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Review

Meta-Analysis of Life Cycle Assessment Studies for Polyethylene Terephthalate Water Bottle System

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Abstract: The life cycle assessment (LCA) serves as a crucial tool for assessing the environmental impact of products, with recent emphasis on polyethylene terephthalate (PET) bottles. Our meta-analytical review of 14 LCA research papers (2010–2022) on PET bottles, aligned with PRISMA guidelines, spans six phases: raw material production (MP), bottle production (BP), distribution and transportation (DT), collection and transport (CT), waste management (WM), and environmental benefits (EB). Utilizing the global warming potential (GWP) as the indicator, our study harmonized data into a consistent functional unit, revealing an average emission of 5.1 kg CO_2 equivalent per 1 kg of PET bottles. Major contributors to global warming were identified across the MP, BP, and DT phases. While the MP and BP phases exhibited low variability due to uniform processes, the CT, WM, and EB phases displayed higher variability due to scenario considerations. A comparison with Korean environmental product declaration data affirmed the methodology's practical utility. Our approach offers potential applicability in diverse product category assessments, emphasizing its relevance for informed decision-making in sustainable product development.

Keywords: life cycle assessment; global warming potential; meta-analysis; PET bottle; packaging

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1. Introduction

The expansion of e-commerce channels, rising purchasing power, and population growth have increased packaging waste-associated environmental burdens [1]. Consequently, there is an increase in demand for eco-friendly packaging solutions. In this context, the life cycle assessment (LCA) methodology has gained prominence in evaluating the environmental performance of packaging solutions [2]. LCA is a systematic process to assess the environmental factors associated with products and services throughout their life cycles [3]. It is commonly referred to as the "cradle-to-grave" approach, encompassing the entire life cycle of a product, from the extraction of raw materials to its disposal. Standards such as ISO 14040:2006 [4] and 14044:2006 [5] provide a uniform framework for conducting the LCA analysis while keeping it a flexible tool for research [6].

The LCA research field has grown exponentially, leading to various attempts to integrate and summarize the studies [1]. Previous LCA reviews have been conducted in a narrative style, focusing on specific topics or product categories. Furberg et al. (2021) [7] conducted a narrative review of reusable bottle LCAs and explored the impact of the packaging size, composition, transportation distance, and end-of-life scenarios on the reuse system. Gomes et al. (2019) [8] presented an overview of the LCA studies of polyethylene terephthalate (PET) packaging, comparing different end-of-life scenarios and evaluating alternative materials, aiming to identify the trends and challenges within the two life phases. Bishop et al. (2021) [9] conducted a review of LCA studies that compared the environmental efficiency of bioplastics with conventional petrochemical plastics to explore the strengths and limitations of the environmental performance of bioplastics. Despite the existence of numerous review papers on LCA studies pertaining to PET bottles, there has been no direct comparison utilizing quantitative values.

In the LCA procedure, Ortiz et al. (2009) [10] analyzed the significance of methodological choices, such as impact category selection, inventory completeness, boundary definition, representation of biogenic carbon, and choice of end-of-life scenarios. Therefore, there is an issue of incomparability in the direct comparison of LCA results across different studies due to the methodological choices and assumptions made by LCA practitioners, as well as the differences in datasets [11]. Notably, when different authors evaluate the same product, significant variability in the results can arise owing to the use of different functional units, assessment methods, and scenarios [11,12]. Guidelines to minimize such variability have been created, including the Product Category Rule for Environmental Product Declarations (EPDs) and the Product Environmental Footprint by the European Commission. These initiatives aim to standardize the evaluation methodologies and datasets for specific product categories [13].

Meta-analysis is a review method used to obtain impartial and quantitative results on a specific topic [14]. It is a statistical technique that combines the results of multiple independent studies on the same research question or topic [15]. By synthesizing data from multiple studies, meta-analysis provides a comprehensive understanding of the research question, allowing for the identification of patterns, trends, and discrepancies in the findings [16]. In the field of medicine, meta-analysis is an essential tool to keep the research knowledge constantly updated and to quantitatively assess the heterogeneity of the results [17]. For instance, multiple clinical trials have been conducted to evaluate the efficacy and safety of inhibitors, and using meta-analysis of the randomized clinical trial data increases the precision of estimates [18].

Thus, to enhance the reliability of environmental impact assessments given the variability in LCA study results, it is essential to develop a methodology that can derive comprehensive conclusions through meta-analysis [19,20]. To provide a detailed explanation of the methodology, the proposed systematic review approach was applied to a comparative LCA of PET-bottled water. Among the quantifiable impact categories expressing environmental impact, we seek to establish an environmental impact assessment procedure for PET water bottles, with a focus on indicators such as the global warming potential (GWP) and greenhouse gas (GHG), which are representative of carbon footprints [21].

PET water bottles were chosen for the case study because of their role in the beverage industry, recording the fastest growth rate in the global plastic market [22]. The increasing consumption of bottled water raises concerns over its environmental footprint owing to the increased amount of PET bottle waste. This issue has been addressed through the use of recycled materials, source reduction, and bio-PET [23]. Consequently, plastic-bottled water has become a subject of many LCA studies, making it a suitable subject for meta-analysis [24].

In this study, we aimed to conduct a meta-analysis of the LCA studies to statistically compare the environmental impacts over its full life cycle. A systematic assessment of multiple studies can offer valuable insights into its environmental impacts. This, in turn, can contribute to the development of a methodology for LCA studies and enable evidence-based decision-making and policy evaluation.

By adhering to the ISO framework, the LCA ensures that all studies clearly define the FU and scope while following a standardized four-step procedure [25]. This standardized assessment tool facilitates a seamless harmonization of diverse research findings through meta-analysis [26]. Meta-analysis facilitates the calculation of the mean estimates and identification of GWP variation factors across the LCA results of different PET bottles. Moreover, through a comparative analysis of the average GWP value derived from meta-analysis and the actual GWP value of commercially available products, one can evaluate the extent to which it faithfully represents typical carbon footprint results. The findings of this study provide detailed guidelines for the systematic and practical evaluation of the environmental impacts of the PET bottle life cycle through LCA.

2. Materials and Methods

This study encompasses a sequential five-step methodology, delineated in Figure 1, which guides the systematic execution of the research process to derive an integrated conclusion. The methodology can be adapted to both products and services by employing an iterative approach that allows for continuous data updates or modifications during the study. The prescribed iterative procedure ensures a systematic and refined evaluation, thereby enhancing the accuracy and comprehensiveness of the assessment.

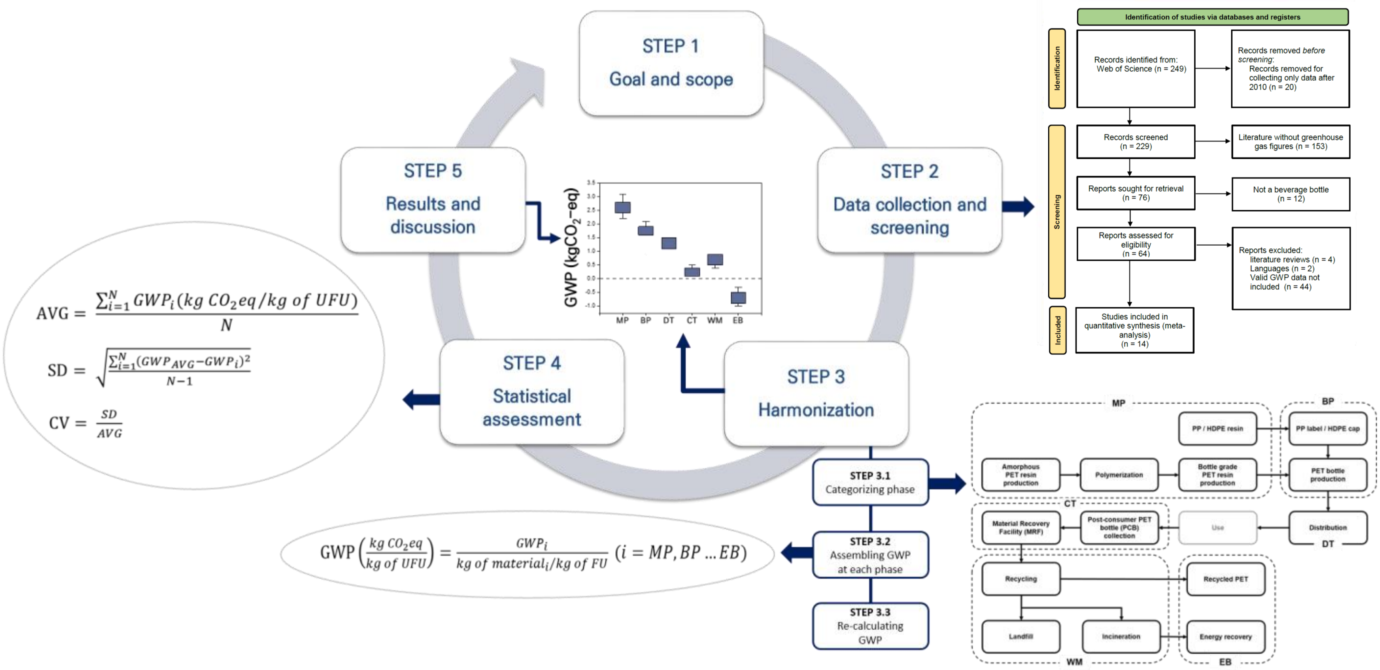


Figure 1. Five-step overview of the research method.

2.1. Goal and Scope

To systematically integrate the results of LCA studies, it is essential to establish a target for meta-analysis. This begins with a clear definition of the study's goal and scope. In this study, the identified goal is to analyze the environmental performance across the entire life cycle of the PET-bottled water system. The defined scope, in alignment with this objective, adopts a cradle-to-cradle perspective, covering from raw material collection to the post-disposal process. The focus of the analysis parameter is specifically on evaluating the GWP.

2.2. Data Collection and Screening Process

LCA studies were compiled from electronic bibliographic databases of scientific literature and web search engines. The references included papers and project reports published in international journals and EPDs. The search method utilizes a specific query to effectively target the subject matter. For this review, LCA research literature was collected from the Web of Science using the following query:

Queries: LCA OR life cycle assessment (All Fields) and PET OR polyethylene terephthalate (All Fields) and bottle OR bever* OR pack* OR water system (All Fields) and GWP OR global warming OR GHG OR CO2 (All Fields) 2010–2023.

To perform the meta-analysis, the selected studies were screened using the PRISMA guidelines. PRISMA is a scientifically grounded essential item for reporting systematic reviews and meta-analyses. It was developed in an attempt to increase the clarity, transparency, and quality of reports [27]. The screening process involved searching for documents in the Web of Science database that specifically addressed LCA and PET bottles. Studies published before 2010 were excluded to ensure that the data is up-to-date. Additionally, only studies focusing on carbon emissions, including terms such as GWP, GHG, and CO_2, were considered for the analysis, whereas studies unrelated to PET bottles or packaging were omitted.

After the initial screening, 64 LCA research articles were selected for further review. The examination involved identifying documents that lack life-cycle phase-specific GWP data, as well as those not adhering to the desired system boundaries or those that primarily consisted of literature reviews that were unsuitable for quantitative analysis. Figure 2 shows a visual representation of the screening process. The final set of 14 selected studies served as the subjects for this meta-analysis. A comprehensive summary of the 14 studies is provided in Table S1 within the Supplementary Materials.

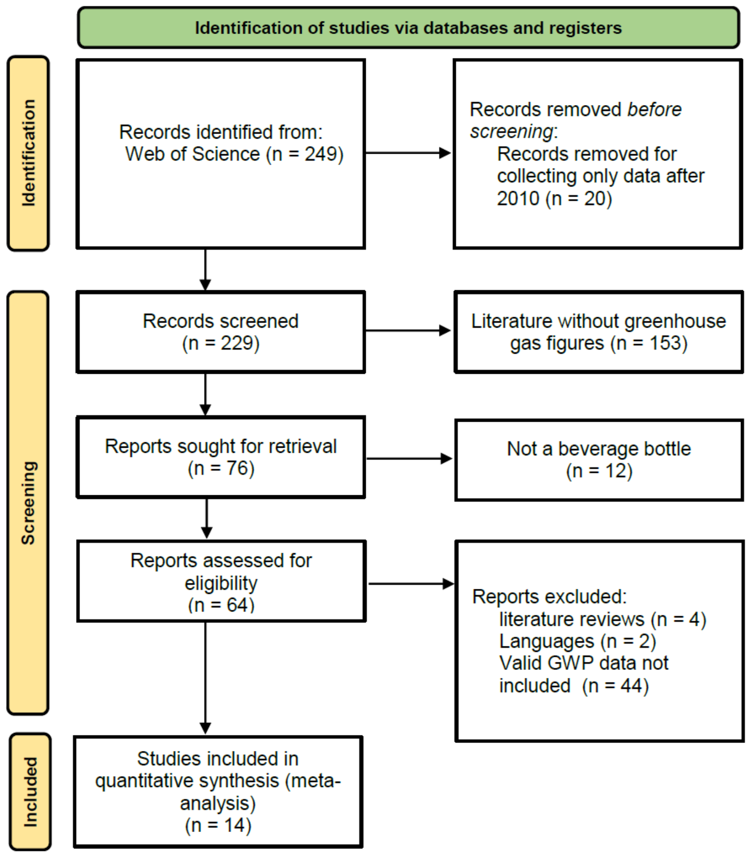


Figure 2. A flow chart of the PRISMA-based screening process for study purposes.

By adhering to the PRISMA guidelines, a systematic and rigorous screening process was ensured, laying the groundwork for a robust and reliable meta-analysis.

Following the literature selection for the review, the differentiation of geographical boundaries, system boundaries, data sources, and FUs for each document is essential for identifying significant parameters. Chapter 3 presents the results of this differentiation process for each element.

2.3. Harmonization of Data

2.3.1. Categorizing Phases for Research Result Collection

The process of synthesizing the literature results is essential to facilitate a quantitative literature review via meta-analysis. To consistently harmonize the GWP results from each study within the determined system boundaries, the life cycle of the PET bottle was subdivided into six phases: Material production (MP), bottle production (BP), distribution transportation (DT), post-consumer PET bottle collection transportation (CT), waste management (WM), and environmental benefits (EB). A flowchart is shown in Figure 3.

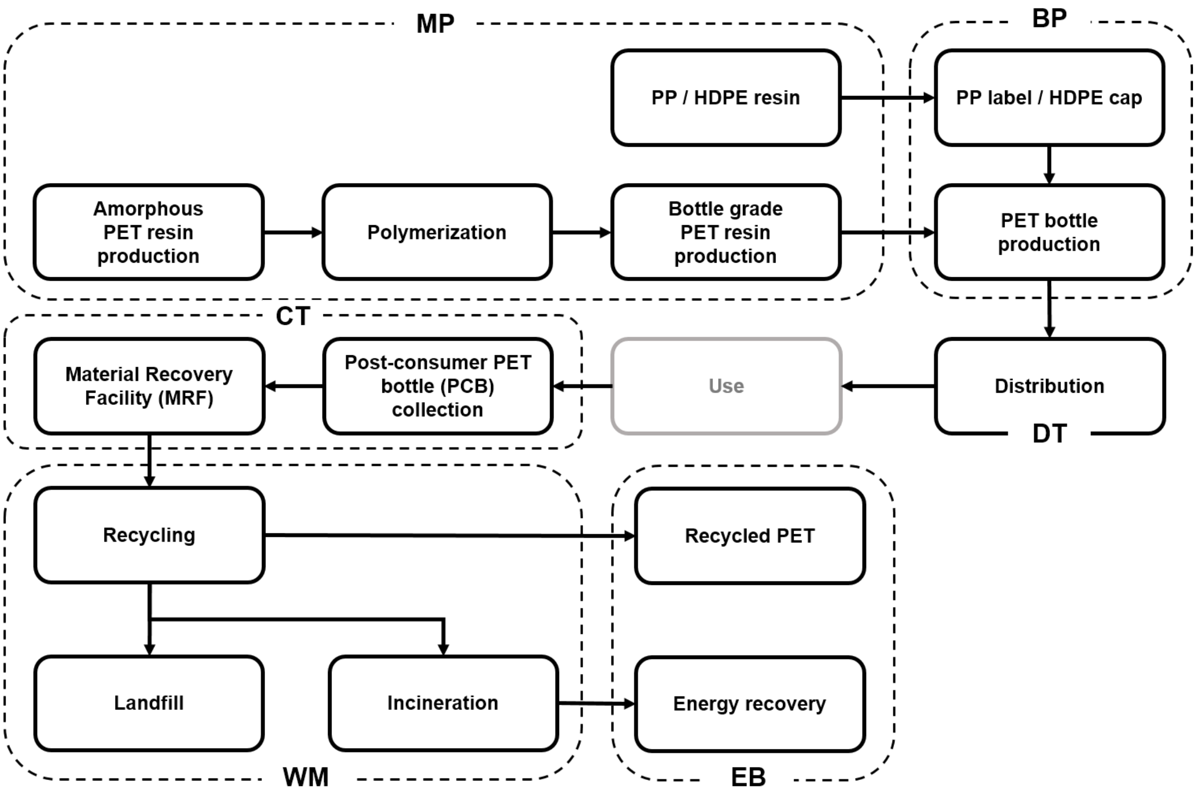


Figure 3. The life phases of a PET bottle within the study system boundaries were used for the harmonization process.

The MP phase involves the production of bottle-grade PET resin from the extraction of crude oil and natural gas through polymerization. It also includes the production of polypropylene (PP), which is used as a label material, and high-density polyethylene (HDPE), which is used as a cap material. The BP phase involves the creation of preforms by injecting PET resin, forming PET bottles through stretch-blow molding, producing labels from the extruded PP film, and making caps through the injection molding of HDPE resin. DT refers to consumer distribution, whereas CT encompasses the transportation process that collects post-consumer PET bottles and moves them to a post-collection treatment facility, such as a material recovery facility. WM consists of measures taken to minimize the environmental impacts through the recycling, incineration, and landfill of collected PET bottles. Recycling involves mechanical and chemical processes. Finally, EB refers to the benefits achieved by utilizing recycled raw materials obtained from recycling during the WM phase, leading to a reduction in the production of new plastic raw materials. Additionally, it includes the heat recovery resulting from incineration. Recycled raw materials can be categorized into open loops, which are recycled into fibers or strings, and closed loops, which are recycled back into PET bottles.

2.3.2. Assembling GWP at Each Phase

At this stage, the 'global warming potential per functional unit (GWP/FU)' values for each phase were extracted from the selected literature. The functional unit of LCA defines the specific quantity and function of a product being analyzed, serving as the reference point for assessing environmental impacts. These values were categorized into six predefined phases. It is important to note that not all studies provided a comprehensive coverage of each phase. Some studies focused solely on specific phases, such as waste disposal, or excluded certain phases, such as transport from system boundaries. In instances where some phases were missing from the literature, only the results from the existing phases were utilized, and the GWP values for the omitted phases were not considered. This approach allows the inclusion of partial results to extend the parameters used in the analysis.

The presentation of the GWP results varied across studies. Some studies had explicitly stated the GWP values for each phase based on a well-defined classification. Conversely, other studies presented the GWP values of the entire product system and displayed the contribution of each phase as a percentage or in a graphical format. When the contribution of each phase was not explicitly provided, the GWP value of a specific phase was derived by multiplying the total GWP value by the contribution of the corresponding phase. Additionally, when data were illustrated as a stacked bar graph, software programs, such as Illustrator, were used to calculate the length of each bar, ensuring the proportional representation of each phase's contribution.

2.3.3. Re-Calculating GWP per Unified Functional Unit

The analyzed literature shared the same product, yet directly comparing the GWP values proved challenging because of the use of different FUs. To address this issue, each functional unit in the references was labeled as "FU", and a unified functional unit that was used in the meta-analysis was established as "UFU".

The literature on LCA defines FUs based on their weight or volume. For instance, with PET beverage bottles, even for the same 0.5 L product, the actual amount of PET raw material can vary. Therefore, the UFU was defined as "1 kg of PET bottles".

To standardize the GWP values, an equation was determined for each document, enabling the conversion from "GWP per FU" to "GWP per UFU" (i.e., UFU = 1 kg of PET bottles). Using this Equation (1), the GWP per UFU value was calculated. The resulting values represented the GWP per UFU and served as quantitative parameters for the meta-analysis.

$$\mathrm{GWP}\left(\frac{\mathrm{kg\ CO_2eq}}{\mathrm{kg\ of\ UFU}}\right) = \frac{\mathrm{GWP_i}}{\mathrm{kg\ of\ material_i/kg\ of\ FU}}\ (i = \mathrm{MP, BP} \ldots \mathrm{EB}) \quad (1)$$

2.4. Statistical Assessment

The harmonized parameters were subjected to statistical analyses. First, the average (AVG), standard deviation (SD), and coefficient variation (CV) of the GWP were analyzed for each phase. AVG, SD, and CV adhere to Equations (2)–(4). By comparing the average GWP estimates for each phase, the hotspot phase with the highest environmental impact could be identified. Additionally, the comparison and analysis of CV revealed the factors contributing to the variation in GWP values and briefly described the resulting tendencies across the environmental impacts. Building upon the insights gained from the factors influencing environmental impact, we propose technologies and strategies designed to effectively reduce the carbon footprint in each phase.

$$\mathrm{AVG} = \frac{\sum_{i=1}^{N} \mathrm{GWP_i(kg\ CO_2eq/\ kg\ of\ UFU)}}{\mathrm{N}}(\mathrm{N} = \text{The number of data for each phase}) \quad (2)$$

$$\mathrm{SD} = \sqrt{\frac{\sum_{i=1}^{N}(\mathrm{GWP_{AVG}} - \mathrm{GWP_i})^2}{\mathrm{N}-1}}(\mathrm{N} = \text{The number of data for each phase}) \quad (3)$$

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{AVG}} \quad (4)$$

Second, to validate whether the GWP values extracted from the literature represented integrated and representative results, they were compared with the GWP values of commercially available products. The EPD system quantifies and discloses the environmental impact of products throughout their life cycle, including raw material collection, production, transportation, use, and disposal. Products with EPD certification in Korea disclose their evaluation scopes, methodologies, and results. By comparing the GWP of EPD-certified products, the validity and usefulness of the GWP estimation methodology for the PET bottle's life cycle were verified through a meta-analysis. In addition, this comparison provides an opportunity to evaluate the quality and authenticity of Korea's environmental evaluation methodology.

In order to compare the statistical difference of product volumes (0.33 L, 0.5 L, 1 L, 2 L), the Games–Howell post hoc test was conducted with a confidence level (α = 0.05) using the IBM Statistical Package for Social Sciences (SPSS) version 29. This test is often used when the assumption of homogeneity of variances of a group is violated [28].

2.5. Assumptions and Limitations

(1) In statistical analysis, a higher number of parameters allows for more accurate conclusions. To increase the number of parameters, only partial values from the PET bottle's life cycle were included in this study, as the entire life cycle was not considered.
(2) To increase the number of parameters, the literature review also included studies on subjects other than bottled water, such as PET flakes. However, cases related to carbonated beverages that exhibited significant differences in PET raw material consumption were excluded from data collection.
(3) While some studies explicitly specified disposal rates, there were cases in which information about how disposal scenarios were set was not adequately provided. In such instances, the environmental impact of recycling, incineration, and landfill processes was collectively termed "waste management" and calculated by aggregating the effects of these processes.

3. Results and Discussion

3.1. Analysis of References

In this study, a total of 14 LCA studies were meticulously selected through a PRISMA screening process. These studies were scrutinized for various parameters, including the study year, geographic location, system boundary, FU, and content type, to comprehensively analyze their implications for PET bottle systems. It is important to note that the year of the study is significant, as the environmental impact results can vary depending on the technology prevalent at the time the study was conducted. Similarly, the geographic location exerts a distinct influence on the environmental load owing to disparities in technological advancements across different countries. Factors such as production technology, energy efficiency, transportation distance, and disposal methods exhibit substantial variations based on geographical considerations.

In terms of system boundaries, our approach aims to consider the entire life cycle comprehensively, encompassing a cradle-to-grave perspective, to collect data to the fullest extent possible. Furthermore, we sought to compile a diverse database that included studies that conducted detailed assessments of specific life-cycle phases. It is worth noting that within the domain of LCA, the definition of the FU not only significantly influences the quantity of raw materials used but also impacts the results of the assessment, which underscores their importance as key parameters to be identified. These parameters are summarized in Table 1 to facilitate meaningful cross-comparisons among the literature sources.

Data were distributed evenly across the years from 2011 to 2022, with a notable concentration of literature in 2021, comprising five articles. Geographically, Europe emerged as the predominant source, contributing six articles. In most cases, the system boundaries were delineated as cradle-to-grave, reflecting a comprehensive life cycle perspective. The definition of the FU is primarily based on volume or weight metrics, often centered on the capacity and quantity of PET beverage bottles. In addition, the literature presents the weights of the PET bottles. Certain instances involved specifying the weight of both the cap and label of a beverage bottle, whereas others concentrated solely on quantifying the weight of the bottle's body.

Table 1. The LCA research literature was selected for the systematic review.

No.	Reference	Year	Geographical Boundary	System Boundaries	Functional Unit (FU)	PET Bottle Weight
1	Gileno and Turci [29]	2021	Brazil	cradle-to-gate	1 t of post-consumer recycled PET resin or 1 t of rPolyester fiber	NA
2	Bataineh [30]	2020	Jordan	cradle-to-grave	1 t of PET flake	NA
3	Kouloumpis, et al. [31]	2020	England	cradle-to-grave	2468 t of PET bottles	NA
4	Tamburini, et al. [32]	2021	Italy	cradle-to-grave	1 year of use: 1095 bottles of PET	19.1 g
5	Grisales, et al. [33]	2022	Italy	cradle-to-grave	The distribution of 100 L mineral water	15.22 g
6	Olatayo, et al. [34]	2021	South Africa	cradle-to-grave	10 single-use 0.5 L PET bottles	20.3 g
7	Lonca, et al. [35]	2020	USA	cradle-to-grave	2.78 t PET bottles (in a year in the US)	NA
8	Gursel, et al. [36]	2021	Europe	cradle-to-grave	Packaging water in one hundred 0.5 L bottles (1 kg PET bottles)	10 g
9	Benavides, et al. [37]	2018	USA	cradle-to-grave	One 26 g 500 mL PET bottle	26 g
10	Martin, et al. [38]	2021	Brazil	cradle-to-grave	1 t of PET waste	NA
11	Papong, et al. [39]	2014	Thailand	cradle-to-gate	1000 units of 250 mL drinking water bottles	NA
12	Kuczenski and Geyer [40]	2013	California	cradle-to-gate	1 L beverages in single-use PET bottles consumed by Californians during the years 2007–2009	40.8 g
13	Gironi and Piemonte [41]	2011	Italy	cradle-to-grave	1000 units of 500 mL PET bottles to be used for drinking water	12.2 g
14	Kim, et al. [42]	2022	Korea	cradle-to-grave	A PET water bottle, 500 mL	17 g

3.2. Harmonization

3.2.1. Categorizing and Extracting GWP

The GWP values were systematically obtained for each of the six phases of the study. Given the diverse unit expressions employed for the GWP values, encompassing both kilograms of CO_2 equivalent (kg CO_2eq) and grams of CO_2 equivalent (g CO_2eq), meticulous efforts were undertaken to standardize all data by converting them into a unified unit of kilograms of CO_2 equivalent (kg CO_2eq).

This comprehensive data collection effort yielded 48 GWP extraction datasets distributed across various phases, including 10 in MP, 10 in BP, 2 in DT, 7 in CT, 12 in WM, and 7 in EB. These datasets were consistently organized and presented as "kg CO_2eq per FU" and are meticulously summarized in Table 2.

Among the distinct phases, the WM phase emerged as the most extensively covered, boasting a higher volume of data, whereas the distribution and transportation phase exhibited a comparatively limited dataset. This can be attributed to the predominant focus of LCA studies on scenarios associated with PET bottle disposal. Furthermore, some studies have incorporated the EB stemming from the waste treatment process, thereby complicating the independent selection of GWP values for the EB phase and potentially yielding lower GWP values for the WM phase compared to other studies.

Table 2. Global warming potential (GWP) values of the chosen studies.

No.	MP	BP	DT	CT	WM	EB
1				134	856	
2	2746			155.560	660.610	−1800
3		8.920×10^6		1.160×10^5	2.300×10^6	-3.500×10^5
4	98.018	25.766			1.675	−7.300
5	6.809	3.450	3.950		1.155	−1.127
6					0.012	−0.011
7	7822	6532		912	1960	
8	2.237	0.920			0.047	
9	0.073	0.046				−0.026
10				26.633	73.445	−56.715
11	48.240	19.640				
12	98.300	80.500		15.700	32.100	
13	33.306	4.636		0.122	0.910	
14	3.910×10^{-2}	1.860×10^{-2}	3.029×10^{-3}		1.860×10^{-2}	

3.2.2. Normalized GWP by Unified FU

To enable a meaningful comparison of the GWP values extracted with various FUs, a harmonization process was implemented. This involved aligning them with the UFU, representing 1 kg of PET bottles. The resultant harmonized GWP values, expressed in kg CO_2eq/1 kg of PET bottles, are presented in Table 3.

Table 3. Data items for GWP (kg CO_2eq) unification by phase in UFU (1 kg of PET bottle).

No.	MP	BP	DT	CT	WM	EB
1				0.134	0.856	
2	2.746			0.156	0.661	−1.800
3		3.614		0.047	0.932	−0.142
4	4.687	1.232			0.080	−0.349
5	2.237	1.133	1.298		0.379	−0.370
6					0.059	−0.056
7	2.813	2.349		0.328	0.705	
8	2.237	0.920			0.047	
9	2.805	1.772				−0.991
10				0.027	0.073	−0.057
11	2.950	1.201				
12	2.409	1.973		0.079	0.787	
13	2.730	0.380		0.010	0.075	
14	2.300	1.094	1.094		0.178	

Previously, the diversity of the GWP values was hindered by variations in the FUs. However, through the systematic organization of these values based on UFU, quantitative comparisons are now attainable. The ensuing step of our analysis involves a comprehensive examination and statistical assessment of the harmonized GWP results.

3.3. Statistical Assessment

3.3.1. Assessment of Harmonized GWP

In the domain of statistical analysis, box plots serve as valuable tools for visually comparing multiple datasets and categories. They offer a succinct overview of the distribution of the environmental impacts among the assessed groups. The plot boxes indicate the interquartile range, with the median represented by the inner line. The lower and upper whiskers extend to values within a predefined range, excluding the outliers. Interpreting the box plot facilitated the identification of central tendencies and the spread of the GWP (kg CO_2eq/1 kg of PET bottle) values for each phase, providing insights into comparative environmental performance. Figure 4 presents a boxplot that excludes outliers to enable a comprehensive analysis.

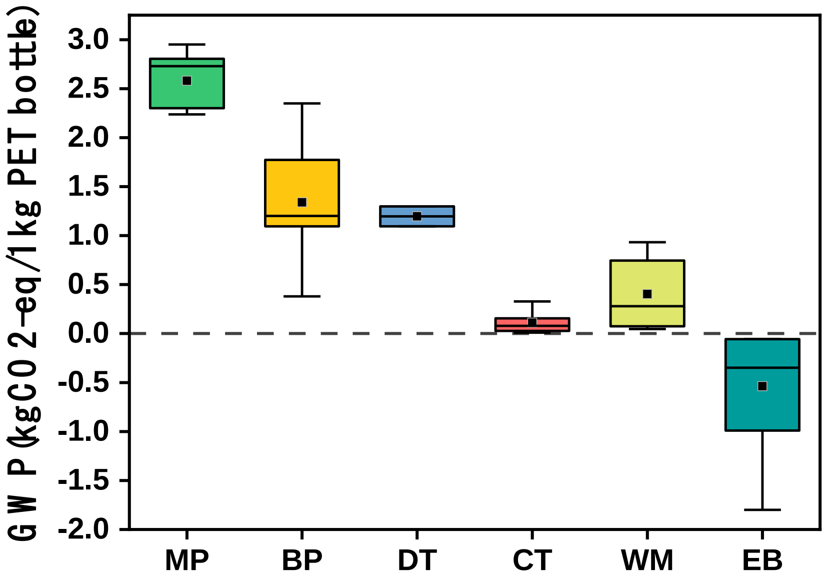


Figure 4. Box plot analysis of GWP values for six phases of the PET bottle.

Two outliers were identified: one in the MP and one in BP. The outliers in the MP phase, as demonstrated by Tamburini et al. (2021) [32], result from meticulous calculations performed by individual companies. These calculations encompass raw material production yields along with the electricity and heat consumption for each process, starting from the synthesis of monoethylene glycol and purified terephthalic acid. This level of scrutiny reveals the distinct regional characteristics that increase the likelihood of energy overlap. Therefore, it is reasonable to designate this data point as an outlier.

The outlier of the BP phase is attributed to the inherent challenge of isolating the PET resin production from the bottle stretch-blow molding process, as detailed in the study by Kouloumpis et al. (2020) [31]. Due to the inseparability of these two processes, they were combined into a single value, resulting in the removal of outliers before subsequent analyses. Additionally, the statistical analysis encompassed key metrics, including the AVG, SD, coefficient of variation (CV), and number of parameters (N) for all life phases of a PET bottle. The analytical findings are summarized in Table 4 for a comprehensive evaluation.

Table 4. The summary of the statistical analyses of the GWP values of each phase.

Phase	MP	BP	DT	CT	WM	EB
AVG	2.581	1.340	1.196	0.111	0.403	−0.538
SD	0.282	0.596	0.144	0.110	0.358	0.643
CV	0.109	0.445	0.120	0.983	0.888	1.196
N	9	9	2	7	12	7

The aggregation of the average values from each phase serves as an indicator of the total greenhouse gas emissions across the life cycle of the PET bottle. The calculated life-cycle carbon emissions, based on data derived from LCA research literature, amounted to 5.093 kg CO_2eq. It is evident that the MP contributes most significantly to the overall global warming impact, followed by the BP, DT, WM, and CT phases.

The CV emerged as a valuable relative dispersion metric that facilitates comparisons among phases with different AVG, SD, and measurement units. This aided in assessing the concentration of data around the mean, with a smaller CV indicating a higher degree of concentration. Notably, the CT, WM, and EB phases exhibit higher CV values. These phases involve a multitude of scenarios within the LCA, signifying a higher degree of variability in the data compared to the MP and BP phases, which are characterized by more consistent processes.

3.3.2. Comprehensive Evaluation of GWP in Each Phase

The environmental impact contributions and factors contributing to the variation were analyzed for each phase. The significant contribution of MP to the overall GWP can be attributed to the energy-intensive nature of plastic raw material production. This process involves high-temperature procedures such as melt polymerization, solid-state polymerization, extrusion, and refining. PET production consists of the polymerization of ethylene glycol and terephthalic acid monomers. Post-polymerization, PET pellets are obtained in a dissolved form, necessitating a solid-state polymerization process to yield crystalline pellets known as bottle-grade granules [23]. The production of PET resin involves multiple high-temperature and high-energy steps, resulting in a substantial environmental burden.

The MP phase can be improved by utilizing recycled PET and bio-PET materials. This choice not only mitigates the environmental impact of raw material production by reducing the need for virgin PET—thereby curbing carbon emissions—but also offers cost-saving opportunities. Moreover, a recent study by Benavides et al. (2018) [37] has indicated that landfilling bio-PET and recycled PET bottles can substantially reduce greenhouse gas emissions from a cradle-to-grave perspective. These reductions can range from 12% to 82% in comparison with fossil-fuel-based virgin PET bottles. This outcome was attributed to the carbon-absorbing capacity of the plants used for the bio-PET raw material supply, creating a carbon dioxide cycle structure.

The BP phase encompasses several distinct processes, including the production of PET bottles, HDPE caps, and PP films. Initially, the PET resin underwent injection molding to create preforms, which were subsequently transformed into PET bottles through stretch-blow molding. Simultaneously, the HDPE resin was subjected to injection molding to craft caps, and the PP film was extruded. Notably, these processes involve the use of high-temperature equipment operating at approximately 280 °C. This results in increased energy consumption, primarily electricity, which contributes to an elevated GWP. In the context of bottled water production, there are instances in which bottles are manufactured within cleanroom facilities. This further amplifies energy consumption and subsequently leads to a heightened GWP [43].

Minimizing energy consumption using lightweight PET bottles contributes to a decrease in carbon emissions. An example involves reducing the bottle weight by 20% by incorporating approximately 100 ppm of inorganic substances into the PET preform. Consequently, the power consumption during stretch-blow molding was decreased by 18%, resulting in a 21% reduction in carbon emissions. Moreover, enhancing process efficiency, implementing steam recycling, and transitioning from thermal power generation to renewable energy sources can further mitigate the environmental impacts.

Despite having a limited database, the DT phase ranks as the third largest contributor to the GWP among the six phases considered. The environmental impact of transportation is measured in kgkm, allowing for variations in geography, transport scenarios, and types.

To reduce the environmental impact of transportation, optimizing resource logistics can reduce exhaust emissions by enhancing the energy efficiency of transportation modes, such as transitioning from truck transport with high exhaust emissions to mass transport options such as railroads and shipping. Second, it is vital to actively promote logistics pooling to improve the utilization and loading capacity, necessitating the selection of appropriate vehicle types based on the logistics volume and optimization of transportation distances. Furthermore, reducing the bottle weight contributes fundamentally to a reduction in the greenhouse gas emissions associated with transportation.

The CT phase exhibited the lowest average GWP among the considered phases. Out of the seven research studies providing GWP data for the CT phase, six specified the collection and transportation distances. Table 5 presents a comprehensive summary, including the GWP (kg CO_2eq per 1 kg of PET bottles), distance (km), and GWP/km (kg CO_2eq per 1 kgkm) for the CT phase. Notably, Kuczenski and Geyer (2013) [40] conducted a comprehensive study covering the entire collection system, encompassing curbside and drop-off methods, in the eastern US, where collection distances were notably extensive. Similarly, Gileno and Turci (2021) [29] modeled the collection conditions in Brazil as a case study. The remaining literature primarily reported simplified distances from curbside collection to recycling and incineration facilities, with the majority falling within 300 km.

Table 5. Collection route distance (km), GWP (kg CO_2eq/1 kg of PET bottles), and GWP/km (kg CO_2eq/1 kgkm) in the CT phase, per reference.

No.	Reference	Distance (km)	GWP (kgCO_2eq)	GWP/km
(1)	Bataineh (2020) [30]	60	0.016	0.000259
(2)	Gironi and Piemonte (2011) [41]	100	0.010	0.000100
(3)	Martin et al. (2021) [38]	160	0.027	0.000169
(4)	Kouloumpis et al. (2020) [31]	286	0.047	0.000164
(5)	Kuczenski and Geyer (2013) [40]	570	0.079	0.000139
(6)	Gileno and Turci (2021) [29]	750	0.134	0.000179

A trend emerged where the GWP increased with longer transportation distances, as shown in Figure 5. The calculation of R-squared, a robust measure of the relationship between independent and dependent variables, yielded a value of 0.964, signifying the strong explanatory power of distance (the independent variable) in relation to the GWP (the dependent variable). LCA employs the unit of kgkm to evaluate the environmental impact during transport, and when normalized to 1 kg, it is directly proportional to kilometers.

The GWP/km, which represents the comparison of GWP for 1 km, is shown in Figure 6 as a scatter plot. Among the six datasets, cases (1) and (2) were determined to be outside of the 95% confidence interval. For instance, the GWP value in Bataineh (2020) [30], which was set at 60 km, was comparatively high. However, this discrepancy arises because of various factors with regard to transportation, such as fuel type, vehicle category, and distance. Similarly, Gironi and Piemonte (2011) [41] found that GWP values can be influenced by factors such as the EURO emission standards and truck types in the transport datasets of the DB. For instance, EURO1′s GWP value is 68% that of EURO6, leading to potential variations in the results within the transportation sector [38]. Consequently, the significant CV observed in the CT phase can be attributed to disparities resulting from factors like EURO standards, truck types, truck sizes, country-specific road conditions, and the diversity of waste recovery systems.

In the CT phase, it is imperative to establish an efficient collection system that minimizes the number of collection routes. Ultimately, consumers must proficiently separate and dispose of their products. This approach facilitates the collection of substantial quantities of PET waste, leading to an increased recycling rate.

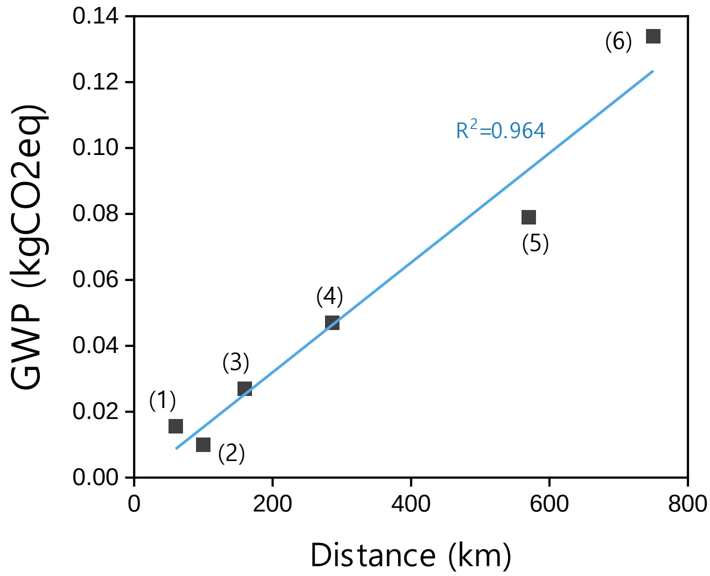


Figure 5. Scatter plot and R-squared values for CT phase GWP converted to "kg CO_2eq per 1 kg of PET bottle". The numbers in parentheses within the figure correspond to the numbers listed in Table 5.

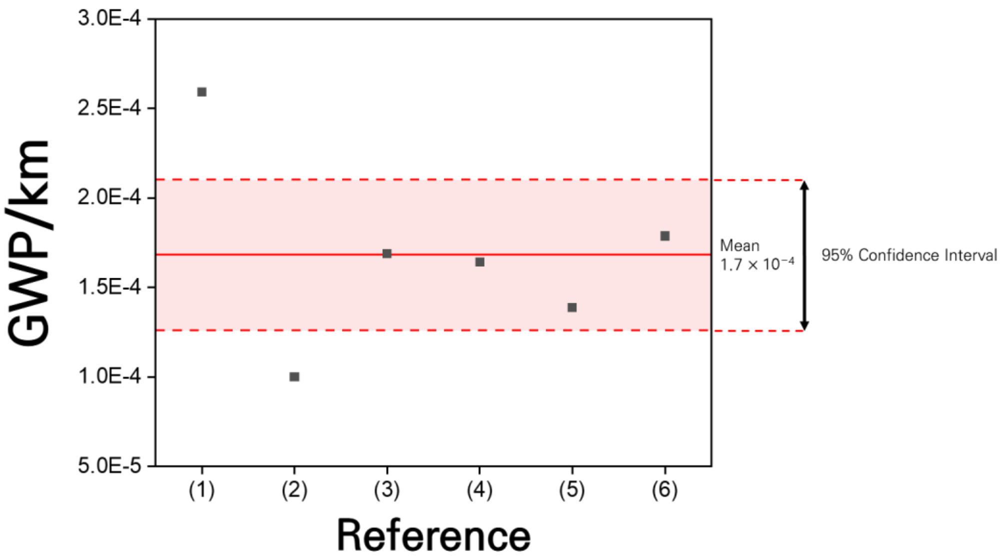


Figure 6. Scatter plot of CT phase GWP values normalized to "kg CO_2eq per 1 kgkm". The numbers in parentheses within the figure correspond to the numbers listed in Table 5.

The WM phase ranked fourth in terms of the GWP and exhibited a high CV. These variations in GWP values were mainly attributed to disparities in the study years and geographical regions. This phase is intricately linked to the evolving landscape of recycling and incineration technologies, wherein improvements in energy efficiency and increased yields in recycled raw material production through recycling play pivotal roles. Moreover, regional differences in GWP values within the WM phase can be attributed to the waste collection systems, disposal technologies, and environmental policies adopted by each country.

Major waste disposal methods include recycling, incineration, and landfill. Recycling is further categorized into physical, chemical, and open-loop or closed-loop processes. Due to the variability in the proportions of recycling, incineration, and landfill in different studies, these factors were treated as variables when calculating the GWP of the WM phase.

Table 6 provides a summary of the specific disposal scenarios utilized in the cited references, with instances of unspecified scenarios marked as "N/A".

Table 6. Rate and type of recycling, incineration, and landfill for disposal scenarios by reference in the WM phase.

No.	Reference	Recycling	Recycling Type	Incineration	Landfill
1	Gileno and Turci (2021) [29]	100%	Closed-loop	N/A	N/A
2	Bataineh (2020) [30]	100%	Open-loop	N/A	N/A
3	Kouloumpis et al. (2020) [31]	52.78%	N/A	47.17%	N/A
4	Tamburini et al. (2021) [32]	100%	Closed-loop	N/A	100%
5	Grisales et al. (2022) [33]	55%	N/A	45%	N/A
6	Olatayo et al. (2021) [34]	46.3%	N/A	N/A	53.7%
7	Lonca et al. (2020) [35]	4.6%	Closed-loop	92%	
8	Gursel et al. (2021) [36]	60%	Open-loop	20%	20%
9	Benavides et al. (2018) [37]	35%	Closed-loop	N/A	65%
10	Martin et al. (2021) [38]	3.6%	N/A	N/A	96.4%
12	Kuczenski and Geyer (2013) [40]	N/A	N/A	N/A	N/A
13	Gironi and Piemonte (2011) [41]	N/A	Closed-loop	N/A	N/A
14	Kim et al. (2022) [42]	36.60%	N/A	48.50%	14.90%

To enable a quantitative comparison of the environmental impacts across various disposal scenarios, we arranged the GWP of the WM phases in ascending order and visually presented them as a heat map, as shown in Table 7. Three discernible trends emerge from the analysis. First, scenarios characterized by elevated landfill rates tend to exhibit lower carbon emissions. When petrochemical-based plastics are disposed of in landfills, they remain non-decomposable for at least 100 years, resulting in minimal greenhouse gas emissions. The fact that the default time frame for calculating the GWP is based on 100 years is the reason why the GWP is calculated low due to the landfill.

Table 7. Ratios of recycling, incineration, and landfill for each reference disposal scenario in the WM phase, organized in ascending order of resulting GWP (kg CO_2eq per 1 kg of PET bottles).

No.	Reference	Recycling	Incineration	Landfill	WM GWP (kg CO_2eq)
8	Gursel et al. (2021) [36]	60%	20%	20%	0.047
6	Olatayo et al. (2021) [34]	46%		54%	0.059
10	Martin et al. (2021) [38]	4%		96%	0.073
13	Gironi and Piemonte (2011) [41]	N/A	N/A	N/A	0.075
4	Tamburini et al. (2021) [32]			100%	0.080
14	Kim et al. (2022) [42]	37%	49%	15%	0.178
5	Grisales et al. (2022) [33]	55%	45%		0.397
2	Bataineh (2020) [30]	100%			0.661
7	Lonca et al. (2020) [35]	4.60%	92%		0.705
12	Kuczenski and Geyer (2013) [40]	N/A	N/A	N/A	0.787
1	Gileno and Turci (2021) [29]	100%			0.856
3	Kouloumpis et al. (2020) [31]	53%	47%		0.932

Second, when comparing the recycling strategies in the WM phase, closed-loop recycling, which involves the conversion of PET to bottle-grade PET, exhibited a higher GWP value than open-loop recycling, which resulted in the production of lower-quality products.

Consequently, from the perspective of the WM phase, closed-loop recycling appears to have a more substantial environmental impact.

Finally, scenarios characterized by high incineration rates tend to yield larger GWP values owing to the significant release of carbon dioxide during the combustion of plastic materials. Within the WM-phase GWP dataset, the highest-impact scenario was observed in a study conducted by Kouloumpis et al. (2020) [31]. This scenario combines recycling and incineration, resulting in increased energy consumption and a heightened environmental impact contribution compared with other studies.

Some studies have combined the WM and EB phases to draw conclusions. Consequently, it is crucial to recognize that when solely considering the WM phase, the GWP values may appear relatively low compared to studies that separate these phases.

Increasing the recycling rate of waste plastics is highly effective for reducing greenhouse gas emissions during disposal. The primary goal is to promote mechanical recycling and concurrently enhance recycling technologies to complement chemical recycling methods. Colorless PET is a clean source that is recognized as suitable for contact with food; hence, it must be meticulously segregated during the recovery and sorting processes. PET obtained through mechanical recycling can then be employed in products intended for food contact.

Chemical recycling is helpful in areas where clean separation and screening are challenging. The focus should be on boosting the recycling rate rather than debating the environmental merits of mechanical versus chemical recycling. Developing technologies for application in both regional and environmental policies is a more pragmatic approach [44].

The EB phase encompasses recycled raw materials and heat derived from recycling and incineration during the WM process. Notably, it exhibited the largest CV among the six phases, signifying a broader range of data compared to other categories. This variance likely arises from the diverse disposal scenarios considered in each study, as all LCA investigations modeled hypothetical scenarios when assessing the EB. The GWP values and associated disposal scenarios for the EB phase are listed in Table 8, have been systematically arranged in ascending order and visually represented as a heat map for comparison.

Table 8. Ratios of recycling, incineration, and landfill for each reference disposal scenario in the EB phase, organized in ascending order of resulting avoided GWP (kg CO_2eq per 1 kg of PET bottles).

No.	Reference	Recycling	Incineration	Landfill	EB GWP (kg CO_2eq)
2	Bataineh (2020) [30]	100%			−1.800
9	Benavides et al. (2018) [37]	35%		65%	−0.991
5	Grisales et al. (2022) [33]	55%	45%		−0.370
4	Tamburini et al. (2021) [32]	100%			−0.349
3	Kouloumpis et al. (2020) [31]	53%	47%		−0.142
10	Martin et al. (2021) [38]	4%		96%	−0.057
6	Olatayo et al. (2021) [34]	46%		54%	−0.056

A limitation of this study pertains to the level of detail provided in the collected references regarding the disposal scenarios. Specifically, some studies did not differentiate between the open-loop or closed-loop methods and mechanical or chemical recycling methods, hindering a precise quantitative comparison between these disposal classifications. Nevertheless, when assessing the EBs of various disposal methods and their combinations, it became evident that scenarios with higher recycling and incineration rates outperformed landfills in terms of the EB.

Closed-loop recycling is expected to yield the most significant EB, primarily because it enables the acquisition of high-quality bottle-grade PET raw materials via chemical recycling. This approach mitigates the environmental burden associated with the production of virgin PET materials. This approach has the potential to mitigate substantial environmental loads compared to the use of low-quality PET products.

However, in the case of Tamburini et al. (2021) [32], despite adopting a 100% closed-loop recycling scenario, it demonstrated fewer benefits than the open-loop 100% and closed-loop 35% disposal scenarios. This discrepancy arises because the study relies on data derived from the external reports available in the literature. It is important to note that this information represents a simplified dataset rather than values derived from comprehensive LCA procedures. Consequently, the introduction of such data, which are not based on research modeling data, introduces uncertainty into the environmental assessment, as it may not fully capture intricate environmental nuances.

Bataineh (2020) [30] reported that the EBs were the greatest despite open-loop recycling through mechanical recycling. This study was conducted by comparing the GWP value calculated by entering the input and output of the PET recycling process in detail with the GWP of PET raw material production established in the database. As a result, it was concluded that PET flake recycling provides a net benefit for greenhouse gas emissions of 1.8 kg of CO_2 equivalent per 1 kg of recycled PET flakes.

Chemical recycling is associated with greenhouse gas emissions and is on par with the production of virgin PET, resulting in a GWP that is four times higher than that of mechanical recycling [45]. However, it offers the advantages of reducing virgin PET usage and solid waste generation by 56% and 64%, respectively. Therefore, when assessing the EBs of closed-loop recycling via chemical recycling alone in terms of the GWP, it may be less efficient than open-loop recycling through mechanical means. It is essential to consider the broader context of circular economies in such evaluations.

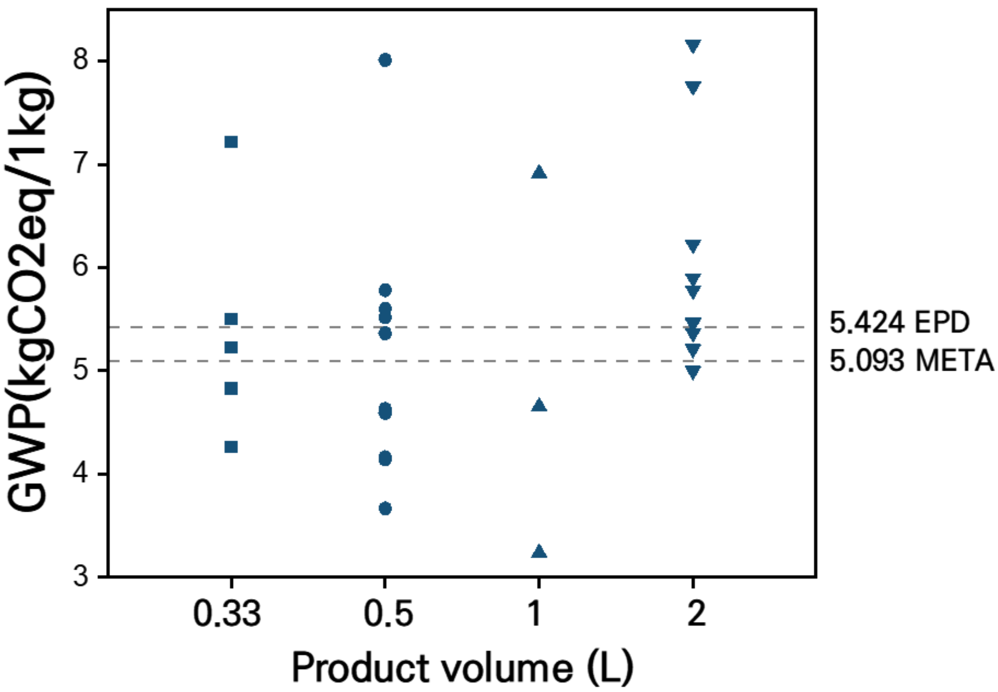
In a study conducted by Olatayo et al. (2021) [34], which demonstrated the lowest EB, an LCA was carried out in South Africa, where approximately 90% of plastic bottle waste enters landfills. This study aims to quantify the potential environmental advantages achievable if the waste slated for landfill disposal is redirected for recycling, assuming a recycling rate of 46.3%. The conclusion of the study suggests that even with a 36.3% increase in recycling rates, the resulting reduction in environmental impact remains relatively modest. However, the need to increase waste collection and recycling rates has been emphasized to reduce plastic generation.

While various methodologies are available for enhancing the environmental benefits, the industry for products reliant on fossil fuels faces challenges in implementing strategies for carbon emission reduction [46]. Hence, there is a growing demand for carbon dioxide reduction through carbon capture, utilization, and storage [47]. Captured carbon dioxide can be applied to the production of bio-based plastic raw materials or mineralized for manufacturing composite materials.

3.3.3. Validation and Utility Assessment: Comparing Meta-Analysis with Korea's EPD

This study presents the total GWP value derived from a comprehensive meta-analysis of LCA studies concerning the life cycle of PET bottles in accordance with the ISO 14040 [4] and 14044 [5] standards. This step aims to demonstrate the utility of a methodology that integrates data from various sources encompassing different years, countries, and scenarios to arrive at quantitative conclusions. Korea's EPD system serves as an eco-labeling initiative that delivers standardized and verified environmental impact information for products across their entire life cycle, adhering to the ISO 14025 specifications [48]. To assign labels, the EPD conducts a thorough LCA, encompassing data related to greenhouse gas emissions, energy consumption during production, resource utilization, and water consumption. Accredited by a professional LCA organization to meet international standards, the EPD system assigns labels that contribute to sustainability goals and mitigate a company's environmental footprint [49].

In the second quarter of 2023, an environmental impact assessment encompassing 32 products within Korea's bottled water bottle classification was conducted, leading to the public disclosure of environmental performance results, including the CO_2 equivalent values, as part of the Korean EPD. These data served as the basis for calculating the average kg CO_2eq per 1 kg of PET bottles in the Korean market. Considering the diverse capacities of bottled water products, ranging from 0.33 L, 0.5 L, 1 L, to 2 L, the "kg CO_2eq per 1 kg of PET bottle" metric was computed using the average weight of the PET bottles corresponding to each capacity. Figure 7 illustrates the resulting scatter and average GWP values for each product capacity. The GWP for the entire life cycle of the Korean PET bottle was 5.424 kg CO_2eq. These values were approximately 6.5% higher than the average GWP estimate of 5.093 kg CO_2eq, which was calculated after removing the outliers through a meta-analysis of the literature. These findings indicate a notable alignment of the average estimates between this study and existing research.



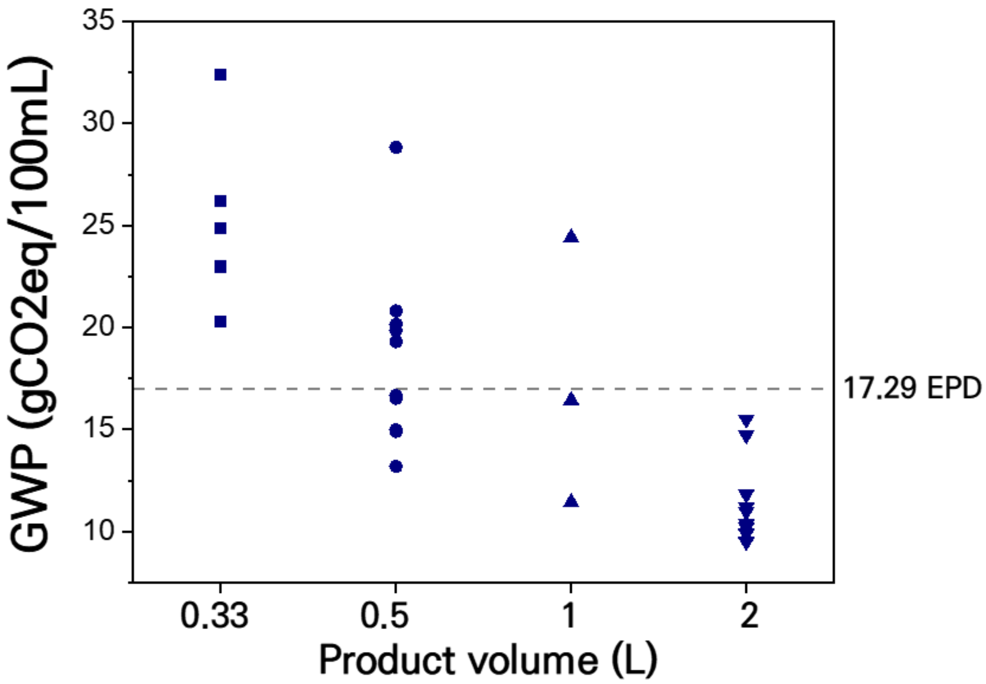
	0.33L	0.5L	1L	2L
AVG	5.34[a]	5.06[a]	4.94[a]	5.98[a]
SD	0.94	1.21	1.85	1.04
CV	0.18	0.24	0.38	0.17

Figure 7. Scatter plot of EPD product values grouped by volume (0.33 L, 0.5 L, 1 L, and 2 L) with GWP normalized to 1 kg PET bottle. Below the scatter plot, the following statistics are provided for each group: average (AVG), standard deviation (SD), and coefficient of variation (CV). Significant differences between groups, determined through statistical techniques, are indicated by superscripts alongside the AVG values. All product volume groups are marked with the superscript "a" indicating the absence of significant differences among them. This is further supported by the post-test results presented in Table S2 within the Supplementary Materials.

Using post hoc analysis, we converted the GWP for each product-volume group to a basis per 1 kg of PET, followed by an assessment of intergroup differences. Underneath Figure 7, the intergroup relationships are depicted, which are indicated by the AVG number superscripts. The post-test results are presented in Table S2 within the Supplementary Materials. There were no significant differences among the four groups, suggesting that when standardized to 1 kg, they could all be considered the same group.

In the subsequent analysis, the GWP for various volumes of EPD products was converted to a standardized measure of 100 mL, and the findings are presented in Figure 8. The average of the EPD products' GWP was calculated at 17.3 g CO_2eq/100 mL, with all

2 L products exhibiting GWP values below the average, whereas the 0.33 L variant was observed to exceed the average emissions load. A cursory examination of Figure 8 reveals a consistent trend in which an increase in product volume leads to a consistent reduction in greenhouse gas emissions per 100 mL. This phenomenon can be attributed to the reduction in the amount of raw plastic materials required to carry water, resulting in a more efficient environmental impact.



	0.33L	0.5L	1L	2L
AVG	25.11[a]	18.20[b]	17.42[a,b,c]	11.36[c]
SD	3.82	4.36	6.54	1.97
CV	0.15	0.24	0.38	0.17

Figure 8. Scatter plot of EPD product values grouped by volume (0.33 L, 0.5 L, 1 L, and 2 L) with GWP normalized to 100 mL PET bottle. Below the scatter plot, the following statistics are provided for each group: average (AVG), standard deviation (SD), and coefficient of variation (CV). Significant differences between product volume groups are denoted by superscripts "a", "b" and "c" corresponding to AVG values, as revealed by Games–Howell post hoc tests.

The Games–Howell post hoc tests showed that there was a significant difference between the 0.33, 0.5, and 2 L product groups. However, no statistically significant difference was observed between the 1 L product group and the other groups. Following the post hoc test, significant relationships among the groups were revealed by examining their respective average values, as depicted in Figure 8. The post hoc results are presented in Table S3 within the Supplementary Materials.

The scatter plots for the 0.33 L, 0.5 L, and 1 L groups revealed that the highest values were consistently associated with products from a specific company. This suggests that these products contain substantial amounts of PET raw materials, leading to increased input and output within the system and resulting in a higher GWP compared with products from other companies. This company exhibited a similar GWP pattern in the scatter plots when considering GWP per 1 kg. Furthermore, companies manufacturing top-tier 2 L products emit substantial quantities of greenhouse gases during the production of plastic raw materials. This implies that the company's 2 L product may have a greater weight than the other 2 L products.

Although the classification method for the product life cycle and GWP units differed between the EPD and meta-analysis, both approaches share the commonality of quantitatively assessing the environmental impacts from raw material collection to disposal using the same LCA technique. Consequently, by standardizing and comparing the meta-analysis and EPD result data on a "kg CO_2eq per 1 kg of PET bottle" basis, similar GWP averages were obtained. This underscores the efficacy of the method, which employs meta-analysis to harmonize the data and derive comprehensive insights into the environmental impacts of the PET bottle's life cycle. While this study serves as a case study for PET bottles, the methodology is applicable to other products, particularly various packaging materials, enabling a holistic evaluation of the environmental impact throughout their life cycles.

4. Conclusions

We systematically collected a broad array of LCA research literature to comprehensively evaluate the environmental impacts of PET bottle life cycles. Subsequently, we performed a meta-analysis to standardize the GWP data by categorizing the PET bottle life into six distinct phases. This systematic review included 14 research studies conducted in eight countries across various study years from 2010 to 2022.

The research conducted involved unifying the units of GWP data extracted from 14 studies, facilitating their comparability. Through comprehensive statistical analysis, it was established that within the six phases of the PET bottle system, the MP phase emerged as the hot spot for the greenhouse effect. Subsequently, the BP, DT, WM, and CT phases exhibited significant environmental impacts. Moreover, the phases of EB, CT, and WM displayed noteworthy coefficients of variation, signifying substantial fluctuations in GWP data. This variance suggests a significant disparity between environmentally superior and inferior data, implying a high potential for environmental improvement in these phases.

The MP phase yields the highest GWP value owing to the presence of energy-intensive processes, such as solid-state polymerization, which are essential for the production of fossil fuel-based plastic resins. In the BP phase, numerous processes involve the use of high-temperature equipment, particularly during injection and stretch-blow molding, which significantly contribute to global warming. In the distribution and collection transportation phases, the GWP was found to be high and dependent on factors such as the weight (kg) and travel distance (km) of the PET bottles.

Waste management is an active area of research, with various countries incorporating disposal scenarios or assumptions. Generally, a high incineration ratio is associated with higher GWP values, whereas a higher recycling and landfill ratio leads to lower GWP values. The EB phase is characterized by the GWP value determined from renewable raw materials and the heat gain from incineration. This phase has a more pronounced impact on disposal scenarios in which the incineration and recycling ratio exceeds that of landfills.

To assess the similarity between the GWPs derived from meta-analysis and the carbon footprint results of commercially available products, a comparative analysis was conducted using Korea's EPD system, the comparison of AVG estimates, presented in kg CO_2eq per 1 kg of PET bottles, revealed a close match, differing by only approximately 6.5%. This demonstrates that meta-analysis serves as an efficient method for inferring the average carbon footprint of commercial products.

This methodology can be considered a suitable technique for deriving comprehensive conclusions, as it facilitates quantitative comparisons independent of the research year, region, or functional unit. This approach can be extended to various product groups, establishing itself as a valuable tool for identifying and assessing greenhouse effects. Furthermore, the application of this methodology supports evidence-based decision-making in the development of sustainable solutions for product systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16020535/s1, Figure S1: Illustration of how to extract the GWP from stacked bar chart; Figure S2: Box plot analysis that encompasses all outliers of GWP values for six phases of the PET bottle system; Table S1: The literature screening forms with the references that passed the final screening criteria. The screening forms contain the type of reference with titles, author, year, and information of references; Table S2: Organization of capacities and GWP values for Korean EPD products; Table S3: Results of the Games–Howell post hoc test for GWP values of EPD products per 1 kg; Table S4: Results of the Games–Howell post hoc test for GWP values of EPD products per 100 mL.

Author Contributions: Conceptualization, Y.-J.G. and D.-H.K.; methodology, Y.-J.G. and D.-H.K.; validation, Y.-J.G. and D.-H.K.; investigation, Y.-J.G. and D.-H.K.; formal analysis, Y.-J.G. and D.-H.K.; data curation, Y.-J.G. and D.-H.K.; writing—original draft, Y.-J.G.; visualization, Y.-J.G.; review and editing, D.-H.K. and J.-H.L.; supervision, H.-J.P. and J.-K.S. All authors have read and agreed to the published version of the manuscript.

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