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Carbon Footprint of Yerba Mate (*Ilex paraguariensis*) Value Chain in Misiones Province (Argentina)

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Abstract: Yerba mate (YM) is an important crop derived from the cultivation of the native tree *Ilex paraguariensis* in northeastern Argentina, used for the preparation of *mate* infusion, which is widely consumed in South America. This study aimed at assessing the environmental impact, namely of CO_2 equivalent (CO_2eq.) emissions, of the YM value chain while identifying environmental hotspots along the production chain, from nursery up to transport. A cradle-to-wholesale approach was carried out, considering as the main functional unit 1 kg of commercial YM produced in Misiones Province and transported to Buenos Aires, the largest YM market in the world. Primary data were gathered from representative nurseries and plantations of the region; processing and packaging data were collected from a local cooperative, while the assessment of the impact due to truck transport was performed considering a distance of 1200 km from Buenos Aires. All the processes were analyzed using LCA methodology following the guidelines outlined in the ISO 14044 regulation (EN ISO 14044); the GaBi software (Sphera Solution, Inc., Chicago, IL, USA), updated to version 10.7.21.8, was used for process modeling, while the CML 2001 calculation method, updated as of the latest release in August 2016, was used to calculate the impacts. The results (1.24 kg CO_2eq./kg. YM produced in Misiones and transported to Buenos Aires) show that the cultivation phase of YM has very little impact, while most of the emissions are related to the drying phase and the subsequent transportation from the production area to Buenos Aires.

Keywords: life cycle assessment; environmental impact; typical regional crop; agrifood; infusion beverage

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1. Introduction

Yerba mate (*Ilex paraguariensis* A. St. Hil.), a woody perennial species native to a wide geographical area located in the borders of Brazil, Argentina, Paraguay and Uruguay, is well known to the South American population since its dried leaves and twigs are used to prepare a beverage by infusion in hot water locally known as *mate* [1]. Traditionally used by the pre-Colombian ethnic groups of the area, the adoption of mate drinking, considered a healthy food rich in nutraceutical compounds [2], has spread widely in South America, and it is very popular in Argentina, Uruguay, Brazil, Paraguay and Chile. Moreover, its consumption is also expanding into new markets such as the US, Europe and Asia [3], as it is also used as an energy drink [4]. The average annual consumption per person of the beverage in Argentina is about 6.24 kg [5]. Argentina, by far the world's leading producer, supplies the demand with 324,621 tons of YM produced yearly [6], 90% of which is destined for domestic consumption while the remainder is exported mainly to Syria, Chile, Uruguay and Brazil [7]. The Argentine industry of yerba mate registers 10,811 producers, 200 industrial drying plants and 104 milling and fractionating establishments [7]. The cultivation of YM, occupying an area of 209,277 ha [8], is one of the main productive activities in northeastern Argentina, and namely in Misiones Province, where its production is family-based and carried out mainly on medium–small plantations (about 10 ha) [9]. The great social and economic importance of the cultivation of YM in the region has driven the development of different studies that generated important technical advances for its production related to yield, product quality, certification and marketing [10–14]. Nevertheless, there is no report on the issues related to the environmental impact of the YM supply chain, and it is a well-known fact that the South American continent has long been facing the onset of soil depletion and increased CO_2eq. emissions [15,16]. YM production area is located within the Atlantic Forest ecosystem known as Mata Atlántica, where almost 85% of its coverage has disappeared due to deforestation [17,18], and the change in land use has generated loss of biodiversity [19,20] and edaphic and water degradation [21]. The Atlantic Forest in Misiones Province represents one of the most important remnants [22], which, due to its biophysical conditions, has a great capacity to offer ecosystem services at a local, regional and global level [23]. The productive use of the land in Misiones is dominated by exotic forestry and diversified agricultural systems based on the production of tobacco, tea, livestock, citrus fruits and YM [24]. Very little is known about the contribution of these crops to GHG emissions in the region, except for a study on tea conducted by Lysiak a few years ago [25]. The present study aims to assess the emission of GHGs (greenhouse gases) generated by the YM value chain by applying the LCA methodology; more specifically, this research is focused on the identification of the hotspots for YM primary production in Misiones Province (Argentina), i.e., plant nursery and cultivation, leaves and twigs harvesting, using as a reference a commercial nursery located in Oberá and a technically advanced commercial plantation in Jardín América, and industrial processing, which includes drying and storage, blending and packaging in Montecarlo [26]. Due to the restricted area of YM production, i.e., in Misiones Province, where the previous primary production and processing are located, transport of the commercial product to the wholesalers in Buenos Aires City, the most important YM market of the world, has been included in this study (Figure 1).

Figure 1. Map of Argentina with the province of Misiones highlighted.

1.1. Yerba Mate Cultivation Phase

The life cycle of YM cultivation can be divided into three well-differentiated stages, as shown in Figure 2.

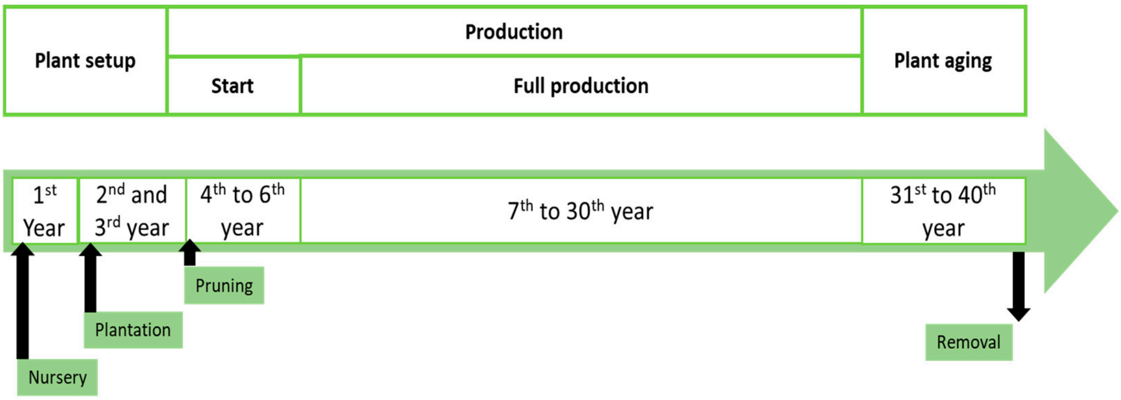

Figure 2. Yerba mate (*Ilex paraguariensis*) tree growth stage and plantation evolution during a lifespan.

Plantation setup. This unproductive period lasts approximately 2 to 3 years, including propagation through seedlings, planting and training; in the first 1–2 years after planting, classical agronomic care is applied (land preparation, weeding, fertilization). During this period the plants are subjected to a slight pruning, and no harvesting is carried out; replacements of dead plants are carried out within one year from planting.

Production phase. YM trees start to produce small amounts of harvestable leaves and twigs after 4–6 years from planting; weed control and occasional pruning are the main practices. The plantation shows the maximum productivity (about 8–10,000 kg/ha/yr average of fresh matter) between the 7th and the 30th year from planting. Harvesting, generally carried out manually once or twice a year, consists of collecting the mature green leaves and a small percentage of twigs. An initial sorting of material to remove dead or dry branches is carried out immediately after harvesting; irrigation is generally not required; weed, pest and disease management tasks are regularly carried out, as well as practices to preserve the chemico-physical characteristics of the soil.

Plant aging. After approximately 30 to 40 years, productivity may decrease, and eventually, YM trees are removed, and a new plantation is carried out.

1.2. Industrial Processing of Harvested Leaves and Twigs

The industrial processing, shown in Figure 3, begins within 24 h of harvesting the green leaves and twigs. The raw material, transported in sackcloth bags by trucks to the drying and packaging plant, is inspected, dried, stored, aged, ground, blended and finally packed. More in detail, the processing includes the following:

First drying. This step, locally known as *sapecado*, consists of exposing the harvested material for about 25″ to high air temperature (400–500 °C) in rotary drum dryers for the purpose of a rapid reduction in the water content of the leaves and twigs by 30 to 50% [10].

Second drying. In the second drying stage, leaves and twigs are exposed to an 80–100 °C air flush for 2–12 h. After the double drying process, the green harvested material will have lost about 65–70% of moisture [10], i.e., from 100 kg of fresh leaves and twigs, about 30 to 35 kg of dried YM are obtained.

Coarse grinding and aging. The dried YM goes through a coarse grinding process, ("*canchado*"), and is then stored in warehouses for a natural (from 6 to 24 months) or accelerated (from 30 to 60 days) aging under temperature- and humidity-controlled conditions in a forced air stream at 50–60 °C. During this time, YM acquires the characteristics and flavor required by consumers [27].

Grinding, blending and packaging. Once the YM is coarse-ground and aged, the final stage of the production cycle is carried out, involving fine grinding, blending (according to brand quality) and packaging in 0.5 or 1 kg containers, such as paper or cardboard bags. The product is now ready for delivery to the consumers [10,28].

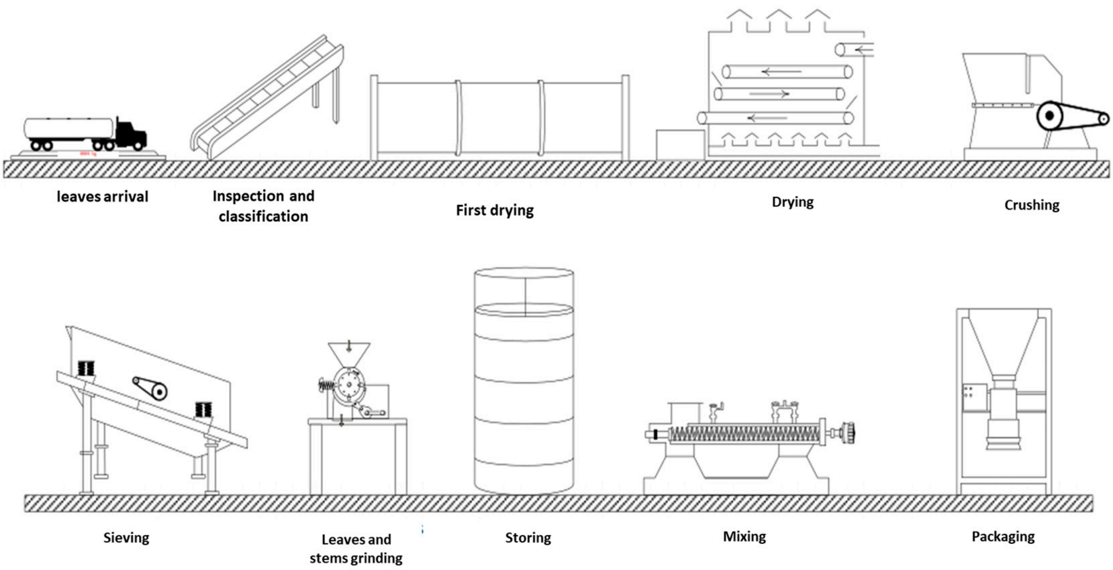

Figure 3. Industrial processing of YM leaves and twigs: from double drying to final grinding, blending and packaging.

2. Materials and Methods

All the processes taken into consideration within this study were analyzed using LCA (life cycle assessment) methodology following the guidelines outlined in the ISO (International Organization for Standardization) 14044 regulation [29]. The calculation of the carbon footprint was carried out using the GABI 10.7.1.28 software and the EcoInvent 3.3 database together with the software's own database, and subsequently, the CML 2001 method updated to 2016 (Sphera Solution, Inc., Chicago, IL, USA) was used for process modeling. For this analysis, the global warming potential (GWP), expressed in kg of CO_2 equivalent, was selected as an impact indicator within the CML 2001. This represents "*the impact of human emissions on the forced irradiation of the atmosphere*" [30]. All emissions were considered over a 100-year period, in compliance with the recommendations of both the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC), regarding the comparison of processes with different types of emissions affecting the global warming potential [31]. This study used an attributional approach based on the analysis of an existing, standardized production cycle without considering future changes and/or technological or process innovations.

2.1. Goal and Scope

This work aims to analyze the impact generated by the YM value chain on global warming based on GHG emissions calculated for its different steps. The data collection and construction of inventories of input and output flows of each link in the production chain includes the following: i. transport of the YM seedlings from the commercial VyO Nursery (Oberá, Misiones, Argentina); ii. green leaf production (primary production), adopting as a model the Tabay S.A. farm (Jardín América, Misiones, Argentina); and iii. processing stages as performed by Cooperativa Agrícola Mixta de Montecarlo, Misiones, Argentina.

2.2. Functional Unit and System Boundary

It was decided to adopt a dual functional unit, as suggested by Nemecek et al. [32]. The first one, which was product-based ($kgCO_2eq./kg$), was chosen to characterize the emissions of 1 kg of packaged YM marketed in the Autonomous City of Buenos Aires; the second functional unit, which was land-based ($kgCO_2eq./ha/yr$) and more suitable to represent the intensity of agricultural input use [33], was used to make comparisons between the YM supply chain and different agricultural cultivations. The system boundaries were set from-cradle-to-wholesale, considering a lifespan of 40 years for a YM plant; all the input and output flows were taken into account for the primary production (transport from plant nursery to cultivation and harvesting of green leaves and twigs), the processing (drying steps, aging, grinding, blending and packaging of harvested leaves and twigs) and the transportation from the packing house in Monte Carlo (Misiones) to the Autonomous City of Buenos Aires. No cut-offs or allocations were considered in the present work.

2.3. Life Cycle Inventory

To proceed with the life cycle analysis, it was first necessary to draw up an inventory of the processes to be taken into consideration to be able to subsequently proceed with the collection of timely data, in the field or in companies.

- Plantation setup: all preliminary tillage of the land (ripping and plowing), the correction of the soil through the application of dolomite and the planting of YM seedlings previously grown in the nursery were considered.
- Cultivation phase: This entry includes all the processes necessary for the maintenance and growth of the plantation, such as pruning, both maintenance and harvesting, grassing of the rows and subsequent shredding. Chemical fertilization, herbicide and pest control through chemicals, application of manure, of which the entire production cycle was also analyzed, and global electricity consumption are also included in this entry; the electricity consumption considered in this study refers to the U.S. grid mix, as the specific mix for Argentina is not available in the database used for this research.
- Industrial phase: At the level of product transformation, the electricity consumption of the grinding and sieving phases and the consumption of wood chips from locally cultivated Eucalyptus, necessary to power the drying ovens, were considered; for the packaging phase, the company's electricity consumption and the materials needed to prepare the packages and pallets for shipment were considered.
- Transports: All transports that occurred within the system boundaries were taken into consideration; this includes the transportation of personnel, machinery, consumables, tools and YM from the collection site to the processing location, as well as the transportation of the finished product from the city of Misiones to Buenos Aires.

The table bringing together the inventory and processes used can be found as Supplementary Data (Table S1). Since multi-year data sets were not available, the research referred to a single year (2022).

2.4. Sensitivity and Uncertainty Analysis

An LCA analysis, however effective and useful it may be in assessing the environmental impacts of a service or product, can present within it sources of uncertainty that can affect its reliability, especially in the case in which the data collected during the LCI phase are inaccurate, non-representative or do not present optimal quality and reliability [34–37]. In the case of this study, it was not deemed necessary to carry out a sensitivity analysis on the data used, as they are mainly primary data, coming from direct measurements carried out by the agricultural company cultivating the mate plants or by the secondary structures in charge for processing the harvest. Similarly, it was decided not to carry out an uncertainty analysis due to the fact that the specific goal of this research was the identification of the main impacts within the YM supply chain, in order to have a first picture of the current emissions of the processes analyzed. A more in-depth approach may be considered in future research.

2.5. Production System Description

The selection of the plantation was based on the following parameters related to the primary production: yield (average of 12 t of green leaves and twigs/ha/yr along the lifespan of the plantation), planting density and plantation management (namely, the adoption of cultivation techniques, weed control, fertilization and harvesting method), level of mechanization and distance from the processing plant. The YM cultivar was neglected since YM plantations consist of transplanted saplings obtained from seeds.

The choice of the processing plant was based on the relevance of the company in terms of the amount of green product processed yearly and the amount of commercial YM sold to retailers in Buenos Aires City.

3. Results

The results of the LCA analysis carried out on the YM production chain show that the 1 kg commercial package transported to Buenos Aires from the production area, 1200 km away, has an overall emission of 1.24 kg CO_2eq. This emission is equivalent to approximately 5216 kg of CO_2eq./ha/yr (Table 1). More specifically, the results clearly show that the cultivation and transport phases are responsible for limited CO_2eq. emissions (0.125 and 0.109 kg/kg YM, respectively), while the phase of the production chain with by far the greatest impact is industrial processing (about 1 kg of CO_2eq. out of 1.24 kg total). Within the cultivation phase, the farm transportation subphase, including all the inputs related to the use of equipment and machinery for the cultivation of YM, amounts to 0.017 kg of CO_2eq./kg YM, much of which is due to the harvesting of YM in the field (0.010 kg CO_2eq./kg YM). Approximately the same emissions (0.019 kg CO_2eq./kg YM) were detected from the inputs included in the operations subphase. In general, these inputs did not have a major impact on the production chain; in fact, the highest emissions came from the application of manure, with a value of 0.006 kg CO_2eq./kg YM. The consumables, on the other hand, were found to be the most impactful subphase within the cultivation phase, due to the use of NPK fertilizers whose emissions were quite relevant (0.081 kg CO_2eq./kg YM). It should be noted that one of the cultivation inputs, cover cropping, has a negative value (meaning C sink), and this is because the GABI software takes into account the C stored in the plant material (ryegrass) used as cover crop. A further consideration can be made for the water used for treatments; it is surface water included in the list of consumables; its contribution to CO_2 emissions is considered to be zero, except for the energy used by pumps (included as electricity). The processing phase of the product, as mentioned above, is by far the most impactful, due to the drying phase, which contributes a total of 0.927 kg CO_2eq./kg YM, mainly due to the large machines used for drying leaves (0.866 kg CO_2eq./kg YM) and, to a lesser extent, due to the energy used in its operation (0.061 kg CO_2eq./kg YM). Finally, the transportation phase to Buenos Aires, which has an emission of 0.109 kg CO_2eq./kg YM, appears to be the least impactful phase of the production cycle, although not much lower than the emissions due to the entire field cultivation phase (0.125 kg CO_2eq./kg YM). From this first table on the various inputs of this production chain and their effect on the C footprint of YM, it can be seen that most of the cultivation inputs considered actually have very little (or no) relevance to the environmental impact of YM production.

Table 1. GHG emissions (kgCO_2eq.) of the different inputs considered, related to 1 kg of packed YM and 1 ha/yr cultivated area.

Phase	Subphase	Input	Emissions (kgCO_2eq.)	
			1 kg YM	**1 ha/yr**
Cultivation	Farm Transportation	Harvest	0.010	42.947
		Personnel	0.006	24.000
		Consumables	0.001	2.947
		Machinery	0.000	1.684
	Operations	Pruning/harvesting	0.005	19.368
		Electricity	0.004	17.684
		Inter-row mowing	0.002	6.737
		Fertilization	0.001	4.632
		Pest/weed control	0.001	2.526

Table 1. *Cont.*

Phase	Subphase	Input	Emissions ($kgCO_2eq.$)	
			1 kg YM	1 ha/yr
	Consumables	Plowing	0.001	3.789
		Pruning and waste disposal	0.000	1.684
		Manure application	0.006	23.579
		NPK fertilizers	0.081	339.366
		Manure	0.005	20.631
		Dolomite	0.004	17.684
		Herbicide/insecticide	0.003	13.052
		Water	0.000	0.004
		Cover cropping (ryegrass)	−0.004	−14.737
Processing	Drying	Drying (wood chips)	0.866	3644.609
		Electricity	0.061	257.262
	Milling/packaging	Electricity	0.014	59.368
		Packaging	0.056	237.051
		Pallet preparation	0.008	31.999
Transport		Transport to BsAs	0.109	458.524
Total Emissions			1.239	5216.393

4. Discussion

The LCA analysis clearly highlighted the contribution of the different stages of the YM production chain to the emission of CO_2eq., thus defining the environmental impact of this particular product. Looking at the three main phases of the production chain, the environmental impact of the industrial process, which accounts for more than 80 percent of total emissions, is clear, while each of the other two stages (cultivation and transport) remain at around 9–10 percent (Figure 4). In fact, the mate cultivation phase, with 527.6 kg/ha/yr, cannot be defined as very impactful in terms of CO_2eq. emissions when compared to the values of other agricultural crops, such as durum wheat (1481.1 kg/ha/yr [38]), onions (3410 kg/ha/yr [39]), citrus (6324 kg/ha/yr [40]) and vineyards (964 kg/ha/yr [40]). More in detail, this lopsided distribution of emissions is mainly due to the drying plant and the energy required to operate it (almost 75% of total emissions) rather than the milling/packaging subphase (Figure 5). This aspect should not be seen in a negative light in the perspective of improving the environmental performance of this production chain. Indeed, the search for a climate-impacting emissions improvement scenario first requires the identification of critical points in the production chain, and, clearly, it is preferable to deal with a single, relevant source of emissions rather than a large and diffuse set of emission sources that may prove difficult to manage.

As a matter of fact, the optimization of leaf drying processes for food or medical applications has the main objective of not only maintaining the highest product quality but also achieving it with the lowest energy consumption. In this perspective, energy optimization of the leaf-drying process is considered a major issue and a real hotspot for future research, as stated by different authors [41,42]. Comparing the environmental impact of the YM supply chain with other productions involving product drying steps (leaves or fruit), such as tea, coffee and tobacco, reveals significant differences in their carbon footprints. Obviously, this type of comparison between different crops in the same environment, or between similar crops in different environments and countries, is influenced by the fact that production processes may vary due to a number of factors (e.g., geographic, economic, technological). Nevertheless, such comparisons can be useful to get a first idea of the level of emissions from a crop that has been relatively less considered in terms of its environmental impact. Specifically, when examining the environmental impact of tobacco, a 2020 study by Boettcher et al. analyzed two types of tobacco and found that the environmental impact for one kilogram of product ranges between 1.40 and 1.83 kg CO_2eq., depending on the type considered [43]. These are values roughly similar to those obtained for mate, but there are substantial differences in the subdivision of the impacts. In fact, a detailed breakdown of these impacts by phase shows that most emissions for tobacco are attributable to the cultivation phase, averaging around 86% of the total emissions (mainly due to heavy N fertilization). This contrasts with the cultivation of YM, where the cultivation phase accounts for only 10% of total emissions. Clearly, the tobacco drying phase has a negligible impact on the total environmental footprint if compared with the drying process for YM. Similar to what has been observed for tobacco, coffee production shows most of the impacts localized in the cultivation phase, both for the production of unroasted coffee beans and for the finished, roasted and ground product. For unroasted coffee beans, a study carried out by Thrin et al. on different types of coffee cultivation shows how 85% of the impacts are due to the use of fertilizers and pesticides, 14.2% due to irrigation, while the remaining phases of harvesting and industrial treatment (drying and packaging of the final product) represent only 0.3% of the total impacts [44]. In the case of the finished product, roasted and ground, the percentage of impact linked to the industrial phases rises to 28% but remains lower than the impacts due to the cultivation phase, which account for 67% of the total [45]. For tea production, however, the results show greater variability because there are different types of tea, each with different growing and processing characteristics. Excluding the production of green tea tablets, which differs greatly from other types both in terms of production method and cultivation yields, a 2019 study shows how the greatest impacts are due to the industrial processing phase (mainly drying), with a contribution varying between 33 and 63%. Then follows the cultivation phase, with percentages, depending on the type of tea, between 22 and 41%. Finally, unlike mate, tobacco and coffee, a significant percentage of the impact is attributable to the packaging phase of tea, in a range that oscillates between 13 and 35% of the total impact [46].

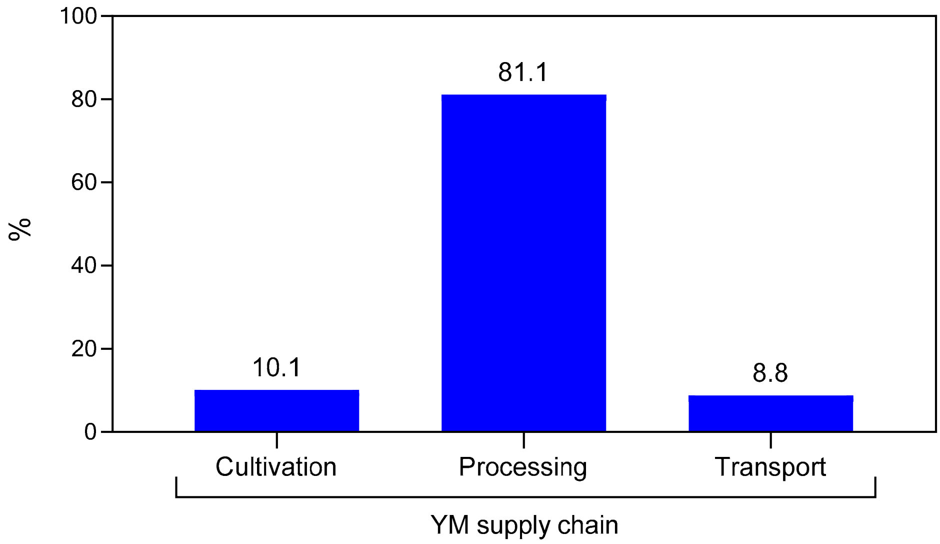

Figure 4. Breakdown (%) of CO_2eq. emissions associated with the main phases of the supply chain.

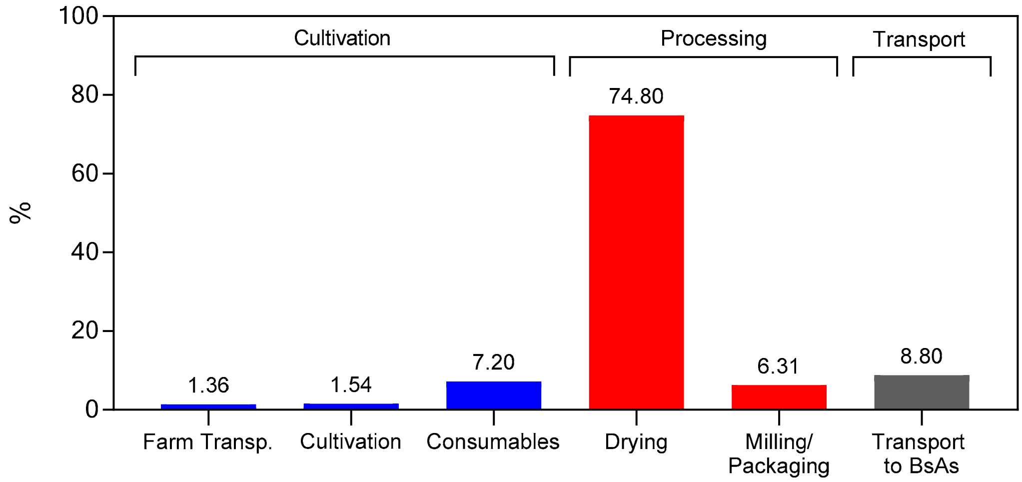

Figure 5. Breakdown (%) of CO_2eq. emissions associated with the different subphases of the supply chain, including transport.

5. Conclusions

The LCA analysis applied to the YM production chain in the province of Misiones, Argentina, pointed out the environmental impact of the various passages in the supply chain, clearly identifying the critical steps in terms of CO_2eq. emissions. Finding these hotspots in a production process becomes crucial when designing an improvement scenario, a possible intervention that will effectively reduce the CO_2eq. emissions of the production chain under consideration. In our study of the impact of YM cultivation calculated both per unit area and per unit product (1 kg package transported to Buenos Aires), it was found that most of the emissions are due to the drying phase of the fresh product. This aspect leads to the conclusion that, in the case under consideration, looking for best practices in cultivation, actually not very impactful in themselves if compared with other crops, is less relevant than working on the optimization of drying facilities, trying to limit energy consumption, which is the real problem in the sustainability of the YM supply chain. As a matter of fact, most current studies suggest the use of lower temperatures in the drying of leaves in order to preserve their properties and/or nutrients [40], and this possibility, if applicable to the drying of YM, could have a positive impact on CO_2eq. emissions. Ultimately, it is necessary to emphasize the importance of the transition of agricultural systems towards low-carbon strategies that can counter increasing trends in emissions from land use in South America [16].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162210127/s1, Table S1: List of the inventory and processes considered in the LCA analysis of Yerba mate.

Author Contributions: Conceptualization, D.H.C., L.G., E.G. and F.P.N.; methodology, L.A. and F.P.N.; software, L.A.; data curation, D.H.C. and L.G.; writing—original draft preparation, D.H.C., L.G., F.P.N. and L.A.; writing—review and editing, F.P.N., E.G. and L.A.; supervision, E.G. and F.P.N. All authors have read and agreed to the published version of the manuscript.

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