

## Case Report

# Environmental Repercussions of Craft Beer Production in Northeast Brazil

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**Abstract:** Beer is the most widely consumed alcoholic beverage in the world, and the craft beer market has been continuously growing in recent years. The objective of this study is to detail the production of craft beer and quantify its environmental impacts. The microbrewery is located in João Pessoa, northeast Brazil, and produces 180,000 L/year. The life cycle assessment methodology is employed, and 16 environmental indicators have been selected. Two environmental impact assessment methods are used: IPCC 2021 GWP 100y and ILCD 2011 Midpoint. The results indicate that the best packaging options (lowest environmental impacts) are 10 L stainless-steel kegs and 330 mL aluminum cans. The primary hotspot is the distribution to the points of sale, which employs diesel vehicles. When electric vehicles substitute diesel ones, the environmental impacts are three times lower. The adoption of electric mobility and increasing the consumption of local products are two strategies that can be explored to further mitigate the environmental impacts associated with craft beer.

**Keywords:** life cycle assessment; carbon emissions; sustainability; electric mobility; SDG 12



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## 1. Introduction

Beer is the third most popular beverage in the world, behind only water and tea [1]. Beer production reached 1.89 billion hectoliters in 2022, with the five leading countries being China, the USA, Brazil, Mexico, and Germany, producing approximately 49% of the global amount [2].

Although the market is dominated by large brewing companies, the craft brewery segment is progressively increasing. In the case of craft breweries, the Brazilian market is growing; in 2022, the number of breweries grew by 11.6% compared to 2021 (180 new establishments were registered in 2022), and by the end of 2022, 1729 breweries were registered in Brazil [3].

Large companies (macrobreweries) have efficiencies of scale, such as being able to treat solid and/or liquid waste in-house. However, the scenario is very different for small producers (e.g., microbreweries), who need to find solutions to address the generation of residues and environmental issues. As microbreweries are operating on a smaller scale, they cannot change their suppliers' processes and therefore must focus on their internal processes to find economically viable sustainable solutions. As mentioned by [4], the increasing number of microbreweries contributes to job creation and economic development within local communities, and this support for the local economy further enhances the appeal of craft beer, including economic reasons, employment, community, self-employment, connecting people, and utilization of local sources.

As Brazil is a country of continental dimensions, craft beer production in the northeast differs greatly from production in the south/southeast, where the main brewers, importers, and distributors of raw materials are concentrated. Depending on the beer style, the brewing process can combine various ingredients, but there are four main ones: water, malt, hops, and yeast. Brazilian standards [5] define beer as the beverage obtained by the

alcoholic fermentation of beer wort, made from barley malt and potable water, by the action of yeast, with the addition of hops.

Beer production is energy-intensive, both thermally and electrically, as its several manufacturing processes require high energy levels and long operational times [6,7]. Transportation throughout the supply chain also contributes to significant environmental impacts (as verified by [8], for wine). The life cycle assessment (LCA) methodology is a powerful tool, as it can quantify environmental impacts and encompass the extraction of raw materials, transportation, manufacture, operation and maintenance, and final disposal.

In Brazil, the association between LCA and breweries remains underexplored; however, several LCA studies have been conducted in breweries around the world: Australia [9], Greece [10], Italy [11], Spain [12], Japan [13], and Wales [14], to name a few. However, the comparison of results is hindered due to the different demographic regions, objectives of the studies, boundaries adopted for the systems adopted, and different methodological choices.

This study aims to expand the knowledge base regarding Brazilian craft beer production and LCA. This is the first study to present detailed data, starting with how a microbrewery based in the Brazilian northeast obtains its ingredients and inputs, with information on the management of local processes, packaging, and distribution. Data are also presented on the co-products and waste generated. Finally, an inventory is built for the microbrewery and an LCA is developed, presenting 16 environmental indicators for the production of craft beer.

## 2. Materials and Methods

The object of study is a craft brewery in João Pessoa (state of Paraíba, northeast Brazil), which produces approximately 180,000 L of beer/year. This microbrewery produces mainly lager-type craft beer, which accounts for 70% of its annual production. The Imperial Pale Ale (IPA) style follows, with 11% of production. Other styles, including seasonal recipes, are produced on a smaller scale, accounting for 19% of the annual output. The geographical location of this brewery brings many challenges, as Brazil presents continental dimensions, and the distances between the suppliers and the brewery are significant.

LCA was used to quantify the environmental impacts and has four iterative steps [15,16]: (i) definition of the objective, where target audience and reasons for carrying out the study are defined (being a decisive stage for all other LCA stages), and definition of the scope, where the boundary of the system is defined along with the methods and impact categories; (ii) construction of the inventory, which is the quantified collection of data on all inputs (materials, energy, and resources) and outputs (products, by-products, and emissions) relevant to functional unit; (iii) impact assessment, when identification and evaluation are carried out in terms of potential impacts on the environment (analysis of inventory); and finally, (iv) interpretation of the results, when the final study report is produced, according to the target audience previously defined. The direct applications of this report can include changes in the company's strategic planning, development and improvement of products and their manufacturing processes, and even formulation of public policies.

The functional unit adopted, to which all inputs and outputs were related, was the production of 1 L of beer, packaged in one of the forms adopted by the company: 330 mL aluminum can, 500 mL glass bottle, 1 L PET growler, and 30 L stainless-steel keg. An expanded boundary is considered to account for the use of malt grain residue as animal feed by local farmers.

An attributional LCA was developed within Simapro v.9.4.0.3 [17], with the Ecoinvent v3.8 database [18] and data collected during visits and interviews with the partners and employees of the brewery. Regarding electricity consumption, the Ecoinvent database was adjusted to reflect the regional electricity mix consumed at the microbrewery. The environmental impact assessment methods selected were the IPCC 2021 GWP 100y [19], which expresses impacts in terms of greenhouse gas emissions, and the ILCD 2011 Midpoint [20], which quantifies 16 impact categories. These environmental indicators were selected to

facilitate comparison with existing studies. The impact categories associated with both methods are described in Table 1.

**Table 1.** Categories of life cycle impacts, methods, and units.

| Unit                    | Method             | Impact Category                                       |
|-------------------------|--------------------|-------------------------------------------------------|
| kg CO <sub>2</sub> eq   | IPCC 2013 GWP 100y | Climate Change                                        |
| kg CFC-11               | ILCD 2011 Midpoint | Ozone Layer Depletion                                 |
| CTUh                    | ILCD 2011 Midpoint | Human Toxicity—Cancer                                 |
| CTUh                    | ILCD 2011 Midpoint | Human Toxicity—Non-Cancerous Effects                  |
| kg PM <sub>2.5</sub> eq | ILCD 2011 Midpoint | Particulate Matter                                    |
| kg U235 eq              | ILCD 2011 Midpoint | Ionizing Radiation                                    |
| CTUe.                   | ILCD 2011 Midpoint | Ionizing Radiation E (provisional)                    |
| kg NMVOC                | ILCD 2011 Midpoint | Photochemical Ozone Formation                         |
| mol H <sup>+</sup> eq   | ILCD 2011 Midpoint | Acidification                                         |
| mol N eq.               | ILCD 2011 Midpoint | Terrestrial Eutrophication                            |
| kg P eq                 | ILCD 2011 Midpoint | Freshwater Eutrophication                             |
| kg N eq                 | ILCD 2011 Midpoint | Marine Eutrophication                                 |
| CTU eq                  | ILCD 2011 Midpoint | Freshwater Ecotoxicity                                |
| kg C deficit            | ILCD 2011 Midpoint | Land Use                                              |
| m <sup>3</sup> water eq | ILCD 2011 Midpoint | Depletion of Water Resources                          |
| kg Sb eq                | ILCD 2011 Midpoint | Depletion of Mineral, Fossil, and Renewable Resources |

The craft beer value chain can be divided into several stages, starting with the cultivation of barley and hops, which are then transported to their processing facilities. After the malting of barley and the drying and pelletizing of hops, these materials are transported to the brewery. At the brewery, several processes take place for beer production and packaging. Once the beer is ready and packaged, it is transported to the points of sale. Waste flows generated are treated. Figure 1 illustrates the beer production process at the microbrewery.

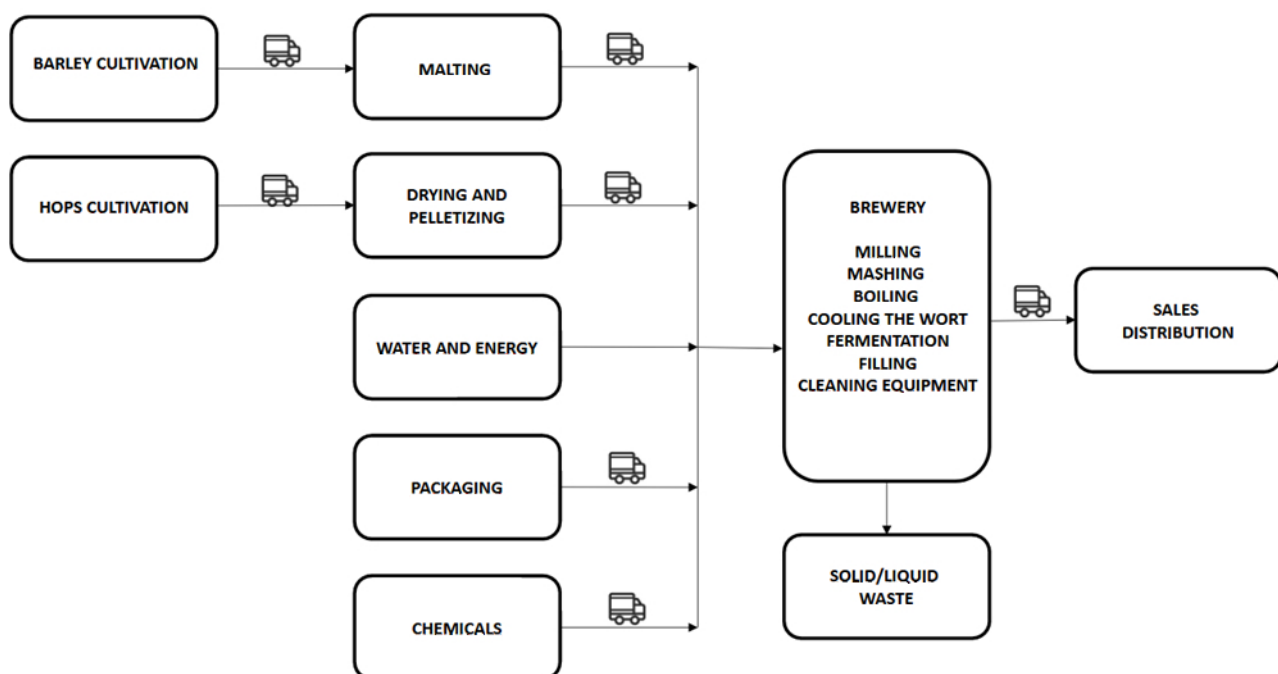


**Figure 1.** Stages in the life cycle of pure malt craft beer.

The following processes were considered for the LCA: (i) barley cultivation, transportation of the barley to the malting plant, malting of the barley, and transportation to the brewery; (ii) cultivation of hops, transportation to the processing facility, drying and pelletization, and transportation to the brewery; (iii) packaging and chemicals, plus

their transportation to the brewery; (iv) consumption of water and energy at the brewery; (v) solid and liquid waste; and (vi) transportation to points of sale.

For barley cultivation, there are two contributions: barley grown in Brazil (domestic malt 52,830 kg/year) and barley grown in Europe (imported malt 7550 kg/year). For domestic malt, the cultivation of barley and subsequent processing using water, heat, and electricity were taken into account. Transportation from the growing sites to the malting plant and from the malting plant to the brewery were also taken into account. For international malt, the same processes were used considering the European scenario, and transportation by ship from Europe to Brazil was included.

For malting, the craft brewery consumes 42,000 kg of domestic malt and 6000 kg of imported malt per year.

Imported hops are used by the brewery at a rate of 240 kg/year. For drying and pelletizing, the thermal and electrical energy used in these processes and transport from the processing plant to the brewery studied were considered.

The microbrewery's production is packaged in four ways: 30 L stainless-steel kegs, 330 mL aluminum cans, 500 mL glass bottles, and 1-L PET (polyethylene terephthalate) growlers. The entire bottling operation is carried out at the brewery, with no need to outsource this process. The packaging considerations are described in Table 2.

**Table 2.** Information on the packaging used by the microbrewery.

| Landfill | Recycling | Reuse    | Distance Traveled | Unit Weight | Annual Quantity | Packaging            |
|----------|-----------|----------|-------------------|-------------|-----------------|----------------------|
| 0%       | 100%      | 120 uses | 25 km             | 12 kg       | 10              | Stainless-steel kegs |
| 0%       | 100%      | 0        | 2.800 km          | 0.015 kg    | 14.784          | Aluminum cans        |
| 75%      | 25%       | 0        | 2.800 km          | 0.36 kg     | 4.224           | Glass bottles        |
| 80%      | 20%       | 10 uses  | 25 km             | 0.031 kg    | 3.000           | PET growlers         |

For the stainless-steel keg, the purchase of 10 barrels per year was considered to replace defective barrels, which are sent for recycling. The microbrewery already has a stock for its operations, and it was considered that these kegs are reused 120 times [14]. As the distributor of the kegs and growlers is in the same city as the brewery, a distance of 25 km was considered for each purchase. For PET growlers, the final disposal scenario followed data from the Brazilian Plastics Industry Association [21] and considered that 20% of growlers are recycled after 10 uses, and 80% are sent to landfills. For aluminum cans, the distance traveled from the supplier to the brewery was considered to be 2800 km. According to the Brazilian Association of Aluminum Can Manufacturers [22], 100% of aluminum beverage cans are recycled. For glass bottles, the distance traveled from the supplier to the brewery was also considered to be 2800 km. The disposal scenario of bottles followed data from the Brazilian Glass Industry Association [23]: 25% recycled, and the remainder is landfilled.

For the chemical products peracetic acid, nitric acid, chlorine, and ammonium quaternary, four purchases are made each year from the same distributor, with each purchase totaling 500 kg and traveling 2800 km between the distributor and the microbrewery.

Regarding water consumption, consultation of the monthly invoices indicated the annual consumption of 1524 m<sup>3</sup> of water. Consultation of electricity invoices indicated a yearly consumption of 27,601 kWh from the electric grid plus 184,714 kWh/year from a solar photovoltaic system installed on site. The northeast electricity mix was considered, constituted of 27% hydro, 17% wind, 9% mineral coal, 16% natural gas, 12% oil, 6% sugarcane bagasse, and 13% imports from other regional subsystems.

In terms of co-products and waste, the microbrewery produces 1000 m<sup>3</sup> of wastewater, which is treated by the local water concessionaire. There is also 42,000 kg of malt grain residue, which is separated after the filtration stage and donated to local animal breeders. One kilogram of malt grain residue replaces 0.47 kg of barley and 0.51 kg of soy as animal feed [24].

Two types of vehicles were considered for distribution: a gasoline-powered light commercial vehicle and a diesel-powered small truck, associated with road distances of 10,000 km and 6240 km, respectively. The light commercial vehicle mainly serves the local market, within the city of João Pessoa, while the small truck distributes beer to other cities in the region.

### 3. Results and Discussion

The first results presented herein are the impacts associated with producing 1 L of beer, with no distinction of the packaging (Table 3). This format was chosen to facilitate comparison with the few existing studies carried out in other geographical regions, covering breweries of different sizes and using different software and databases. Unfortunately, no Brazilian studies were found for comparison purposes.

In the Climate Change category, the Brazilian microbrewery emits 2.46 kg CO<sub>2</sub>-eq/L, and Morgan et al. (2021) reported values between 0.760 and 1.90 kg CO<sub>2</sub>-eq/L for seven breweries in Wales, UK. Amienyo et al. (2016) verified that, depending on the type of packaging (glass bottles, aluminum and steel cans), 1 L of beer emits between 0.510 and 0.842 kg CO<sub>2</sub>-eq/L in the UK.

When comparing the results of [14,25], and those presented herein, it is observed that the size of the breweries has a significant influence on the environmental impacts, as large breweries can be more efficient both in brewing and in distribution. Cimini [26] had already identified that the emissions associated with beer vary with brewery size and primary packaging materials, and when brewery size reduced from  $300 \times 10^6$  L/y to  $60 \times 10^3$  L/y, the emissions increased from 1.27 to 1.92 kg CO<sub>2</sub>-eq/L when using 660 mL bottles.

Analysis of Table 3 reveals that the local beer distribution stage (numbers in bold) presents the highest environmental impacts. These values are close to those reported by [14] in a comparative study of seven microbreweries in Wales, especially for Brewery F, with a production capacity close to that of the Brazilian microbrewery (191,000 L). Figure 2 presents a breakdown of the greenhouse gas emissions associated with the brewery, which shows that the local beer distribution is responsible for around 83% of the environmental impacts. The contributions of the different processes differ for various reasons, ranging from production capacity to the geographical location of the brewery. One of the first LCA studies on breweries, carried out by [27], reported that agricultural production contributed to almost 80% of the environmental impacts, with transportation accounting for only 8% of environmental impacts in a large brewery in Europe. Koroneos [10] included the manufacture of bottles and found that 94% of overall emissions related to beer production were actually related to the manufacturing of glass bottles.

**Table 3.** Environmental impacts associated with producing 1 L of beer packaged in different formats.

| Landfill               | Recycling              | Wastewater             | Solid Waste<br>(Animal Feed) | Energy                | Packaging             | Intercity<br>Distribution | Local<br>Distribution                   | Raw Material<br>Transport | Water                  | Raw<br>Material       |                                                                     |
|------------------------|------------------------|------------------------|------------------------------|-----------------------|-----------------------|---------------------------|-----------------------------------------|---------------------------|------------------------|-----------------------|---------------------------------------------------------------------|
| $1.30 \times 10^{-2}$  | $-1.17 \times 10^{-1}$ | $3.04 \times 10^{-3}$  | $-3.06 \times 10^{-1}$       | $1.28 \times 10^{-1}$ | $1.07 \times 10^{-1}$ | $5.01 \times 10^{-2}$     | <b><math>2.05 \times 10^0</math></b>    | $2.17 \times 10^{-1}$     | $5.60 \times 10^{-3}$  | $2.39 \times 10^{-1}$ | Climate Change<br>(kg CO <sub>2</sub> eq)                           |
| $8.00 \times 10^{-11}$ | $-4.05 \times 10^{-9}$ | $1.90 \times 10^{-10}$ | $-8.05 \times 10^{-9}$       | $1.17 \times 10^{-8}$ | $1.20 \times 10^{-8}$ | $3.02 \times 10^{-9}$     | <b><math>3.26 \times 10^{-7}</math></b> | $1.47 \times 10^{-8}$     | $4.74 \times 10^{-10}$ | $3.05 \times 10^{-8}$ | Ozone Depletion<br>(kg CFC-11 eq)                                   |
| $5.81 \times 10^{-10}$ | $-2.93 \times 10^{-8}$ | $1.63 \times 10^{-9}$  | $-1.30 \times 10^{-8}$       | $1.42 \times 10^{-8}$ | $2.86 \times 10^{-8}$ | $4.24 \times 10^{-9}$     | <b><math>2.05 \times 10^{-7}</math></b> | $1.32 \times 10^{-8}$     | $7.13 \times 10^{-9}$  | $2.38 \times 10^{-8}$ | Human Toxicity—Cancer<br>Effects (CTUh)                             |
| $3.84 \times 10^{-8}$  | $-3.04 \times 10^{-8}$ | $1.66 \times 10^{-8}$  | $3.31 \times 10^{-8}$        | $8.47 \times 10^{-8}$ | $3.76 \times 10^{-8}$ | $1.09 \times 10^{-8}$     | <b><math>7.26 \times 10^{-7}</math></b> | $3.67 \times 10^{-8}$     | $5.61 \times 10^{-9}$  | $9.10 \times 10^{-8}$ | Human Toxicity—Non-<br>Cancer Effects (CTUh)                        |
| $5.95 \times 10^{-7}$  | $-1.33 \times 10^{-4}$ | $5.96 \times 10^{-6}$  | $-1.30 \times 10^{-4}$       | $1.16 \times 10^{-4}$ | $1.32 \times 10^{-4}$ | $3.09 \times 10^{-5}$     | <b><math>1.29 \times 10^{-3}</math></b> | $1.28 \times 10^{-4}$     | $5.45 \times 10^{-6}$  | $1.24 \times 10^{-4}$ | Particulate Matter<br>(kg PM2.5 eq.)                                |
| $6.23 \times 10^{-5}$  | $-1.90 \times 10^{-3}$ | $1.88 \times 10^{-4}$  | $-3.75 \times 10^{-3}$       | $8.83 \times 10^{-3}$ | $9.13 \times 10^{-3}$ | $3.97 \times 10^{-3}$     | <b><math>1.66 \times 10^{-1}</math></b> | $1.76 \times 10^{-2}$     | $4.19 \times 10^{-4}$  | $7.92 \times 10^{-3}$ | Ionizing Radiation HH<br>(kBq U235 eq.)                             |
| $2.92 \times 10^{-10}$ | $-8.97 \times 10^{-9}$ | $7.53 \times 10^{-10}$ | $-1.68 \times 10^{-8}$       | $3.53 \times 10^{-8}$ | $3.25 \times 10^{-8}$ | $2.46 \times 10^{-8}$     | <b><math>9.27 \times 10^{-7}</math></b> | $1.12 \times 10^{-7}$     | $1.54 \times 10^{-9}$  | $3.71 \times 10^{-8}$ | Ionizing Radiation E<br>interim (CTUe)                              |
| $8.89 \times 10^{-6}$  | $-3.71 \times 10^{-4}$ | $1.37 \times 10^{-5}$  | $-5.79 \times 10^{-4}$       | $4.61 \times 10^{-4}$ | $4.32 \times 10^{-4}$ | $2.64 \times 10^{-4}$     | <b><math>1.17 \times 10^{-2}</math></b> | $1.26 \times 10^{-3}$     | $2.09 \times 10^{-5}$  | $7.84 \times 10^{-4}$ | Photochemical Ozone<br>Formation<br>(kg NMVOC eq.)                  |
| $4.92 \times 10^{-6}$  | $-7.99 \times 10^{-4}$ | $3.31 \times 10^{-5}$  | $-1.14 \times 10^{-3}$       | $1.15 \times 10^{-3}$ | $7.87 \times 10^{-4}$ | $2.57 \times 10^{-4}$     | <b><math>1.16 \times 10^{-2}</math></b> | $1.12 \times 10^{-3}$     | $4.66 \times 10^{-5}$  | $2.21 \times 10^{-3}$ | Acidification (mol H+ eq.)                                          |
| $1.23 \times 10^{-5}$  | $-1.40 \times 10^{-3}$ | $9.39 \times 10^{-5}$  | $-4.40 \times 10^{-3}$       | $1.72 \times 10^{-3}$ | $1.44 \times 10^{-3}$ | $9.84 \times 10^{-4}$     | <b><math>3.83 \times 10^{-2}</math></b> | $4.51 \times 10^{-3}$     | $7.79 \times 10^{-5}$  | $8.62 \times 10^{-3}$ | Terrestrial Eutrophication<br>(molc N eq.)                          |
| $4.38 \times 10^{-7}$  | $-3.49 \times 10^{-5}$ | $6.12 \times 10^{-6}$  | $-1.88 \times 10^{-4}$       | $5.60 \times 10^{-5}$ | $5.50 \times 10^{-5}$ | $5.18 \times 10^{-6}$     | <b><math>3.12 \times 10^{-4}</math></b> | $1.68 \times 10^{-5}$     | $2.56 \times 10^{-6}$  | $4.60 \times 10^{-5}$ | Freshwater Eutrophication<br>(kg P eq.)                             |
| $4.56 \times 10^{-5}$  | $-1.32 \times 10^{-4}$ | $1.15 \times 10^{-4}$  | $-2.32 \times 10^{-3}$       | $1.69 \times 10^{-4}$ | $1.48 \times 10^{-4}$ | $8.91 \times 10^{-5}$     | <b><math>3.49 \times 10^{-3}</math></b> | $4.07 \times 10^{-4}$     | $7.37 \times 10^{-6}$  | $2.93 \times 10^{-3}$ | Marine Eutrophication<br>(kg N eq.)                                 |
| $2.86 \times 10^0$     | $-1.43 \times 10^0$    | $1.05 \times 10^{-1}$  | $-1.86 \times 10^0$          | $1.14 \times 10$      | $2.00 \times 10^0$    | $4.55 \times 10^{-1}$     | <b><math>4.19 \times 10</math></b>      | $1.45 \times 10^0$        | $3.08 \times 10^{-1}$  | $2.81 \times 10^0$    | Freshwater Ecotoxicity<br>(CTUe)                                    |
| $4.29 \times 10^{-3}$  | $-1.17 \times 10^{-1}$ | $2.62 \times 10^{-2}$  | $-4.57 \times 10^0$          | $4.19 \times 10^{-1}$ | $2.36 \times 10^{-1}$ | $1.23 \times 10^{-1}$     | <b><math>6.15 \times 10^0</math></b>    | $6.77 \times 10^{-1}$     | $2.27 \times 10^{-2}$  | $5.62 \times 10^0$    | Land Use (kg C deficit)                                             |
| $3.36 \times 10^{-7}$  | $-3.62 \times 10^{-5}$ | $-8.05 \times 10^{-4}$ | $-2.10 \times 10^{-2}$       | $1.08 \times 10^{-3}$ | $4.48 \times 10^{-4}$ | $7.47 \times 10^{-6}$     | <b><math>5.33 \times 10^{-4}</math></b> | $8.65 \times 10^{-5}$     | $-7.46 \times 10^{-5}$ | $5.79 \times 10^{-2}$ | Water Resource Depletion<br>(m <sup>3</sup> Water eq.)              |
| $1.06 \times 10^{-8}$  | $-7.22 \times 10^{-7}$ | $8.53 \times 10^{-8}$  | $-2.65 \times 10^{-5}$       | $2.14 \times 10^{-5}$ | $5.06 \times 10^{-6}$ | $7.63 \times 10^{-7}$     | <b><math>5.66 \times 10^{-5}</math></b> | $2.29 \times 10^{-6}$     | $4.58 \times 10^{-7}$  | $4.09 \times 10^{-6}$ | Mineral, Fossil, and<br>Renewable Resource<br>Depletion (kg Sb eq.) |

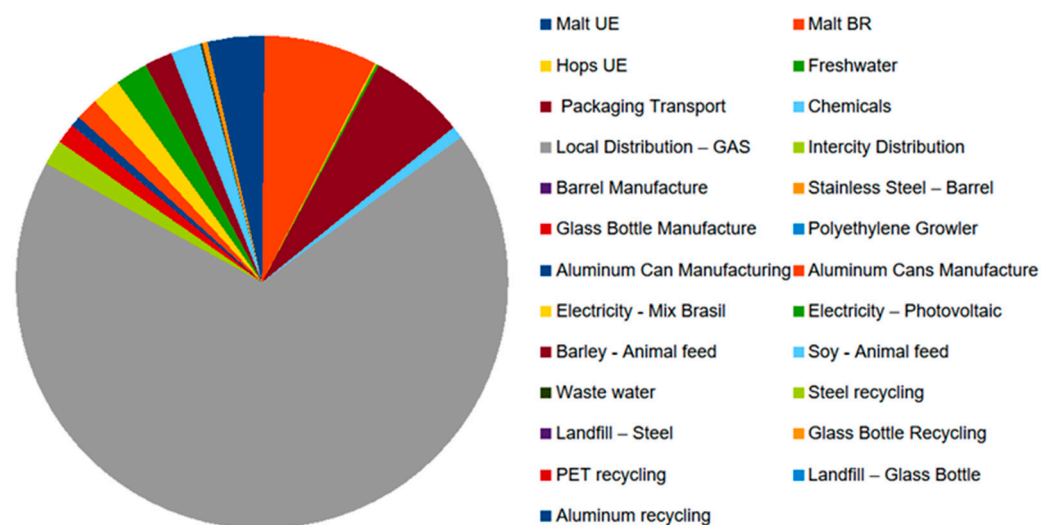


**Figure 2.** Breakdown of greenhouse gas emissions for the production of 1 L of craft beer packaged in different formats.

Table 4 shows the environmental impacts associated when distinguishing between the four types of packaging used by the brewery (production percentages follow Table 2).

**Table 4.** Environmental impacts associated with 1 L of beer in different packaging.

| Glass Bottle          | Growler               | Aluminum Can          | Keg                   | Unit                    | Impact Category                                   |
|-----------------------|-----------------------|-----------------------|-----------------------|-------------------------|---------------------------------------------------|
| $3.25 \times 10^0$    | $2.20 \times 10^0$    | $1.95 \times 10^0$    | $2.16 \times 10^0$    | kg CO <sub>2</sub> eq   | Climate change                                    |
| $4.35 \times 10^{-7}$ | $3.77 \times 10^{-7}$ | $4.03 \times 10^{-7}$ | $3.64 \times 10^{-7}$ | kg CFC-11 eq            | Ozone depletion                                   |
| $3.68 \times 10^{-7}$ | $2.45 \times 10^{-7}$ | $1.66 \times 10^{-7}$ | $2.42 \times 10^{-7}$ | CTUh                    | Human toxicity—cancer effects                     |
| $1.44 \times 10^{-6}$ | $9.75 \times 10^{-7}$ | $9.98 \times 10^{-7}$ | $9.65 \times 10^{-7}$ | CTUh                    | Human toxicity—non-cancer effects                 |
| $2.21 \times 10^{-3}$ | $1.46 \times 10^{-3}$ | $1.15 \times 10^{-3}$ | $1.44 \times 10^{-3}$ | kg PM <sub>2.5</sub> eq | Particulate matter                                |
| $2.62 \times 10^{-1}$ | $1.86 \times 10^{-1}$ | $2.43 \times 10^{-1}$ | $1.83 \times 10^{-1}$ | kBq U235 eq             | Ionizing radiation HH                             |
| $1.46 \times 10^{-6}$ | $1.02 \times 10^{-6}$ | $1.23 \times 10^{-6}$ | $1.01 \times 10^{-6}$ | CTUe                    | Ionizing radiation E (interim)                    |
| $1.78 \times 10^{-2}$ | $1.28 \times 10^{-2}$ | $1.30 \times 10^{-2}$ | $1.26 \times 10^{-2}$ | kg NMVOC eq             | Photochemical ozone formation                     |
| $2.00 \times 10^{-2}$ | $1.43 \times 10^{-2}$ | $1.24 \times 10^{-2}$ | $1.41 \times 10^{-2}$ | molc H <sup>+</sup> eq  | Acidification                                     |
| $6.43 \times 10^{-2}$ | $4.60 \times 10^{-2}$ | $4.46 \times 10^{-2}$ | $4.53 \times 10^{-2}$ | molc N eq               | Terrestrial eutrophication                        |
| $4.93 \times 10^{-4}$ | $2.42 \times 10^{-4}$ | $2.00 \times 10^{-4}$ | $2.38 \times 10^{-4}$ | kg P eq                 | Freshwater eutrophication                         |
| $6.54 \times 10^{-3}$ | $4.52 \times 10^{-3}$ | $4.42 \times 10^{-3}$ | $4.46 \times 10^{-3}$ | kg N eq                 | Marine eutrophication                             |
| $8.43 \times 10$      | $5.55 \times 10$      | $5.77 \times 10$      | $5.50 \times 10$      | CTUe                    | Freshwater ecotoxicity                            |
| $1.04 \times 10$      | $7.87 \times 10^0$    | $8.44 \times 10^0$    | $7.78 \times 10^0$    | kg C deficit            | Land use                                          |
| $3.95 \times 10^{-2}$ | $3.77 \times 10^{-2}$ | $3.90 \times 10^{-2}$ | $3.77 \times 10^{-2}$ | m <sup>3</sup> water eq | Water resource depletion                          |
| $7.83 \times 10^{-5}$ | $5.76 \times 10^{-5}$ | $8.77 \times 10^{-5}$ | $5.66 \times 10^{-5}$ | kg Sb eq                | Mineral, fossil, and renewable resource depletion |

Beer packaging in stainless-steel kegs presents the lowest environmental impacts in the nine impact categories. This is due to the high reusability rates of kegs, which can reach 120 reuse cycles [14]. After the lifetime ends, the brewery sends all kegs to a recycling facility.

Aluminum cans presented the lowest impacts in the seven selected categories, including the lowest value in the Climate Change category. In 2022, Brazil reached the historic milestone of recycling 100% of the aluminum cans manufactured in the period, reaching 390,000 tons of recycled cans [22]. Although the data are positive from an environmental point of view, they demonstrate an important social issue, as most of the recycled cans are collected by people who are in a fragile social situation, with the collection of aluminum cans being their main source of income. Informal waste pickers are primarily responsible for

garbage management and recycling in low- and middle-income developing countries [28]. Poor and marginalized socioeconomic groups rely on scavenging and rubbish picking as a source of income [29]. A 2021 report [30] mentions that Brazil has been a leader in recognizing its more than 281,000 informal waste pickers in recycling chains; nevertheless, [31] reported that the legal framework concerning the integration of informal recyclable waste pickers in Brazil is still pending.

The PET growler presents the third lowest environmental impacts, with impact values close to those of cans and kegs. This is due to the high reuse rates of growler packaging (according to the microbrewery, consumers reuse their growlers 10 times on average). Another added point is that the growler distributor is in the same city as the brewery, reducing the impact of transportation.

Glass bottles obtained the highest values across all the impact categories studied. Several factors contribute to these high values: these are single-use bottles, and the recycling percentage is only 25% [23]. Glass bottles are the most popular format, accounting for a larger share of the distribution stage, especially local distribution that employs a gasoline-fueled light commercial vehicle.

Regarding the life cycle impacts of packaging materials beyond the distribution phase, the concept of a waste hierarchy can help with understanding how to manage packaging waste. Waste hierarchy is the European Union's approach to waste management [32], which is based on a ranking of priority of waste management options: prevention, preparing for reuse, recycling, other recovery options, and disposal. Prevention is the most preferred, and disposal is the least. Considering the options available for the microbrewery, reutilization of packaging can be coupled with a circular economic model, creating an environmentally conscientious alternative that ensures materials are reused again and again. The aim is to design waste out of the system, where packaging can be used multiple times by being collected, washed, and reused. Diprose [33] highlighted the significant collaboration and emerging networks needed to transition away from single-use packaging and indicated how investment towards the top of the waste hierarchy in reuse could contribute to a more circular economy.

Cimini and Moresi [34] reported that the environmental loads associated with beer packaging options could be reduced by employing lighter bottles or kegs, bottles with a higher percentage of recycled materials, and containers reusable as many times as possible. The authors mention that a 10% decrease in the weight of glass bottles could reduce the carbon footprint by 5%, and when nanoclay-enriched PET bottles were used, the reduction was 30%. The authors also present a detailed discussion on the different waste hierarchy options for beer packaging. Lemaire [35] mentions the eco-conception of packaging as a strategy for microbreweries, such as the use of a screen-printing technique that washes away without polluting the water. Standardization practices applied to beer bottles can enable more circularity among breweries, collecting points and bottle washers.

In addition to encouraging the use of less impactful packaging, one possibility for reducing the impacts generated by the microbrewery would be to adopt electric vehicles. The results when considering electric vehicles are shown in Table 5. Particularly in Brazil, the use of electric vehicles is beneficial, as the Brazilian electricity mix is mainly constituted of renewable energy sources.

As distribution to the points of sale is a critical point where the brewery can act, the adoption of electric vehicles can be an environmentally viable alternative. Maintaining the same mileage and delivery routes, in one year an electric vehicle emits around 117 t CO<sub>2</sub>-eq compared to 443 t CO<sub>2</sub>-eq for a gasoline vehicle, avoiding the emission of 326 t CO<sub>2</sub>-eq.

Microbreweries face several challenges due to the small scale of production. Because of the low volume of purchases compared to large breweries, microbreweries are unable to control their suppliers' processes, thus reducing the options for mitigating the associated environmental impacts.

**Table 5.** Environmental impacts associated with the distribution of 1 L of beer packaged in different formats.

| Electric Reduction | Electric              | Gasoline              | Unit                    | Impact Category                                   |
|--------------------|-----------------------|-----------------------|-------------------------|---------------------------------------------------|
| −74%               | $6.50 \times 10^{-1}$ | $2.46 \times 10^0$    | kg CO <sub>2</sub> eq   | Climate change                                    |
| −78%               | $9.10 \times 10^{-8}$ | $4.05 \times 10^{-7}$ | kg CFC-11 eq            | Ozone depletion                                   |
| −59%               | $1.13 \times 10^{-7}$ | $2.73 \times 10^{-7}$ | CTUh                    | Human toxicity—cancer effects                     |
| −55%               | $4.59 \times 10^{-7}$ | $1.03 \times 10^{-6}$ | CTUh                    | Human toxicity—non-cancer effects                 |
| −62%               | $6.29 \times 10^{-4}$ | $1.65 \times 10^{-3}$ | kg PM <sub>2.5</sub> eq | Particulate matter                                |
| −65%               | $7.26 \times 10^{-2}$ | $2.07 \times 10^{-1}$ | kBq U235 eq             | Ionizing radiation HH                             |
| −71%               | $3.26 \times 10^{-7}$ | $1.14 \times 10^{-6}$ | CTUe                    | Ionizing radiation E (interim)                    |
| −73%               | $3.77 \times 10^{-3}$ | $1.42 \times 10^{-2}$ | kg NMVOC eq             | Photochemical ozone formation                     |
| −63%               | $5.79 \times 10^{-3}$ | $1.58 \times 10^{-2}$ | molc H <sup>+</sup> eq  | Acidification                                     |
| −70%               | $1.53 \times 10^{-2}$ | $5.09 \times 10^{-2}$ | molc N eq               | Terrestrial eutrophication                        |
| −58%               | $1.23 \times 10^{-4}$ | $2.93 \times 10^{-4}$ | kg P eq                 | Freshwater eutrophication                         |
| −64%               | $1.77 \times 10^{-3}$ | $4.98 \times 10^{-3}$ | kg N eq                 | Marine eutrophication                             |
| −44%               | $3.25 \times 10$      | $5.78 \times 10$      | CTUe                    | Freshwater ecotoxicity                            |
| −66%               | $2.90 \times 10^0$    | $8.65 \times 10^0$    | kg C deficit            | Land use                                          |
| −3%                | $3.69 \times 10^{-2}$ | $3.80 \times 10^{-2}$ | m <sup>3</sup> water eq | Water resource depletion                          |
| −45%               | $3.41 \times 10^{-5}$ | $6.23 \times 10^{-5}$ | kg Sb eq                | Mineral, fossil, and renewable resource depletion |

The direct comparison of results with other (few) existing studies is hindered because results can depend on brewery size and geography. Also, LCA methodological selections can influence the results obtained. The size of the brewery has a major influence because it brings with it an efficiency of scale. For example, a large brewery can treat all its liquid effluent in its own treatment plant, as the large amount of effluent makes its operation viable, bringing environmental benefits to the brewery. In the case of geography, a microbrewery that is close to its main input suppliers will have a more sustainable operation, as all transport of inputs will be minimized. It should be noted here that due to their large territory, Brazilian microbreweries located outside the south/southeast tend to have greater difficulty in acquiring brewing supplies, from raw materials to packaging and chemicals.

The methodological options for this type of study are constantly being developed, so whenever possible, a comparison is made with current studies, but comparisons with older studies are also valid with the intention of demonstrating that the methodology has been modernized, making the studies increasingly complete and effective.

As far as liquid waste is concerned, being a small brewery, it is not justifiable to invest in an effluent treatment plant, and all liquid waste is sent for treatment by the municipal water and sewage company. As for the solid waste, which is made up almost entirely of malt collected after the filtration stage, it is collected by local farmers, who take this material from the brewery and use it as animal feed, as it is a nutrient-rich food, thus avoiding the purchase of industrialized feed and managing to avoid the emissions and impacts related to its production.

Another option to reduce the environmental impact of the microbrewery can include an incentive to increase and promote the sale of reusable packaging, such as kegs and growlers. As mentioned by [36], the type of packaging has a significant contribution to the overall impact of the beverage value chain. Motivating customers to bring their own refillable packaging (glass or PET) is a way of encouraging local consumption and reducing the need for distribution. Ness [37] carried out a survey of craft breweries with a sustainability profile and verified that breweries often switched from conventional bottles to lightweight bottles or cans, some used glass bottles with a high amount of recycled glass, and others emphasized returnable and refillable growlers with the promotion of reusable bottles or kegs. However, [38] mentioned that the experiences with reusable packaging systems are mixed: in Germany and the Netherlands, reusable glass bottles are used for

beer. There is a challenging interaction between economics (reusable bottles entail lower costs), distribution, marketing, and national cultures, to name a few factors.

Although these data are positive from an environmental point of view, they demonstrate an important social issue, since most of the recycled cans are collected by people who are in a fragile social situation, with the collection of aluminum cans being their main source of income. These actions bring many environmental benefits and align the microbrewery with some of the 17 Sustainable Development Goals [39], especially SDG 12—Responsible Consumption and Production and SDG 13—Action against Global Climate Change. These actions have great potential in a market that is growing, with new microbreweries being set up all over the country.

#### 4. Conclusions

This study is a pioneer in presenting detailed data on the production process of a microbrewery, followed by the quantification of environmental impacts for a craft microbrewery located in northeast Brazil using attributional life cycle assessment with an expanded boundary to account for the use of malt grain residue as animal feed by local farmers.

The local beer distribution stage presented the highest share of environmental impacts across all categories considered. When simulating the use of electric vehicles, the impacts were generally three times lower than the actual reference scenario (traditional internal combustion engines that consume gasoline).

The direct comparison of results with existing studies is hampered by differences regarding the sizes of the breweries, as well as the processes and environmental assessments carried out. It was observed that the size of the brewery presented the most influence on the final result, as large breweries can be more efficient in both brewing and distribution. When the comparison was possible, the impact values were very close and the hotspots similar, with the distribution to the points of sale and the cultivation stage (agriculture) being the two phases with the highest emissions.

Regarding the type of packaging, stainless-steel kegs presented the lowest impacts in nine out of sixteen categories, and one of the reasons for this positive performance is due to its great reusability, with each barrel being reused around 120 times. Aluminum cans had the lowest impact in seven of the categories studied, due to the 100% recycling rate in Brazil. PET growlers have proved to be a good packaging option, mainly because they are reusable and have a good recycling rate when properly disposed of. Glass bottles obtained the highest environmental impacts across all categories, due to them being single use with recycling rates of only 25%.

Suggestions for future work include a broader assessment of emissions from the national supply chain such as, for example, from malt grown in the south and hops grown in southeast Brazil. In addition, by recognizing that the economics of beer brewing are a significant aspect in beer production, future work can focus on life cycle costing (LCC), as its application is often connected with LCA.

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