addition to the ISO 14040 guidelines, the SETAC/UNEP guidelines [9,10] were used. The results of the environmental and social LCAs were used to establish the weights between the scenarios and determine the consistency ratio, as described in Section 3.

4.4. Env-LCA Results

The results of the Env-LCA are presented in Table 2. The values in Table 2 were normalized on a scale from 0 to 1 using the results obtained from [13], where a value close to 1 indicates a greater positive impact. To determine the preference matrix between the scenarios, an expert panel was not used, as is typical when using the AHP method, because

this approach is criticized in the literature for its partiality in the judgments and influence on the final result. To address this problem, the normalized results of the Env-LCA were used as a basis for comparison between scenarios. The maximum score was used as a basis for other scenarios. A value greater than 1 indicates that the scenario is better than the other scenario. Table 3, which represents the preference matrix, shows these results.

Table 2. Normalized scores for environmental LCA.

Impact Category	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9
Global Warming Potential	kg CO ₂ eq	2.27×10^{-2}	4.63×10^{-1}	2.44×10^{-1}	5.25×10^{-1}	9.98×10^{-1}	4.96×10^{-2}	1.00×10^0	9.99×10^{-1}	1.00×10^0
Ozone Depletion	kg CFC-11 eq	8.37×10^{-1}	3.50×10^{-1}	3.98×10^{-1}	8.53×10^{-1}	9.75×10^{-1}	1.00×10^0	7.06×10^{-1}	9.85×10^{-1}	1.00×10^0
Terrestrial Acidification	kg SO ₂ eq	9.81×10^{-3}	4.85×10^{-1}	4.61×10^{-1}	7.00×10^{-1}	9.97×10^{-1}	4.00×10^{-1}	1.00×10^0	9.98×10^{-1}	1.00×10^0
Freshwater eutrophication	kg P eq	2.98×10^{-2}	4.96×10^{-1}	4.98×10^{-1}	8.64×10^{-1}	9.99×10^{-1}	1.00×10^0	7.28×10^{-1}	1.00×10^0	1.00×10^0
Human toxicity	kg 1,4-DB eq	3.89×10^{-1}	2.77×10^{-1}	6.10×10^{-2}	7.20×10^{-1}	9.98×10^{-1}	4.40×10^{-1}	1.00×10^0	9.99×10^{-1}	1.00×10^0
Terrestrial Ecotoxicity	kg 1,4-DB eq	1.99×10^{-1}	3.28×10^{-1}	2.31×10^{-1}	6.16×10^{-1}	9.91×10^{-1}	2.32×10^{-1}	1.00×10^0	9.95×10^{-1}	1.00×10^0
Freshwater ecotoxicity	kg 1,4-DB eq	6.28×10^{-1}	3.03×10^{-1}	5.10×10^{-1}	8.26×10^{-1}	9.96×10^{-1}	6.53×10^{-1}	1.00×10^0	9.97×10^{-1}	1.00×10^0
Normalized [0–1]		0.302	0.386	0.343	0.729	0.994	0.539	0.919	0.996	1.000

Table 3. Importance intensity (preference) attributed to the nine alternative scenarios (Env-LCA).

Scenarios										Priorities among Scenarios Environmental LCA	
	S1	S2	S3	S4	S5	S6	S7	S8	S9	Weight	Hierarchy
S1	1.00	0.78	0.88	0.41	0.30	0.56	0.33	0.30	0.30	0.049	9
S2	1.28	1.00	1.12	0.53	0.39	0.72	0.42	0.39	0.39	0.062	7
S3	1.14	0.89	1.00	0.47	0.35	0.64	0.37	0.34	0.34	0.055	8
S4	2.41	1.89	2.12	1.00	0.73	1.35	0.79	0.73	0.73	0.117	5
S5	3.29	2.57	2.89	1.36	1.00	1.84	1.08	1.00	0.99	0.160	3
S6	1.79	1.40	1.57	0.74	0.54	1.00	0.59	0.54	0.54	0.087	6
S7	3.04	2.38	2.68	1.26	0.93	1.70	1.00	0.92	0.92	0.148	4
S8	3.30	2.58	2.90	1.37	1.00	1.85	1.08	1.00	1.00	0.160	2
S9	3.31	2.59	2.91	1.37	1.01	1.85	1.09	1.00	1.00	0.161	1

The highlighted value in bold shows that scenario 9 is 3.31 more important than scenario 1. This value is obtained by dividing the normalized performance from scenario 9 by the normalized performance of scenario 1. The weight presents the priority hierarchy among the scenarios, obtained by applying the Eigen Vector weight consistency test method.

4.5. S-LCA Results

Table 4 presents the social LCA (S-LCA) results obtained in previous work [14] and normalized on a scale from 0 to 1, where a higher value indicates a greater positive impact. In the table's first column, the scenarios are listed in decreasing order of normalized score.

The importance intensity attribution among scenarios was determined in a manner analogous to that presented in the environmental LCA section. The results for social LCA are presented in Table 4, as well as for the importance intensity and priority matrix among scenarios.

4.6. Determine the Weights for the Social and Environmental Pillars

The weights generated for each scenario in the environmental (Table 3) and social (Table 4) LCAs were used to normalize the pillars. Table 5 displays the scores (normalized values in Tables 3 and 4) of each scenario for both pillars, as well as the normalized value of each pillar (Nor.). The priority matrix between the two pillars was then computed from their normalized values, and the priorities (weights) of the pillars were determined and presented in Table 5.

Table 4. Normalized scores; importance intensity attributed to the nine scenarios; priority matrix for S-LCA.

Normalized Scores for Social LCA			Importance Intensity Attributed to the Nine Scenarios (S-LCA)										Priority Matrix	
Scenarios	Score	Normalization *	Scenarios										Weight	Hierarchy
			S1	S2	S3	S4	S5	S6	S7	S8	S9			
S9	26.75	1.00	S1	1.00	0.86	0.78	0.90	0.74	1.01	0.81	0.73	0.73	0.09	8
S8	26.75	1.00	S2	1.17	1.00	0.91	1.05	0.87	1.18	0.95	0.85	0.85	0.11	6
S5	26.25	0.98	S3	1.29	1.10	1.00	1.16	0.96	1.31	1.05	0.94	0.94	0.12	4
S3	25.13	0.94	S4	1.11	0.95	0.86	1.00	0.82	1.12	0.90	0.81	0.81	0.10	7
S7	24.00	0.90	S5	1.35	1.15	1.04	1.21	1.00	1.36	1.09	0.98	0.98	0.12	3
S2	22.75	0.85	S6	0.99	0.85	0.77	0.89	0.73	1.00	0.80	0.72	0.72	0.09	9
S4	21.63	0.81	S7	1.23	1.05	0.96	1.11	0.91	1.25	1.00	0.90	0.90	0.11	5
S1	19.50	0.73	S8	1.37	1.18	1.06	1.24	1.02	1.39	1.11	1.00	1.00	0.13	2
S6	19.25	0.72	S9	1.37	1.18	1.06	1.24	1.02	1.39	1.11	1.00	1.00	0.13	1

* Normalization [scale 0–1] Relative to highest score.

Table 5. Standard scores for environmental and social criteria and priority matrix.

Standard Scores for Environmental and Social Criteria										
	S1	S2	S3	S4	S5	S6	S7	S8	S9	Nor *.
Environmental	0.30	0.39	0.34	0.73	0.99	0.54	0.92	1.00	1.00	0.69
Social	0.73	0.85	0.94	0.81	0.98	0.72	0.90	1.00	1.00	0.88

Importance intensity attributed to the two pillars and their priority (weights)			
Priority Matrix			Weight
Environmental		Social	
Environmental	1	0.78	0.44
Social	1.28	1	0.56

* Values normalized [0–1].

4.7. Final Weighting of the Scenarios

The weights attributed to each pillar (0.44—environmental and 0.56—social) were used to ponder the environmental and social weights, respectively, of each scenario, thus providing the final weight of each scenario from a socio-environmental perspective. For example, the final weight of S1 was calculated as: $0.44 \times 0.049 + 0.56 \times 0.09 = 0.073$. The final weight of each scenario is shown in Table 6, in which scenarios are ordered from the highest to lowest weight.

Table 6. Sustainability index for each scenario.

Scenario	Weight Final	Hierarchy
S9	0.142	1
S8	0.141	2
S5	0.140	3
S7	0.129	4
S4	0.109	5
S3	0.091	6
S6	0.089	7
S2	0.087	8
S1	0.073	9

The results indicate that recycling scenarios (S5, S8 and S9) performed better when both environmental and social factors are considered, followed by incineration (0.129) and landfill (0.073). The hybrid scenarios had an intermediate classification according to the percentage of Recycling, Incineration and Landfill.

Within the recycling scenarios, the highest percentage of selective collection through Ecopoints generated a better classification.

The worst scenario regarding the socio-environmental pillars was the base scenario (S1), where 96.4% of the reference flow is sent to landfills and only 3.6% is sent to sorting cooperatives for recycling.

For model validation purposes, a sensitivity analysis (presented in Table 7) was carried out to verify whether a change in the weights between the social and environmental pillars would influence the final sustainability indexes.

Table 7. Sensitivity analysis of sustainability indexes.

Sc.	H.	Weight 50% E 50% S	H.	Weight 70% E 30% S	H.	Weight 30% E 70% S	Weight 44% E 56% S	Hierarchy Found in This Study
1	9	0.07	9	0.06	9	0.079	0.073	9
2	8	0.08	7	0.08	7	0.094	0.087	8
3	7	0.09	8	0.07	6	0.100	0.091	7
4	5	0.11	5	0.11	5	0.107	0.109	5
5	3	0.14	3	0.15	3	0.135	0.140	3
6	6	0.09	6	0.09	8	0.090	0.089	6
7	4	0.13	4	0.14	4	0.124	0.129	4
8	2	0.14	2	0.15	2	0.136	0.141	2
9	1	0.14	1	0.15	1	0.137	0.142	1

Note: H—hierarchy; Sc.—scenarios; E—environmental; S—social.

It is evident that the top five positions remain unchanged regardless of the varying weights assigned to the social and environmental pillars. However, the rankings for positions 6–9 are influenced by the performance of each scenario relative to the pillar assigned the highest weight in the sensitivity analysis.

The integration of social aspects in the study of PET bottle waste disposal through integrated Life Cycle Assessment (LCA) offers valuable insights into sustainable waste management practices. Comparative analysis with relevant studies allows for a deeper understanding of the social implications and potential solutions. Moreover, the research conducted in the Republic of Mauritius [26,27] is highly relevant, as it pioneers the modeling of a PET waste evaluation system using the ISO 14040 and ISO 14044 methodologies. This research, along with subsequent articles on environmental, social, and economic LCA application and integration [28], generates valuable results.

Research by [29] emphasizes the importance of considering societal actors and their roles in enabling consumer action, highlighting the need for a multi-stakeholder approach. Additionally, findings from [30] suggest that the social dimension plays a significant role in determining appropriate waste management strategies, with incineration for electricity generation and industrial incineration emerging as potential options in Hong Kong. These findings underscore the significance of considering the social implications and stakeholders' perspectives in waste management decision-making.

The study by [31] also highlights the social factors that influence PET bottle waste management practices, emphasizing the role of legislation, stakeholder collaboration, and well-established recycling infrastructure in achieving higher recycling rates and reducing environmental impacts. This underscores the need for tailored policies and strong governmental support to promote sustainable PET bottle waste management.

4.8. Challenges and Opportunities for Waste Management Practices in Bauru

Through the results obtained from the analysis of the scenarios and the application of the framework, it was possible to draw the following challenges and opportunities:

- **Limited infrastructure:** Insufficient waste management infrastructure, including collection systems, recycling facilities, and disposal sites, hampers effective waste management.
- **Lack of awareness and education:** The population's limited knowledge and understanding of proper waste management practices poses a challenge. Increasing public awareness through education and community engagement can drive behavioral change.
- **Inefficient waste segregation:** Proper waste segregation is crucial for recycling and reducing landfill waste. Enhancing waste segregation practices through education and improved infrastructure can improve recycling rates.
- **Informal waste sector:** The presence of informal waste pickers offers both challenges and opportunities. Formalizing and supporting the informal sector can enhance waste management practices and provide economic benefits.
- **Policy and regulatory framework:** Developing and enforcing waste management regulations can provide a clear direction for sustainable practices. Strengthening partnerships among stakeholders is vital for effective policy implementation.
- **Technological advancements:** Embracing advanced waste sorting and recycling technologies can improve efficiency and reduce environmental impacts. Partnering with technology providers and fostering innovation can unlock opportunities.
- **Circular economy approach:** Transitioning to a circular economy model, focusing on waste prevention, resource recovery, and recycling, can create a more sustainable waste management system. Promoting eco-design, product reuse, and local recycling industries can yield long-term benefits.

Addressing these challenges and seizing opportunities can enhance waste management practices in Bauru, leading to improved environmental sustainability and a more resilient waste management system.

4.9. Implications for Practice

Based on the research findings and the focus on PET bottle waste disposal in the city of Bauru, several specific recommendations can be made for decision-makers to improve sustainability in this context:

- **Implement a comprehensive recycling infrastructure:** Decision-makers should prioritize the development and implementation of an efficient recycling infrastructure specifically designed for PET bottle waste. This includes establishing collection systems, recycling facilities, and promoting public awareness campaigns to encourage residents and businesses to actively participate in recycling initiatives.
- **Promote circular economy principles:** Decision-makers should support and incentivize the adoption of circular economy principles in the management of PET bottle waste. This involves encouraging the use of recycled PET materials in the production of new bottles, promoting bottle-to-bottle recycling, and fostering partnerships with industries to increase the demand for recycled PET.
- **Enhance waste management regulations:** Policy implications can involve strengthening waste management regulations related to PET bottle waste disposal. This may include implementing extended producer responsibility (EPR) programs, where manufacturers bear the responsibility for the collection, recycling, and proper disposal of PET bottles. Introducing policies that promote waste reduction, reuse, and recycling can also be beneficial.
- **Facilitate collaboration between stakeholders:** Decision-makers should facilitate collaboration among various stakeholders, including government bodies, recycling companies, NGOs, and local communities. Engaging stakeholders in joint initiatives and establishing public-private partnerships can accelerate the progress towards sustainable PET bottle waste management.

Regarding the extension of this study to other regions and countries, the findings and recommendations can serve as a starting point for similar assessments. However, it is essential to consider the local context, waste management infrastructure, and socio-economic factors when applying these recommendations to different regions and countries. Conducting further research and adapting the findings to the specific circumstances of each area is necessary to ensure effective and sustainable outcomes.

Social and integrated Life Cycle Assessment (LCA) approaches provide valuable insights into the social and environmental impacts of products. However, it is important to recognize their limitations and uncertainties. These include challenges related to data availability and quality, the subjective nature of assessing social impacts, and the complexity of defining system boundaries. Additionally, selecting appropriate indicators and impact assessment methods can be challenging, and the results may be context-specific. To ensure the reliability of findings, it is crucial for researchers and practitioners to openly acknowledge these limitations, conduct sensitivity analyses, and validate their results.

Sensitivity analysis, a technique used in LCA, helps to understand the robustness and reliability of study results by varying key input parameters or assumptions within predefined ranges to assess their impact on the outcomes. Scenarios are an effective way to perform a sensitivity analysis as they allow for researchers to explore different plausible futures or alternative assumptions, thereby evaluating their influence on the LCA results. By defining and analyzing various scenarios, the sensitivity of the results to different factors can be assessed, providing a deeper understanding of the uncertainties and limitations of the study.

However, the integrated framework has some limitations and disadvantages that should be acknowledged. These include challenges related to data availability and quality, complexity and subjectivity in the analysis, resource and time requirements for data collection and analysis, and the context-specific nature of the results. Factors such as local regulations, infrastructure, and social dynamics can significantly influence the outcomes, limiting the generalizability of the findings to other contexts.

By recognizing these advantages and limitations, researchers and decision-makers can gain a better understanding of the integrated framework and make informed decisions about its application and interpretation in waste management assessments.

4.10. Social Impacts of PET Bottle Waste Disposal: The Role of Waste-Pickers in Developing Countries

In developing countries, the social impacts of PET bottle waste disposal are closely tied to the role of waste-pickers in the informal recycling sector. These marginalized individuals play a vital role in collecting and recycling PET bottles for their livelihoods. Addressing the social aspects, particularly those regarding waste-pickers, is crucial to promoting social equity, poverty alleviation, and sustainable development.

The formal integration of waste pickers into the waste management system has the potential to generate employment opportunities and improve their economic well-being. By offering stable jobs, fair wages, and access to social benefits, waste-pickers can be empowered and their overall well-being enhanced.

Promoting social equity is another critical consideration. Many waste-pickers face social exclusion, discrimination, and limited access to essential services. Ensuring inclusive and equitable waste management systems involves providing safe working conditions, social protection, and opportunities for the development of skills. By championing social equity, waste management initiatives can contribute to poverty reduction and the empowerment of marginalized communities.

Community engagement and participation are key to developing countries' waste management systems. Involving waste-pickers in decision-making processes and recognizing their knowledge and expertise leads to more effective and sustainable waste management practices. Collaborative partnerships among waste-pickers, local communities, government agencies, and stakeholders foster a sense of ownership, promote social cohesion, and enhance the effectiveness of waste management initiatives.

However, challenges exist in integrating waste-pickers into formal waste management systems, including limited resources, inadequate infrastructure, and regulatory barriers. These challenges can be addressed through supportive policies, capacity-building programs, and inclusive governance structures. Continuous monitoring and evaluations of the social and economic impacts of integrating waste-pickers are crucial to safeguard their rights and well-being.

5. Conclusions

This study aimed to establish a foundational framework for integrating Life Cycle Assessments (LCAs) using a modified Analytic Hierarchy Process (AHP) methodology, which consisted of five stages: (1) setting objectives, (2) conducting LCA for each selected sustainability pillar, (3) determining weights and consistency ratios for the scenarios, (4) establishing weights and consistency ratios for the environmental and social pillars, and (5) finalizing the weighting of the scenarios.

To address a common criticism of traditional AHP, the use of normalized LCA results was employed as a basis for weighting the scenarios. The same approach was applied to the social and environmental pillars. By utilizing the Eigen Vector method, priorities (weights) were assigned to the entities analyzed (scenarios and pillars) without the involvement of specialists. This impartial decision-making process was centered on the analyzed impact results.

The case study conducted in the city of Bauru revealed a more sustainable path for PET bottle waste management. Recycling scenarios exhibited a better performance from a social–environmental perspective, followed by incineration and landfill. The base scenario displayed the lowest sustainability index, indicating potential to improve the social and environmental impacts of the current waste management system through the expansion of recyclable waste collection via Ecopoints. Strategies such as marketing campaigns, incentives such as refunds for using Ecopoints, and the introduction of new Ecopoint locations citywide could facilitate this improvement.

S7 was included to explore the feasibility of establishing an incineration plant in the city. However, recycling scenarios (S5, S8, and S9) outperformed S7, underscoring the importance of investing in the recycling sector not only to sort PET bottle waste but also to add value through processes such as flake and grain production.

It is important to acknowledge the limitations of the study's applicability to different regions and countries. The unique socio-cultural contexts, waste management infrastructures, and regulatory frameworks of each location may affect the generalization of the findings. Future research should focus on understanding the social dynamics, consumer behavior, and socio-economic conditions specific to each region to develop context-specific waste management strategies. Also, future research endeavors could utilize the developed framework and modified AHP methodology to integrate environmental and social sustainability pillars. Furthermore, for studies incorporating economic LCA, the framework presented in this study can be expanded to encompass all three pillars of sustainability.

Author Contributions: Conceptualization, B.S.B. and E.J.P.M.; methodology, B.S.B. and E.J.P.M.; software D.S.B.L.O.; validation, formal analysis, investigation, E.J.P.M., D.S.B.L.O. and L.S.B.L.O.; data curation, E.J.P.M.; writing—original draft preparation, E.J.P.M.; writing—review and editing, B.S.B., D.S.B.L.O. and L.S.B.L.O.; visualization, D.S.B.L.O. and L.S.B.L.O.; supervision, B.S.B.; project administration, E.J.P.M.; funding acquisition, B.S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES and CNPq PQ/2020.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data will be available upon request.

Acknowledgments: The authors would like to thank the Municipality of Bauru and the cooperatives for the data availability.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABNT	Brazilian Association of Technical Standards
AHP	Analytic Hierarchy Process
ASCAM	Association of Recyclable Material Collectors of Bauru and Region
S-LCA	Social Life Cycle Assessment
LCA	Life Cycle Assessment
BR	Brazil
DS	Desenvolvimento Sustentável
Econ-LCA	Economic Life Cycle Assessment (Life Cycle Cost Analysis)
EMBURD	Empresa Municipal de Desenvolvimento Urbano e Rural de Bauru
Env-LCA	Environmental Life Cycle Assessment
ETAR	Wastewater treatment plant
EURO	Europe
FEB	Faculty of Engineering of Bauru
I-LCA	Integrated Life Cycle Assessment
ISO	International Organization for Standardization
LCSA	Life Cycle Sustainability Assessment
MAVT	Multiattribute Value Theory
MDCA	Multi-criteria decision analysis
PE	Polyethylene
PET	Polyethylene Terephthalate
PNRS	National Solid Waste Policy
PROMITHEE	Preference Ranking Organization Method for Enriched Evaluation
SEMMA	Secretaria Municipal do Meio Ambiente
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UNESP	Sao Paulo State University “Júlio de Mesquita Filho”

References

- Arivumani, A.; Vijayalaxmi, I. Sustainable Development. *Adv. Nat. Appl. Sci.* **2017**, *11*, 296–300.
- Wall, G. Beyond sustainable development. *Tour. Recreat. Res.* **2018**, *43*, 390–399.
- Zimdars, C.; Haas, A.; Pfister, S. Enhancing comprehensive measurement of social impacts in S-LCA by including environmental and economic aspects. *Int. J. Life Cycle Assess.* **2018**, *23*, 133–146.
- Brasil. Lei No 12.305, de 02 de Agosto de 2010: Institui a Política Nacional de Resíduos Sólido. Brasília, Brasil. 2010. Available online: http://www.planalto.gov.br/ccivil_03/_Ato2007-2010/2010/Lei/L12305.htm (accessed on 10 January 2023).
- ABIPET. Associação Brasileira da Indústria do PET. *Censo da Reciclagem No Brasil*; ABIPET: São Paulo, Brazil, 2016; p. 10.
- Kloepffer, W. Life cycle sustainability assessment of products. *Int. J. Life Cycle Assess.* **2008**, *13*, 89.
- Costa, D.; Quinteiro, P.; Dias, A.C. A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. *Sci. Total Environ.* **2019**, *686*, 774–787.
- Visentin, C.; Trentin, A.W.d.S.; Braun, A.B.; Thomé, A. Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies. *J. Clean. Prod.* **2020**, *270*, 122509.
- UNEP/SETAC. *Guidelines for Social Life Cycle Assessment of Products*; United Nations Environment Program SETAC Life Cycle Initiative United Nations Environment Programme: Paris, France, 2009.
- UNEP/SETAC. *Guidelines for Social Life Cycle Assessment of Products*; United Nations Environment Program SETAC Life Cycle Initiative United Nations Environment Programme: Paris, France, 2020.
- UNEP/SETAC. *The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)*; United Nations Environment Program SETAC Life Cycle Initiative United Nations Environment Programme: Paris, France, 2013.
- UNEP/SETAC. *The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA)*; United Nations Environment Program SETAC Life Cycle Initiative United Nations Environment Programme: Paris, France, 2021.
- Martin, E.J.P.; Oliveira, D.S.; Oliveira, L.S.; Bezerra, B.S. Life cycle comparative assessment of pet bottle waste management options: A case study for the city of Bauru, Brazil. *Waste Manag.* **2021**, *119*, 226–234.
- Martin, E.J.P. Evaluation of Environmental and Social Aspects of the Reverse Supply Chain of PET Bottles. PhD Thesis, Industrial Engineering Graduate Program, São Paulo State University (UNESP), Sao Paulo, Brazil, 2020. (In Portuguese).
- Opher, T.; Friedler, E.; Shapira, A. Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. *Int. J. Life Cycle Assess.* **2019**, *24*, 1319–1332.

16. Aziz, R.; Chevakidagarn, P.; Danteravanich, S. Life cycle sustainability assessment of community composting of agricultural and agro industrial wastes. *J. Sustain. Sci. Manag.* **2016**, *11*, 57–69.
17. Nzila, C.; Dewulf, J.; Spanjers, H.; Tuigong, D.; Kiriamiti, H.; van Langenhove, H. Multi criteria sustainability assessment of biogas production in Kenya. *Appl. Energy* **2012**, *93*, 496–506.
18. Wulf, C.; Zapp, P.; Schreiber, A.; Marx, J.; Schlör, H. Lessons Learned from a Life Cycle Sustainability Assessment of Rare Earth Permanent Magnets. *J. Ind. Ecol.* **2017**, *21*, 1578–1590.
19. Akhtar, S.; Reza, B.; Hewage, K.; Shahriar, A.; Zargar, A.; Sadiq, R. Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials. *Clean Technol. Environ. Policy* **2015**, *17*, 973–992.
20. De Luca, A.I.; Falcone, G.; Stillitano, T.; Iofrida, N.; Strano, A.; Gulisano, G. Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy. *J. Clean. Prod.* **2018**, *171*, 1187–1202.
21. Hossaini, N.; Reza, B.; Akhtar, S.; Sadiq, R.; Hewage, K. AHP based life cycle sustainability assessment (LCSA) framework: A case study of six storey wood frame and concrete frame buildings in Vancouver. *J. Environ. Plan. Manag.* **2015**, *58*, 1217–1241.
22. Ekener, E.; Hansson, J.; Larsson, A.; Peck, P. Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting—Tested on biomass based and fossil transportation fuels. *J. Clean. Prod.* **2018**, *181*, 337–351.
23. Ayan, B.; Abacioğlu, S.; Basilio, M.P. Uma Revisão Abrangente dos Novos Métodos de Ponderação para Tomada de Decisão Multicritério. *Informações* **2023**, *14*, 285. [[CrossRef](#)]
24. ABNT. Associação Brasileira de Normas Técnicas. *NBR ISO 14040 and 14044: Gestão Ambiental: Avaliação do Ciclo de Vida: Princípios e Estrutura*; ABNT: Rio de Janeiro, Brazil, 2014. (In Portuguese)
25. Sousa, S.R. Normalização de Critérios Ambientais Aplicados à Avaliação do Ciclo de Vida. Master's Degree. Universidade Federal de Santa Catarina, Centro Tecnológico. Programa de Pós-Graduação em Engenharia Ambiental, Brazil, 2008. Repositório Institucional UFSC. Available online: <https://repositorio.ufsc.br/handle/123456789/92080> (accessed on 15 January 2020).
26. Foolmaun, R.K.; Ramjeeawon, T. Comparative life cycle assessment and social life cycle assessment of used polyethylene terephthalate (PET) bottles in Mauritius. *Int. J. Life Cycle Assess.* **2013**, *18*, 155–171.
27. Foolmaun, R.K.; Ramjeeawon, T. Disposal of post-consumer polyethylene terephthalate (PET) bottles: Comparison of five disposal alternatives in the small island state of Mauritius using a life cycle assessment tool. *Environ. Technol.* **2012**, *33*, 563–572.
28. Foolmaun, R.K.; Ramjeeawon, T. Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius. *Environ. Dev. Sustain.* **2013**, *15*, 783–806.
29. Steinhorst, J.; Beyerl, K. First reduce and reuse, then recycle! Enabling consumers to tackle the plastic crisis—Qualitative expert interviews in Germany. *J. Clean. Prod.* **2021**, *313*, 127782. [[CrossRef](#)]
30. Hossain, U.; Ng, S.T.; Dong, Y.; Amor, B. Strategies for mitigating plastic wastes management problem: A lifecycle assessment study in Hong Kong. *Waste Manag.* **2021**, *131*, 412–422. [[CrossRef](#)] [[PubMed](#)]
31. Zhang, H.; Wen, Z.-G. The consumption and recycling collection system of PET bottles: A case study of Beijing, China. *Waste Manag.* **2014**, *34*, 987–998. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.