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Evaluation of Vinegar Bottles' Environmental Footprint Using the Life Cycle Approach: A Preliminary Analysis

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Abstract: This paper provides a comprehensive life cycle assessment (LCA) comparing glass and PET vinegar bottles in the Greek market to determine the more eco-friendly option. The analysis covers a 500 mL glass bottle and a 390 mL PET bottle, examining eleven subsystems from raw material acquisition to recycling. The initial findings indicate that glass bottles require more resources and have a greater environmental impact than PET bottles across several factors, despite the traditional perception of glass as being environmentally superior. This difference is partly due to the heavier weight of glass bottles than PET bottles. The results highlight the complexity of LCA studies. While LCA methodology has limitations, such as data collection quality, system boundary definitions, assessment challenges, and costs, it provides valuable indicators. This study underscores the need for more extensive data collection and systematic LCA application. By integrating LCA methodology through pilot projects and developing internal expertise, companies can make more accurate assessments, leading to sustainable industrial practices and growth.

Keywords: life cycle assessment; sustainability; PET bottles; glass bottles

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1. Introduction

In recent years, industries and businesses have increasingly recognised the importance of assessing how their activities affect the environment [1]. Consumers have become increasingly concerned about environmental protection and related issues [2–4], including climate change, environmental degradation, ecosystem loss, and biodiversity decline. Numerous businesses have introduced greener products and processes in response to this heightened awareness. The environmental performance of products and processes has become a significant concern, prompting companies to investigate methods for reducing their environmental footprints [5]. Furthermore, companies are being pushed to adopt eco-friendly practices due to regulatory requirements, government incentives, and public pressure. This involves actions such as using renewable resources, redesigning products to minimise waste, and implementing environmentally friendly management systems [6]. Access to knowledge is essential for these initiatives. When assessing the environmental impacts of products and services, it is crucial to consider their entire life cycle. Failing to do so may lead to shifting problems from one stage of the life cycle to another or from one geographical area to another [7].

The environmental impact of packaging materials is a critical consideration in today's sustainability-driven market. Glass and polyethylene terephthalate (PET) bottles are widely used for products like vinegar. Glass recycling rates have been increasing, leading to a noticeable reduction in emissions associated with glass bottles. However, research indicates that shifting to alternative packaging materials can result in a more rapid reduction in emissions than solely focusing on increasing glass recycling initiatives [8].

Over the last few decades, the use of PET bottles has significantly increased in packaging [9], commonly utilised in the beverage and cosmetics industries [10]. For instance, in the wine industry, where glass has traditionally been the primary packaging material [11], alternative packaging options such as PET bottles are increasingly accepted, especially for lower-priced wines [12].

PET, a commonly used thermoplastic polymer resin in the polyester family, combines ethylene glycol and terephthalic acid, forming a polymer chain [13] that can be easily moulded into different shapes through injection stretch blow moulding (ISBM) processes [10,14]. PET bottles are praised for their lightweight. Their average weight is significantly lower than that of glass bottles, reducing transportation's environmental impact and associated carbon emissions [13]. Additionally, studies have confirmed that PET bottles have low permeability to gas, aroma, and water, making them suitable for preserving the quality of the products stored within them [15].

While PET bottles have numerous benefits, they also have limitations. One major limitation is that the PET recycling process is not infinite as, over time, the plastic degrades in structural integrity. The growing use of PET has resulted in substantial plastic waste, leading to environmental and health concerns, as PET does not degrade naturally [9]. Critical issues in plastic recycling, such as achieving closed-loop recycling [16] and potential contamination [17], further complicate the environmental impact of PET.

Glass bottles, on the other hand, are gaining popularity in eco-conscious communities due to their environmentally friendly characteristics [18]. Glass production is generally less carbon- and energy-intensive compared to the production of other materials [19] and can be easily reused [20]. However, research indicates that for glass bottles to have a reduced environmental impact, they must be of a certain size [19] and weight [21].

The production process of vinegar bottles, regardless of the material, involves multiple stages that contribute to their environmental footprint. The extraction and processing of raw materials, manufacturing, and transportation all require significant energy inputs and emit greenhouse gases. For example, the extraction of sand for glass production can lead to habitat destruction and ecosystem disruption [22]. The transportation of raw materials and finished bottles also adds to the environmental burden through increased energy consumption and greenhouse gas emissions.

In order to make environmentally conscious decisions, it is important to consider the environmental impacts of different products, processes, or activities throughout their life cycle [23]. The life cycle assessment (LCA) is a widely used method for evaluating environmental impacts [24] and facilitating decision-making [25,26]. It was internationally standardised from 1997 to 2000 as ISO 14040-43 and updated to ISO 14040/44 in 2006 [27,28]. This standard provides a comprehensive analysis of the environmental impact associated with the entire life cycle of a product or service [29]. This analysis quantitatively and qualitatively identifies and describes its energy and material requirements, as well as the emissions and waste released into the environment [30]. Other codes of practice have been developed to support LCA practitioners in operationalising the LCA, following these standards [31,32]. The importance of the LCA lies in its ability to encompass all processes. Addressing all relevant environmental issues throughout a product's life cycle enables a comprehensive assessment that includes aspects from raw material extraction to final disposal [5,33].

This study evaluates the environmental impact of the vinegar bottles used in the Greek industry. Its aim is to determine which type of bottle, glass, or PET is more eco-friendly by analysing the resources required from raw material extraction to final distribution. This study provides valuable insights into the environmental implications of packaging choices in a region where such analyses have not been previously conducted. Notably, this is the first LCA focused specifically on vinegar bottles within the Greek market.

2. Methodology

The LCA process is a systematic phased approach consisting of four components [5,34]:

1. Goal definition and scoping: this involves outlining the study's objectives, intended use and audience, system boundaries, and defining the functional unit, which quantitatively measures the functions provided by the goods or services;
2. Inventory analysis: This results in a compilation of inputs and outputs throughout the product's life cycle in terms of the functional unit. It includes quantitative data on the direct and indirect materials/energy inputs and waste emissions;
3. Impact assessment: this evaluates the potential human and ecological impacts of energy, water, and material usage, as well as the environmental emissions identified in the previous phase;
4. Interpretation: the outcomes of the preceding phases are evaluated based on the goal and scope, leading to findings and recommendations.

The first three phases are described in the following sub-sections, while the final phase is addressed in the subsequent section (Section 3).

In line with other LCA studies on similar topics, the functional unit (FU) of the study was all packaging components required for the bottling and distribution of 1000 L of vinegar.

During the life cycle impact assessment (LCIA), we chose to use the Eco-Indicator 99 method to evaluate the environmental impact. This method simplifies the interpretation and weighting of the LCA results by focusing on endpoint impacts rather than intermediate impacts [34]. While there are other methods available, this approach specifically evaluates the damage categories at the end of a product's life cycle, including human health, ecosystem quality, and resource depletion. This aligns closely with our study's primary focus, which is to assess the overall environmental impact of using glass versus PET bottles for vinegar packaging.

2.1. Goal and Scope

This LCA aims to compare the environmental impacts of glass and PET bottles used for packaging vinegar in the Greek market. The study evaluates each material's life cycle stages from raw material extraction and manufacturing to distribution, use, and disposal. The following environmental impacts are assessed across three main categories using the Eco-Indicator 99 methodology: human health, ecosystem quality, and resource depletion. These categories help to quantify the emissions, energy consumption, and resource use associated with each bottle type throughout its life cycle. The findings aim to support informed decision-making towards more sustainable packaging solutions.

2.2. Life Cycle Inventory Analysis

Typically, life cycle studies have two main parts: an inventory of all the energy and resources used for a specific product or process, along with their environmental releases to the air, water, and land, and a subsequent analysis for improvement [35]. Figure 1 illustrates the general materials flow in a "cradle-to-grave" analysis of a product system. The life cycle begins with raw material acquisition and continues through materials manufacture, product manufacture, and product use or consumption, ultimately ending with final disposition. Energy is required at every phase, and managing environmental releases is critical throughout the process.

In the present LCA, we examine and compare vinegar bottles made from glass and PET in different sizes on the Greek market. More specifically, the glass bottle has a capacity of 500 mL, and the PET bottle has a capacity of 390 mL. The life cycle system consisted of the following eleven subsystems:

(1) Raw materials acquisition and materials manufacture: this system consists of the activities required to produce or manufacture the materials from which the bottles are made, i.e., the glass and the PET;
(2) Materials transportation: this subsystem includes the transfer of raw materials to the bottle production units;

(3) Containers fabrication: this subsystem includes the activity of producing bottles from glass or PET;
(4) Containers transportation: this subsystem includes the transportation of empty bottles from the production plant to the bottling plant;
(5) Filling—final product production: The bottling subsystem consists of activities that relate to the final product (fill-in vinegar bottles). The most important of these activities is the filling of the bottles with the product. The subsystem and, generally, the analysis does not include the product with which the bottles are filled, i.e., vinegar;
(6) Final product transportation: this subsystem includes the activity of transporting the final product, that is, the complete vinegar bottles, from the bottling units to its consumer locations (the weight of the bottled vinegar is not taken into account);
(7) Final product distribution and use: this subsystem includes the activities of disposing of the final product to consumers and its use;
(8) Solid waste collection and transportation for landfilling: After consumers use the product, empty bottles are left. Those that are not reused or recycled will end up in municipal waste, where they are collected and transported to their disposal sites. These collection and transport activities are included in this subsystem;
(9) Solid waste landfilling: this subsystem includes the activities required for landfill but not the environmental burden of decomposing these wastes due to a lack of sufficient and reliable disposal elements;
(10) Used container collection and refilling: this subsystem includes the collection activities of empty bottles and their subsequent processing to prepare them for new refilling;
(11) Recycling: this subsystem includes the recycling activities of empty bottles.

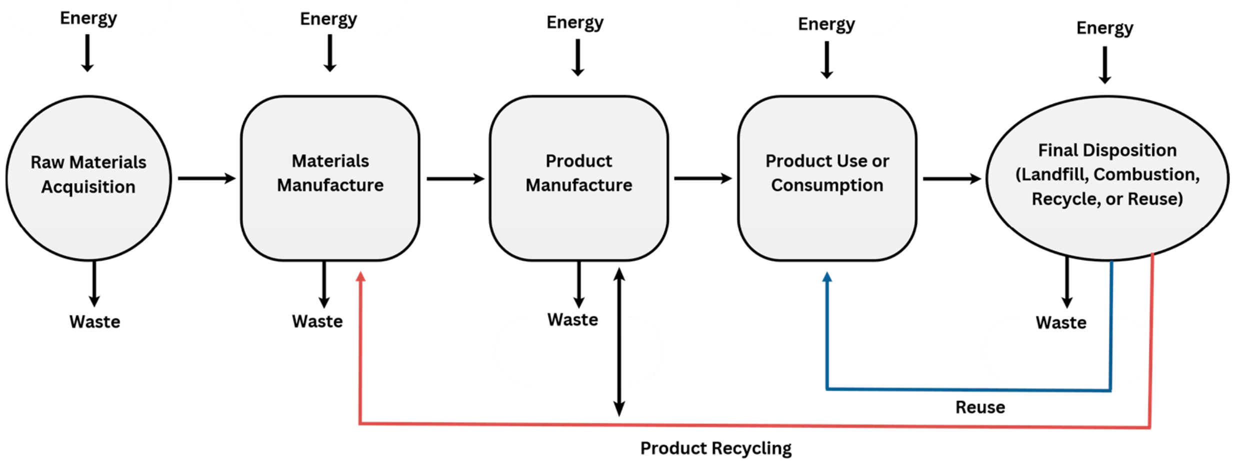

Figure 1. General materials flow "cradle-to-grave" analysis of a product system [35].

All 11 subsystems that constitute the LCI system are included in Figure 2. Other parameters affect and constrain the system [36]:

- Basis of comparison: 1.000 L of vinegar;
- Level of technology: the combination of current technologies in use;
- Capital equipment: the energy and emissions involved with capital equipment;
- Basis of allocation: weight proportioned (per kg);
- Energy system: the national basic energy sources and the national average fuel mix and grid for electricity.

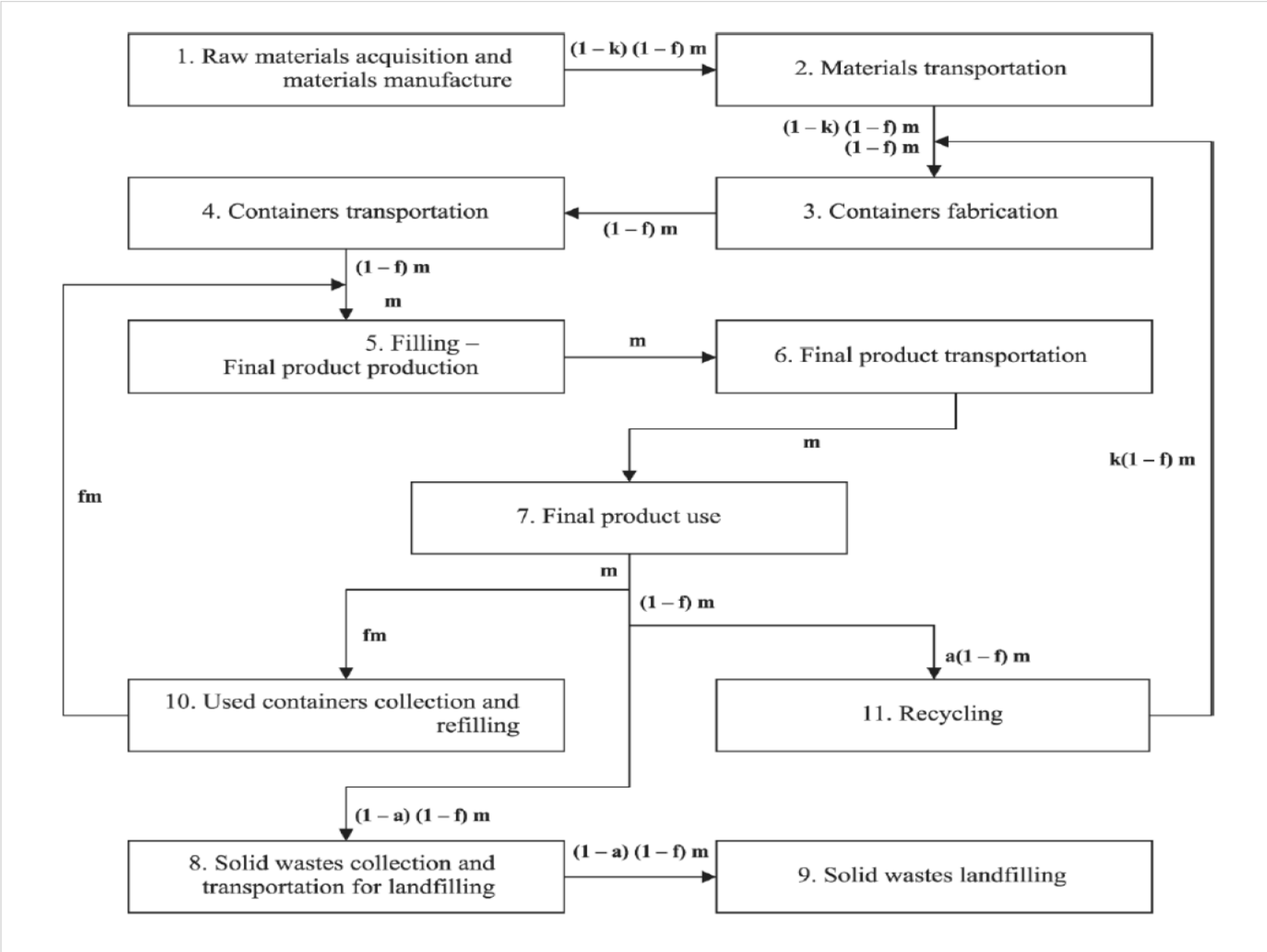

Figure 2. The stages of the system [36].

In a comparative LCI, it is important to ensure that the basis of comparison is equivalent usage [37]. This means defining the system in a way that delivers a functionally equal amount of product to the consumer. Equivalent usage can be based on volume or weight. For example, in this LCI, the basis of comparison is 1000 L of vinegar [36].

The mathematical model was developed in earlier research [36]. We need this model to calculate the total energy and resources used, as well as the environmental releases from the overall system. The model is constructed to sum the energy, raw materials, and various emission values that result from the energy and material flows for each stage of the product's life cycle according to the system.

Equation (1) calculates the total energy consumption of the system (E_{total}) as follows:

$$E_{total} = E_1 + E_2 + E_3 + E_4 + E_5 + E_6 + E_7 + E_8 + E_9 + E_{10} + E_{11} \quad (1)$$

The energy consumed in each of the subsystems (E_j where j = 1, 2, 3 . . . 11) is determined by the specific energy of the subsystem, which expresses the energy consumption per unit mass (MJ/Kg), and the mass of each subsystem (m_j where j = 1, 2, 3 . . . 11), which results from the mass balance of the system as follows:

$$E_{total} = (e_1 + e_2) \times (1 - f) \times (1 - k) \times m + (e_3 + e_4) \times (1 - f) \times m + (e_5 + e_6 + e_7) \times m + e_8 \times (1 - f) \times [1 - a(1 - b)] \times m + e_9 \times (1 - f) \times [1 - a(1 - b)] \times c \times m + e_{10} \times f \times m + e_{11} \times (1 - f) \times a \times m$$

where "m" is the reference mass, which is determined for each type of bottle by the following equation:

$$m = [(\text{weight})/(\text{capacity})] \times 1000$$

The glass bottle weighs 365 g and has a capacity of 500 mL, and the PET bottle weighs 21 g and has a capacity of 390 mL.

Equation (2) calculates the total consumption of any raw material or the total release of any waste in the system (X_{total}) as follows:

$$\begin{aligned} X_{total} &= X_1 + X_2 + X_3 + X_4 + X_5 + X_6 + X_7 + X_8 + X_9 + X_{10} + X_{11} \\ X_{total} &= (x_1 + x_2) \times (1 - f) \times (1 - k) \times m + (x_3 + x_4) \times (1 - f) \times m + (x_5 + x_6 + x_7) \\ &\times m + x_8 \times (1 - f) \times [1 - a(1 - b)] \times m + x_9 \times (1 - f) \times [1 - a(1 - b)] \times c \times m + \\ &x_{10} \times f \times m + x_{11} \times (1 - f) \times a \times m \end{aligned} \quad (2)$$

In the above equation, X denotes the amount of any material consumed in the system and the waste produced.

The variables used in Equations (1) and (2) are discussed below as follows:

- a: the recycling rate of each bottle;
- b: the fraction of the bottles collected for recycling that are rejected;
- c: the percentage of municipal solid wastes that are landfilled;
- f: the refilling rate of each bottle;
- k: the recycled content level of the bottles;
- m: the total mass of each type of bottle that serves 1000 L of vinegar.

The values of parameters a and k are 25.3% and 41.18%, respectively, for the glass bottle and 0.86% and 0.93% for the PET bottle, while the values of b, f, and c are 0% for the two bottles that we are examining [38].

The model used during this phase [36] is related to the production, transportation, usage, and disposal of a product. It was illustrated as a flow chart or process tree, outlining all the relevant processes and collected information on the inputs and outputs of each process. The inventory aims to track the environmental impacts, such as emissions and other inputs and outputs to the environment, throughout the product's life cycle [39]. The LCI serves as a valuable tool for identifying areas where significant opportunities for environmental enhancements exist through resource conservation and emissions reductions. By using the LCI, we can make changes within a product's life cycle that may lead to positive or negative implications in other cycle stages. Embracing this "life cycle thinking" during the product design phase helps us to identify true opportunities for improvement [35].

Table 1 presents the life cycle inventory results and illustrates the final LCI cumulative results.

Table 1. Inventory analysis of vinegar glass and PET bottles of the Greek market.

Inputs and Outputs	**Type of Container**	
	Glass Bottle 500 mL	**PET Bottle 390 mL**
	Glass Bottle Weight 365 g	**PET Bottle Weight 21 g**
Energy Consumption (MJ/1000 L)		
Total Fuel plus Feedstock	15,775.53	5250.66
Raw Material Consumption (g/1000 L)		
Silica Sand	75.497	-
Limestone	29.491	-
Soda Ash	23.593	-

Table 1. *Cont.*

Inputs and Outputs	Type of Container	
	Glass Bottle 500 mL	PET Bottle 390 mL
	Glass Bottle Weight 365 g	PET Bottle Weight 21 g
Hydrogen	-	0.609
Oxygen	-	13.642
Sodium Hydroxide	-	0.012
Auxiliary Materials	23.593	0.518
Water	277.213	38.569
Atmospheric Emissions (g/1000 L)		
Particles	1081.44	103.31
Carbon Monoxide	102.84	368.98
Hydrocarbons	227.28	511.04
Nitrogen Oxides	1211.07	738.76
Nitrous Oxide	6.70	32.27
Sulphur Dioxide	2105.56	1283.77
Aldehydes	10.63	3.36
Organic Compounds	1.46	3.38
Ammonia	0.36	0.03
Hydrogen Chloride	4.25	1.75
Fluoride & Hydrogen Fluoride	1.65	0.00003
Lead	1.06	-
Volatile Organic Compounds	40.12	11.03
Waterborne Waste (g/1000 L)		
Suspended Materials	0.12	0.01
Dissolved Materials	213.34	819.63
BOD	0.12	0.01
COD	0.36	0.03
Oil	2.87	10.13
Phenol	-	0.01
Fluoride	0.009	0.057
Ammonia	0.004	0.023
Sulphate	0.002	0.009
Nitrate	0.004	0.009
Chloride	0.00017	0.00057
Na-ions	0.00215	0.00575
Fe-ions	0.00002	0.00009
Solid Waste (cm^3/1000 L)		
Municipal Waste, etc.	78,761.25	15,516.15

2.3. Life Cycle Impact Assessment

The impact assessment involves categorising and classifying the results from the inventory into different environmental impacts. In this LCA, we use the Eco-Indicator

99 methodology, which has the following three primary "environment damage" categories: ecosystem quality, human health, and resource.

During the classification step, the substances listed in Table 1 are allocated to the impact categories they affect. It is important to note that some substances might affect multiple categories while others only affect one. The characterisation process assesses the environmental impact caused by a particular input or output listed in the inventory. The severity of the impact can vary, even for equal amounts of the two substances.

To assess the impact of disease or injury, the DALY (Disability-Adjusted Life Year) metric is utilised. This metric encompasses the years of life lost due to premature mortality and the years lived with disability, adjusted for prevalent cases of the disease or health condition in a population. According to the World Health Organization, one DALY represents the loss of the equivalent of one year of full health.

To quantify the potential impact of various environmental stressors on ecosystems, the PDF metric has been employed. This metric serves as a measure of the proportion of species that are potentially affected or at risk of disappearance due to environmental damage.

3. Results and Discussion

Tables 2 and 3 present the results of the impact assessment on human health for both materials: glass and PET. In particular, Table 2 displays the impact of different substances released during the production and disposal of glass, focusing on their respiratory effects on humans. Table 3 shows similar data for PET.

The impact assessment indicates that glass bottles significantly impact human health more than PET bottles. The primary contributor to this impact for both glass and PET bottles is particles, with glass bottles containing a much higher amount of particles, resulting in a larger overall impact. Sulphur dioxide is another significant factor for both types of bottles, with glass bottles once again showing a higher impact. Although PET bottles have a slightly higher impact from hydrocarbons and nitrous oxide than glass bottles, these impacts are relatively minor compared to the effects of particles and sulphur dioxide.

Table 2. Impact assessment on human health (glass).

Name	Total Amount	Normalised Damage Factor	Impact Assessment
Particles (respiratory effects on humans caused by inorganic substances)	1.08 kg	4.55×10^{-2} DALY/kg	4.92×10^{-2} DALY
Hydrocarbons (respiratory effects on humans caused by organic substances)	2.27×10^{-1} kg	2.27×10^{-5} DALY/kg	5.16×10^{-6} DALY
Nitrogen oxides (respiratory effects on humans caused by inorganic substances)	1.21 kg	5.76×10^{-3} DALY/kg	6.98×10^{-3} DALY
Nitrous oxide (respiratory effects on humans caused by inorganic substances)	6.70×10^{-3} kg	8.90×10^{-3} DALY/kg	5.96×10^{-5} DALY
Sulphur dioxide (respiratory effects on humans caused by inorganic substances)	2.11 kg	3.55×10^{-3} DALY/kg	7.47×10^{-3} DALY
Aldehydes (respiratory effects on humans caused by organic substances)	1.06×10^{-2} kg	9.09×10^{-5} DALY/kg	9.66×10^{-7} DALY
Ammonia (respiratory effects on humans caused by inorganic substances)	3.60×10^{-4} kg	5.52×10^{-3} DALY/kg	1.99×10^{-6} DALY
Volatile organic compounds (respiratory effects on humans caused by organic substances)	4.01×10^{-2} kg	4.19×10^{-5} DALY/kg	1.68×10^{-6} DALY
Total Impact on Human Health			6.37×10^{-2} DALY

Table 3. Impact assessment on human health (PET).

Name	Total Amount	Normalised Damage Factor	Impact Assessment
Particles (respiratory effects on humans caused by inorganic substances)	1.03×10^{-1} kg	4.55×10^{-2} DALY/kg	4.69×10^{-3} DALY
Hydrocarbons (respiratory effects on humans caused by organic substances)	5.11×10^{-1} kg	2.27×10^{-5} DALY/kg	1.16×10^{-5} DALY
Nitrogen oxides (respiratory effects on humans caused by inorganic substances)	7.39×10^{-1} kg	5.76×10^{-3} DALY/kg	4.26×10^{-3} DALY
Nitrous oxide (respiratory effects on humans caused by inorganic substances)	3.23×10^{-2} kg	8.90×10^{-3} DALY/kg	2.87×10^{-4} DALY
Sulphur dioxide (respiratory effects on humans caused by inorganic substances)	1.28 kg	3.55×10^{-3} DALY/kg	4.56×10^{-3} DALY
Aldehydes (respiratory effects on humans caused by organic substances)	3.36×10^{-3} kg	9.09×10^{-5} DALY/kg	3.05×10^{-7} DALY
Ammonia (respiratory effects on humans caused by inorganic substances)	3.00×10^{-5} kg	5.52×10^{-3} DALY/kg	1.66×10^{-7} DALY
Volatile organic compounds (respiratory effects on humans caused by organic substances)	1.10×10^{-2} kg	4.19×10^{-5} DALY/kg	4.62×10^{-7} DALY
Total Impact on Human Health			1.38×10^{-2} DALY

The following tables present the results of the impact assessment on ecosystem quality and the resources in relation to glass and PET bottles. Table 4 summarises the impact of various substances and energy consumption related to glass production and disposal, focusing on their effects on ecosystem quality and resource depletion. Table 5 offers analogous data for PET.

Table 4. Impact assessment in ecosystem quality and resources (glass).

Name	Total Amount	Normalised Damage Factor	Impact Assessment
Nitrogen oxides (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	1.21 kg	1.11×10^{-3} PDF·m^2·yr/kg	1.34×10^{-3} PDF·m^2·yr
Nitrous oxide (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	6.70×10^{-3} kg	1.71×10^{-3} PDF·m^2·yr/kg	1.15×10^{-5} PDF·m^2·yr
Sulphur dioxide (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	2.11 kg	2.03×10^{-4} PDF·m^2·yr/kg	4.27×10^{-4} PDF·m^2·yr
Lead (damage to ecosystem quality caused by ecotoxic emissions)	1.06×10^{-3} kg	4.95×10^{-1} PDF·m^2·yr/kg	5.25×10^{-4} PDF·m^2·yr
Total Impact on Ecosystem Quality			2.31×10^{-3} PDF·m^2·yr
Energy from coal (damage to resources caused by extraction of fossil fuels)	1.58×10^{4} MJ	1.02×10^{-6}	1.61×10^{-2} MJ
Total Impact on Resources			1.61×10^{-2} MJ

Table 5. Impact assessment in ecosystem quality and resources (PET).

Name	Total Amount	Normalised Damage Factor	Impact Assessment
Nitrogen oxides (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	7.39×10^{-1} kg	1.11×10^{-3} PDF·m^2·yr/kg	8.20×10^{-4} PDF·m^2·yr
Nitrous oxide (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	3.23×10^{-2} kg	1.71×10^{-3} PDF·m^2·yr/kg	5.52×10^{-5} PDF·m^2·yr
Sulphur dioxide (damage to ecosystem quality caused by the combined effect of acidification and eutrophication)	1.28 kg	2.03×10^{-4} PDF·m^2·yr/kg	2.61×10^{-4} PDF·m^2·yr
Lead (damage to ecosystem quality caused by ecotoxic emissions)	0	4.95×10^{-1} PDF·m^2·yr/kg	0
Total Impact on Ecosystem Quality			1.14×10^{-3} PDF·m^2·yr
Energy from coal (damage to resources caused by extractions of fossil fuels)	5.25×10^{3} MJ	1.02×10^{-6}	5.36×10^{-3} MJ
Total Impact on Resources			5.36×10^{-3} MJ

In Table 4, the environmental impact assessment for glass reveals a significant negative impact on both ecosystem quality and resource use. Glass shows a total ecosystem quality impact of 2.31×10^{-3} PDF·m^2·yr, primarily driven by substantial contributions from nitrogen oxides and lead. It is noteworthy that PET emits zero lead, presenting a considerable advantage over glass.

Moreover, the resource impact is notably high for glass bottles, with energy consumption from coal amounting to 1.58×10^{4} MJ, leading to a total resource impact of 1.61×10^{-2} MJ. PET, on the other hand, has an energy consumption from coal of 5.25×10^{3} MJ, resulting in a total resource impact of 5.36×10^{-3} MJ.

These figures indicate that PET is a more environmentally friendly option compared to glass. Glass production exerts a significant environmental burden, particularly due to the substantial energy required from coal and the harmful emissions affecting ecosystem quality.

The weighting process converts each impact category's results into a comparable unit using value-based numerical factors, referred to as "weighting factors". The Eco Indicator ′99 methodology provides specific priority values [40], as shown in Table 6.

Table 6. Magnitude factors of category indicators.

Impact Category	Weighting Factor	Unit
Human health	400	ECO 99 unit/DALY
Ecosystem quality	400	ECO 99 unit/PDF·m^2·yr
Resources	200	ECO 99 unit/MJ

To calculate the environmental impact of glass bottles, the weighting factors from Table 6 were multiplied by the results obtained from Tables 2 and 4. Table 7 summarises the impact categories, their respective calculations, and the results in ECO 99 units.

Similarly, Table 8 was derived for PET bottles by multiplying the weighting factors from Table 6 with the results from Tables 3 and 5.

Table 7. Final results of category indicators (glass).

Impact Category	Total Impact Calculated × Weighting Factor	Total Weighted Impact
Human's health deterioration	6.37×10^{-2} DALY × 400 (ECO 99 unit/DALY)	25.5 ECO 99 units
Downgrading of the ecosystem quality	2.31×10^{-3} PDF·m^2·yr × 400 (ECO 99 unit/PDF·m^2·yr)	9.23×10^{-1} ECO 99 units
Natural resources depletion	1.61×10^{-2} MJ × 200 (ECO 99 unit/MJ)	3.22 ECO 99 units

Table 8. Final results of category indicators (PET).

Impact Category	Total Impact Calculated × Weighting Factor	Total Weighted Impact
Human's health deterioration	1.38×10^{-2} DALY × 400 (ECO 99 unit/DALY)	5.52 ECO 99 units
Downgrading of the ecosystem quality	1.14×10^{3} PDF·m^2·yr × 400 (ECO 99 unit/PDF·m^2·yr)	4.54×10^{-1} ECO 99 units
Natural resources depletion	5.36×10^{3} MJ × 200 (ECO 99 unit/MJ)	1.07 ECO 99 units

The analysis shows clear differences in the environmental impacts of glass and PET bottles, with glass bottles having a higher overall weighted impact across all categories compared to PET bottles. The production of glass bottles consumes more resources and has a greater overall impact than PET bottles. Specifically, for each category of the Eco Indicator ′99 methodology, the study has recorded the following:

Human Health Impact: The primary contributor to glass bottles' higher human health impact is the emission of particles during the production and disposal phases. In particular, glass bottles release 1.08 kg of particles compared to 0.103 kg from PET bottles, leading to a much higher impact assessment (4.92×10^{-2} DALY for glass vs. 4.69×10^{-3} DALY for PET). Moreover, higher emissions of sulphur dioxide from glass production further deteriorate respiratory health problems.

Ecosystem Quality Impact: The impact on ecosystem quality is measured by the potential for acidification, eutrophication, and ecotoxic emissions. Glass bottles have a higher impact due to greater emissions of nitrogen oxides and lead. Nitrogen oxides contribute significantly to acidification and eutrophication, affecting biodiversity and ecosystem function. The lower effect of PET bottles is partly due to the absence of lead emissions. Nitrogen oxides and sulphur dioxide are still present but are in lesser quantities compared to glass.

Resources Depletion Impact: Resource depletion is primarily due to energy consumption. Glass bottle production demands a significant amount of energy, particularly from coal, resulting in a higher resource depletion impact. The melting and forming processes are extremely energy-intensive, requiring large amounts of fossil fuel energy. In contrast, PET production demonstrates a lower energy intensity and reduced dependence on fossil fuel resources, resulting in a comparatively lower impact on resource depletion.

The major distinction between the two scenarios—glass and PET—lies in the energy consumption and pollutant emission profiles of their respective life cycles. Glass bottle production is more energy-intensive and emits higher levels of harmful substances during various stages, including raw materials acquisition and manufacturing, container fabrication, transportation, solid waste collection and landfilling, and recycling processes. PET bottles, while not free from environmental impact, pose a relatively lower burden due to more efficient energy use and lower emissions of critical pollutants.

Our findings align with several studies that applied the LCA methodology to compare the environmental performances of PET and glass bottles for various beverages and soft drinks [16,41–43], water [41,44,45], and milk [46]. These studies show that PET bottles have a lower environmental impact compared to glass, primarily due to the high-energy demand in glass bottle production, its weight, and the transport phase.

Overall, the literature suggests that the most effective environmental packaging solutions depend on the following three main factors [45]: the weight of the two types of bottles, the number of times a glass bottle can be reused, and the recycling rate of glass and PET.

It is important to note that our analysis is based on comparing a single bottle of each material, and the weight of each material significantly influences the results. In this case, the glass bottle is substantially heavier than the PET bottle. Reducing the weight of the glass bottle could help reduce the environmental impact [47]. Manfredi and Vignali [48] conducted a sensitivity analysis on glass bottles used for tomato puree. They identified that by reducing the weight of the glass bottles, the overall environmental impact could also be significantly decreased.

When assessing the life cycle of PET bottles, it is crucial to understand the significance of recycling in reducing the environmental impact. The environmental impact of PET bottles, especially in terms of recycling and reuse, has become a significant focus due to concerns about plastic waste and the sustainability goals set by regulatory bodies like the EU [49]. Research has shown that the environmental benefits of PET bottles are enhanced when recycled PET (R-PET). Increasing the recycling rates of PET bottles is highly effective in reducing their associated environmental impacts [43,44,50].

On the other hand, glass bottles are known for their durability and high rates of recyclability. However, reusable glass bottles need to be reused multiple times to achieve comparable environmental impacts to PET bottles [42].

The findings of this study are intricate and do not safely point to a single conclusion regarding which container has the lowest environmental impact. In addition to the previously mentioned limitations—only using one bottle of each material and the weight of the bottles—this study does not explore the social and economic dimensions of packaging, which are crucial for a comprehensive understanding of the environmental impacts. Furthermore, the LCA methodology itself has inherent limitations, as it often yields numerous environmental impacts expressed in different units, making it challenging to draw definitive conclusions. However, the LCA remains valuable for companies and policymakers in environmental management, as it provides indicators such as greenhouse gas emissions, climate change, and resource depletion, which help evaluate the sustainability of industrial systems [38].

Georgakellos [38] suggested that companies could increase the implementation of the LCA through a process that starts with pilot projects, followed by the creation of internal knowledge, which leads to a more systematic and prospective implementation. If companies worldwide collect data and apply the LCA methodology, the results could be closer to reality and help transform industries to operate in a more environmentally friendly way, resulting in sustainable growth.

4. Conclusions

In this study, a comparative LCA was performed to analyse the environmental impact of two commonly used packaging materials for vinegar in the Greek market: the 390 mL PET bottle and the 500 mL glass bottle. The aim was to determine the most environmentally friendly option or, in other words, to examine which alternative presents the least impact. The findings reveal that, when used for vinegar packaging, PET has a lower environmental impact compared to glass due to the more efficient energy use and lower emissions of critical pollutants.

Strategies such as reducing the weight of glass bottles, increasing recycling rates for both PET and glass bottles, and enhancing production efficiency are essential to effectively reduce the environmental impacts identified. Additionally, assessing the social and economic dimensions of packaging and improving the accuracy of the LCA by addressing its limitations will offer a more comprehensive understanding of the environmental impacts.

An integrated LCA version should be set up to identify all crucial parameters, either case-specific (product specifications) or process-specific (production and use specifications), that affect the environmental impact. A model that would allow for case testing, with adjustments on these parameters, should then be employed to estimate the optimum mix of characteristics that answer both the need to use the product and present the lesser environmental impact at the same time.

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