sustainability

MDPI

Article

Opportunities for Improving the Environmental Profile of Silk Cocoon Production under Brazilian Conditions

Silvia Mara Bortoloto Damasceno Barcelos [1,2,3,*], Rodrigo Salvador [3], Maria da Graça Guedes [1] and Antonio Carlos de Francisco [3]

1 Science and Technology Center Textile, Azurém Campus, Engineering School, University of Minho (Uminho), 4800-058 Guimarães, Portugal; mgg@det.uminho.pt
2 Cianorte Campus, Design and Fashion Department, Universidade Estadual de Maringá (UEM), 598 Dom Pedro II St. Zona 01, Cianorte, PR 87200-055, Brazil
3 Ponta Grossa Campus, Post-Graduate Program in Industrial Engineering, Department of Industrial Engineering, Sustainable Production Systems Laboratory (LESP), Universidade Tecnológica Federal do Paraná (UTFPR), 330 Doutor Washington Subtil Chueire St. Jardim Carvalho, Ponta Grossa, PR 84017-220, Brazil; salvador.rodrigors@gmail.com (R.S.); acfrancisco@gmail.com (A.C.d.F.)
* Correspondence: smbdamasceno@uem.br; Tel.: +55-44-99905-7766

Received: 10 March 2020; Accepted: 25 March 2020; Published: 16 April 2020

Abstract: Brazilian silk production is amongst the five largest in the world. Nonetheless, there is no life cycle assessment study on silk cocoon production and its upstream processes, pertaining to the mulberry production (fundamental upstream process for silk production), in the existing literature. The objective of this study was to identify opportunities to improve the environmental profile of mulberry and silk cocoon production under Brazilian conditions. To that end, a life cycle assessment was conducted for the core processes of mulberry and silk cocoon production and upstream processes of raw material production, using the ReCiPe method for life cycle impact assessment using nine impact categories. Overall, the mulberry production showed greater impacts than the cocoon production for the impact categories analyzed. A few opportunities for improving the environmental profile of mulberry and silk cocoon production under Brazilian conditions included replacing the Kraft paper used to cover the rearing beds, replacing the standard tractor used to fetch mulberry leaves, replacing light bulbs, conducting a more sustainable mulberry and cocoon production, and setting a reverse logistics system for plastic and paper packaging waste. Nevertheless, many of these measures are long-term strategies. Besides, many of them need further economic feasibility assessment.

Keywords: silk cocoon; life cycle assessment; Brazilian silk; mulberry production; life cycle inventory; LCA; LCI; environmental impact

1. Introduction

In the Western world, Brazil is the largest silk cocoon producer on a commercial scale [1]. Brazilian silk production is the fifth largest in the world. The world leaders in silk production are China at 146,000 t/y, India at 28,708 t/y, Uzbekistan at 1100 t/y, Thailand at 692 t/y, and Brazil at 560 t/y [2]. In the first half of 2019, Brazil exported around 108 million tons of textiles and apparel (excluding cotton fiber), and almost 689 million tons when including cotton fiber. Considering Brazilian exports of textile and apparel products, textile fibers and yarns total 622.603 million tons (cotton fiber included). Considering only natural textile fibers and yarns, the result is 616.745 million tons (cotton fiber included) [3,4].

Cotton is the most commonly recognized fiber, when considering natural fibers, as it is predominant in the context of textile production in Brazil and worldwide. However, silk has been gaining prominence among natural fibers, not only for the Brazilian export agenda but also for generating income to small farmers. The export of textile fiber and silk yarn from Brazil in the first half of 2019 was 311 thousand tons [3,4].

The expected production of silk cocoons was three thousand tons in the 2018/2019 harvest, and the silk yarn production was projected at 507 tons for 2019. Moreover, 80% of that total comprises high-quality yarns, from which 94% are destined for exports. This results in a 2% increase in revenue from shipments of silk yarn, even costing 15%-20% more than its main competitor, China [5].

In Brazil, the north and northwest regions of Paraná constitute the main silk production center, contributing to income generation and encouraging the settlement of workers in rural areas [1]. Paraná is responsible for 84% of the Brazilian silk production, seeking to meet the worldwide silk demand. A quality production makes Brazil competitive to other silk producer countries, such as China. The strengthening of sericulture can be seen in the change of producers' profile, and the technological innovation that is being introduced to the silk production, where new producers see these technological innovations as opportunities for expansion and profitability [6].

Paraná's sericulture is represented by about 1867 small producers in 161 municipalities, occupying an area of 3.78 thousand hectares that resulted in a production of 2.47 tons of green cocoons, and generated about US$ 16 million in revenues from the export of silk yarn and silk fibers in the first half of 2019 [4,6].

Some of the biggest buyers of Brazilian silk yarn are countries like France, Italy, Switzerland, and Japan. Brazilian silk production is concentrated mainly in the state of Paraná, specifically in the north and northwest regions of the state. Efforts have been made for silk production to maintain its position. Economic factors, such as sericulturists' aging and the exodus of the young to cities, have stimulated the sector to change, initiating its modernization to attract young workers who seek good income and contribute to the technological development [7]. In Brazil, sericulture has been an important source of income for small rural producers and has helped encourage families to settle in rural areas [8]. It is an activity that can advance satisfactorily within the agroindustry, and it is likely to develop the rural economy of a country [9].

As a way to overcome labor force scarcity, the mechanization of the harvesting of mulberry leaves (which is the only food for the silkworm) adds to the technological changes related to new climate conditions, as with lower rain occurrence throughout the year, it provides the possibility of irrigating the mulberry fields in the state of Paraná, which was unlikely up until not long ago [7].

The key element that maintains the activity is a high-quality production, since Brazilian producers have control over the entire production process, from the supply of larvae to rural producers to the processing of silk cocoons, besides the integrated system with silkworm breeders [6]. That does not seem to be the case in Asian countries, where small or micro-producers are independent, which might result in a lack of uniformity, not meeting the quality standards required by a global market [8]. In the case of Brazil, defective cocoons are discarded or used in the production of lower quality or unique fabrics, which are incorporated into fashion by fashion designers, which is the case of the Brazilian company "O Casulo Feliz" (The Happy Cocoon) [8]. The silk yarn production in Brazil focuses on exports, which brings great opportunities to the internal market. The modernization of the sericulture has increased the income of producers' families, where climate, care with soil, and the genetic improvement of silkworms influence the quality of cocoons produced in Brazil [10].

Silk is known as a high-cost raw material. It is a non-synthetic, renewable, and biodegradable fiber. Great value is given to its characteristics of good trim, lightness, gloss, strength, and softness. It also has a neutral pH, high absorption capacity, elasticity, and anti-static properties. In fact, the silk fabric is very comfortable, being used for clothing in blouses, dresses, shirts, shawls, ties, gloves, for decorating curtains, cushions, and upholstery. Silk is also used in the electronic, aeronautical, and medical industries. Nonetheless, the representativeness of silk within the textile fibers is still small, accounting for only 0.2% [9,10].

In the context of sustainability, concerns with the use of materials, and management of processes and products have encouraged researchers, producers, and textile manufacturers to seek sustainable and biodegradable fibers as a more effective alternative in order to reduce environmental impacts. Environmental impacts are the effects caused to the environment, due to the material and energy exchanges between the biosphere (natural environment) and the technosphere (technical/technological environment). Silk has been tested as a new biomaterial, presenting excellent mechanical properties, biodegradability, compatibility, and particularities of cellular interaction, with technical applications in filters (of different sorts), membranes, paper, textiles, leather, in the field of biosensors, and in the medical and biomedical sectors [9].

Silk has presented a promising future and may prove to be revolutionary in the coming decades. Although traditionally produced for textile products, new approaches have increased silk use in several areas such as nutrition, cosmetics, biomaterials, pharmaceuticals, bioengineering, biomedical, automobile manufacturing, home building, crafts, and arts. Global demand is growing, and along with it, increased stakeholder awareness, entrepreneurial experience sharing, and consumer accessibility are needed [11]. In this context, Rana et al. reported the textile industry to be one of the main contributors to GHG emissions in the world and the highest quantity of GHG emissions per unit of material [12]. Environmental impacts of silk production have been increasing customer awareness and regulation pressure [13], and sericulture is said to cause small environmental impacts due to the small area necessary for cultivating the mulberry trees and the installation of barns/sheds [14]. Nevertheless, Vollrath et al. also argue that even though silks are thought of as sustainable materials, these should be no exception to a thorough assessment of their ecological concerns [13]. Nonetheless, studies analyzing the direct or indirect environmental impacts of silk production are scarce in Brazil and in the world. To the Brazilian silk, especially, little or no attention has been paid thus far. Only a few issues seem to have been raised on the GHG emissions of Brazilian silk production (see [1]), while more extensive studies have been carried out for the Indian silk [13,15]. In this context, life cycle assessment (LCA) is a tool used to quantify environmental impacts, assisting in decision making for process improvements [15].

Vollrath et al. claim that, in most cases, studies on the environmental impacts of manmade fibers and natural fibers use the LCA methodological framework [13]. Among the many possible approaches to assess environmental impacts of processes and organizations, LCA seems the most promising one, since it can help minimize the environmental impacts of a given system [16], and many companies and governments view LCA as a valuable means to measure, communicate, and thus, improve product sustainability [17]. Since its rise in the 1980s, LCA has been increasingly becoming a strategic [18], solid [19], and versatile [20] tool. To Löfgren, Tillman and Rinde LCA is the most important tool for environmental management [21], whereas Bocken and Allwood conclude that LCA is the most complex but also the most complete tool for environmental assessment [22]. Other methods for environmental assessment might not be as data, time, and resource-intensive. Nonetheless, they do not provide as complete results as an LCA.

LCA is a process for assessing the environmental impacts associated with a product, service, process, or activity. Based on the identification and quantification of materials and energy used in the production processes and the emissions to the environment, it provides information that enables the assessment and implementation of measures to improve the environmental performance of the system under study [23]. One of the main goals of an LCA is to enable informed decision-making [24]. An LCA study can take into account all phases of the product life cycle, from natural resource extraction to the manufacturing process, transportation and distribution, reuse, maintenance, recycling and final disposal [25] ("cradle to grave" approach) [24].

An LCA comprises four steps [24], which are (i) objective and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment, and (iv) interpretation. In (i), the objective of the study, as well as the boundaries and the characteristics of the system under study, are identified. In (ii), all inputs (materials and energy) and outputs (finals products, coproducts, byproducts, and emissions) of all processes within said system are accounted for. In (iii), qualitative and quantitative analyses of all environmental impacts are conducted, aided by software tools and life cycle impact assessment methods. In (iv), all data and information from the previous phases are taken into consideration to enable informed decision-making, identifying where the main impacts of the system are (hotspots), and establishing a plan towards improving the system's environmental profile. It can be noted that those phases are iterative and changes in one might trigger changes in others. Moreover, phases (i), (ii), and (iii) are directly linked to interpretation (iv), and, as highlighted in the ISO 14040 [24], an LCA study shows potential impacts, thus those might not be absolute or precise. The interpretation needs to be conducted according to the intricacies of the system under study.

A couple of LCA studies on silk production could be found in the existing literature. Edlund et al. [26] addressed the environmental impacts of synthetic spider silk production from Escherichia coli, where the authors identified the global warming potential (GWP) in terms of greenhouse gases (GHGs) of the baseline *E. coli* process. Astudillo et al. [15] conducted an LCA of Indian silk, where the authors assessed the mulberry production, silkworm rearing, cocoon drying, and cocoon cooking-reeling. The authors identified the mulberry production to be the main environmental hotspot for silk production.

Nonetheless, to the best of our knowledge, to date, no studies have been identified on the life cycle assessment of Brazilian silk production. Based on the aforementioned, the research question that motivated this study was "how to optimize the environmental performance of mulberry and silk cocoon production under Brazilian conditions?" To that end, this study's aim was to identify opportunities to improve the environmental profile of mulberry and silk cocoon production under Brazilian conditions.

This article is structured as follows. The first section provided the initial considerations on the need for investigating the environmental profile of silk production in Brazil and stated the objective of the article. Section 2 presents the methods used in this study. Section 3 depicts the results for the life cycle impact assessment of the mulberry and silk cocoon production. Section 4 presents opportunities for improving the environmental profile of silk cocoon production. Lastly, Section 5 draws on the conclusions, limitations, and suggestions for further and future research.

2. Methods

The LCA methodology, as described in the ISO standards for Life Cycle Assessment [24,27], and the LCA software Umberto NXT Universal were used to conduct this study. A cradle-to-gate (C2G) approach was used to define the boundaries of the system here addressed. The analysis was not restricted to the core processes (mulberry and cocoon production), including also all upstream processes (production of raw materials). Figure 1 illustrates the system boundaries and material flows for the system. Data gathering was mostly done in collaboration with actors of the supply chain.

The system is considered C2G since it embeds the production of raw materials (upstream processes), and mulberry and cocoon production (core processes), up to cocoon delivery at the gate of the silk yarn manufacturing company. Primary sources provided all input data for the core processes. Ecoinvent 3.3 life cycle inventory (LCI) datasets were used for modeling the upstream processes, hence, information about the production of raw materials was secondary. The detailed inventory can be seen in Appendix A (Tables A1 and A2).

The analyses were conducted with the ReCiPe Midpoint (H) [28], using a midpoint approach for nine impact categories. The ReCiPe method [29] is one of the most complete life cycle impact assessment methods in terms of a number of impact categories, and it received an update in 2016 [30]. Moreover, the method enables a harmonized implementation of cause-effect paths for calculating both midpoint and endpoint characterization factors, and its update provided characterization factors that are representative at a global scale, whilst still maintaining the possibility of impact categories to implement characterization factors at a country scale [31]. The impact categories analyzed in the analysis of this study were: Freshwater Ecotoxicity (FETP), Human Toxicity (HTP), Terrestrial Ecotoxicity (TETP), Climate Change (GWP), Freshwater Eutrophication (FEP), Agricultural Land

Occupation (ALOP), Water Depletion (WDP), Terrestrial Acidification (TAP), and Natural Land Transformation (NLTP). The Ecoinvent v.3.3 database and the cut-off system were used for modeling the system [32]. Furthermore, the considered system does not generate any co-products up to the point of cocoon production. Therefore, allocation procedures were not necessary.

The reference flow for the present study was on a mass basis (1 kg of silk cocoon, including packaging). The functional unit for the study was 1 kg of silk cocoon (including packaging) delivered to the silk yarn manufacturing company.

Given that most of the processes could not be designed with information for Brazilian conditions, due to the lack of such in the LCI (Ecoinvent v.3.3) database [33], there is some uncertainty undergoing the presented system, since the reference used may not truly represent the local reality.

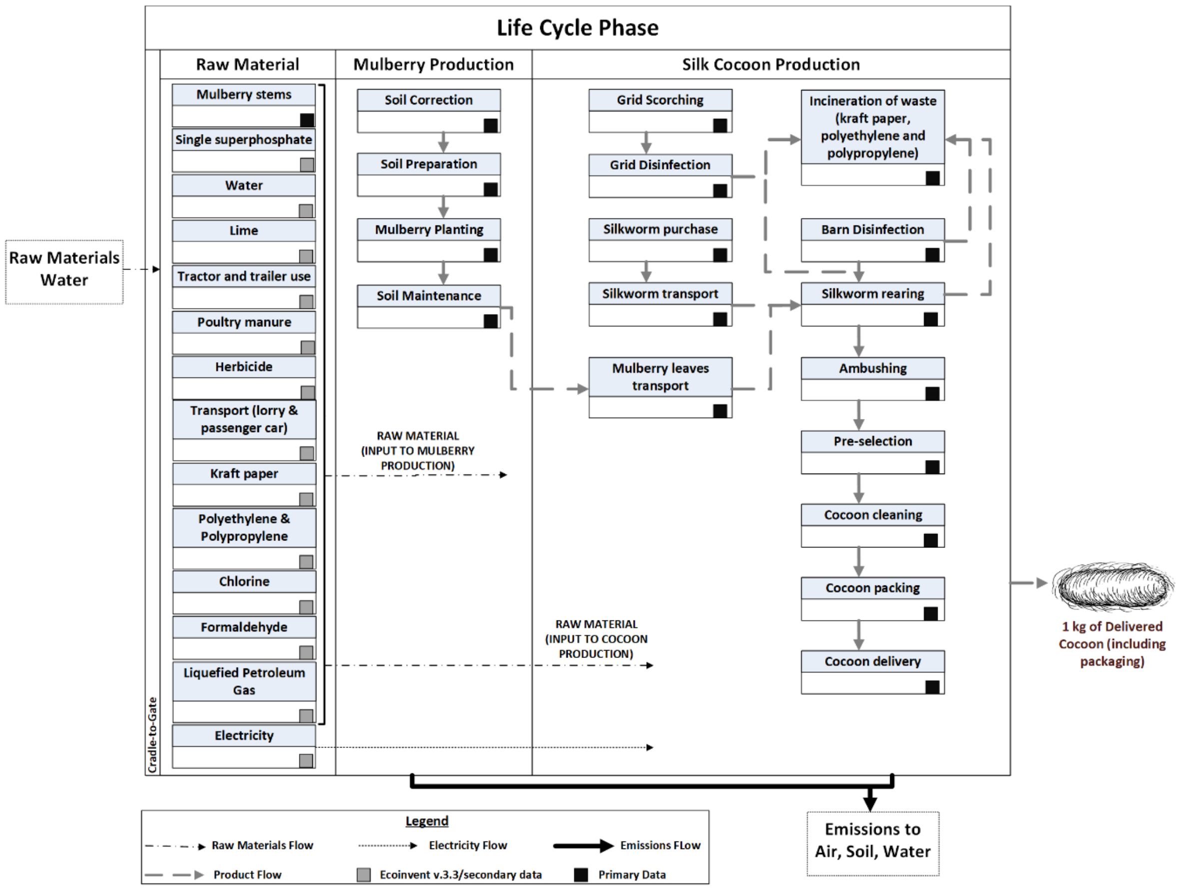

Figure 1. Life cycle boundaries.

2.1. Data Quality

The data quality objective for this study was to use the data that most accurately represented the processes (production of the silk cocoon) under Brazilian conditions.

- Reliability: Data for core processes (mulberry and cocoon production) were gathered together with the silk cocoon producers;
- Completeness: Data from all processes were considered for a period of a year (2018–2019 production), evening out normal eventual fluctuations;
- Temporal correlation: All data gathered were related to 2018-2019 production.
- Geographical correlation: All inventory data for core processes (mulberry and cocoon production) were from the area under study, representing the local reality. The inventory data for upstream processes (production of raw material) were from Ecoinvent v.3.3;

- Technological correlation: Data came from primary sources, directly acquired from the organizations involved in the study, via interviews, surveys, and meetings with internal and external stakeholders.

2.2. Assumptions and Limitations

As allocation method, for the upstream processes (production of raw materials) we used the cut-off, thus, all impacts were attributed to the process that generated it, not penalizing other entries [34]. Moreover, the geography Rest of the World (RoW) was given priority when modeling the processes that used secondary data, since inventories under Brazilian conditions are scarce. The choice was based on the fact that RoW is an exact copy of the Global geography, but with uncertainty adjustment [35]. Moreover, we used the process type Result for each process designed with secondary data, for it considers the aggregated environmental exchanges and the impacts of the product system related to a specific product of a specific activity [32].

Except for transportation, infrastructure processes (facilities, equipment necessary for production activities, both for mulberry and cocoon production) were not included within the system boundaries, thus their impacts were not accounted for.

3. Results

Overall, the mulberry production presented higher impacts than cocoon production, as it can be seen in Figure 2.

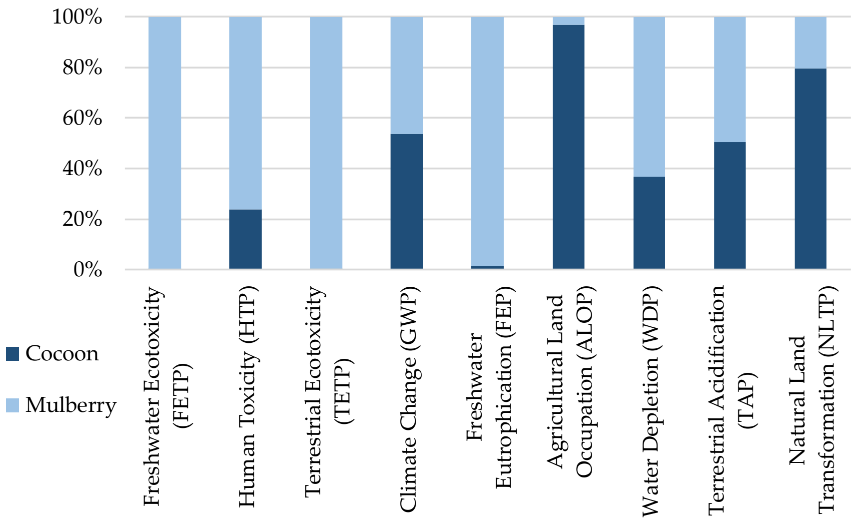

Figure 2. Overall impact—mulberry vs. cocoon production.

For most of the impact categories, mulberry production represented the greatest impacts, which is quantitatively shown in Table 1.

Table 1. Impacts of mulberry and cocoon production per category.

Impact Category	Cocoon Production	Mulberry Production	Unit
Freshwater Ecotoxicity (FETP)	0.06634242	42.4201456	kg 1,4-DCB-Eq
Human Toxicity (HTP)	1.84418266	5.86542442	kg 1,4-DCB-Eq
Terrestrial Ecotoxicity (TETP)	0.00252807	0.66828710	kg 1,4-DCB-Eq
Climate Change (GWP)	0.24426012	0.21049633	kg CO_2-Eq
Freshwater Eutrophication (FEP)	0.00525119	0.38386647	kg P-Eq
Agricultural Land Occupation (ALOP)	0.37053544	0.01178299	m^2a
Water Depletion (WDP)	0.00774722	0.01335418	m^3
Terrestrial Acidification (TAP)	0.00125469	0.00123549	kg SO_2-Eq
Natural Land Transformation (NLTP)	0.00007966	0.00002053	m^2

Figure 3 shows the detailed analysis of impacts (by process) for mulberry production. The processes highlighted in bold blue font were the main contributors to environmental impacts.

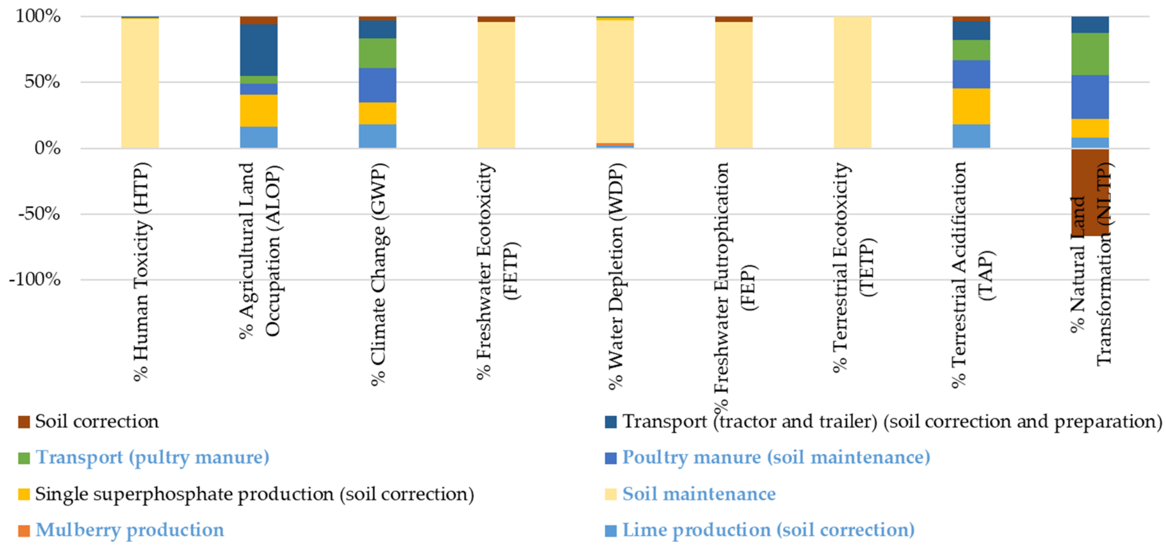

Figure 3. Impact assessment—mulberry production.

For Freshwater Ecotoxicity and Freshwater Eutrophication, the hotspots were in the processes of soil correction and maintenance, due to the use of phosphorus and the production of single superphosphate, which has emissions of metal to water, such as copper, nickel, manganese, and zinc.

For Human Toxicity, the hotspot was also in the soil maintenance, due to the single superphosphate production (emissions of manganese, arsenic, mercury, selenium, and lead), and the use of organic fertilizer, once again due to the emission of metals such as manganese, molybdenum, arsenium, and zinc to water and/or soil, and antimony, lead, and mercury to air.

For Natural Land Transformation, the greatest impact was due to the limestone residue remaining on the soil, which has a beneficial impact, in the process of soil correction. The negative impacts were due to the transformation of natural land due to poultry farming and the consequent production of organic fertilizer (poultry manure), and the production of single superphosphate for soil correction.

For Terrestrial Acidification, the hotspots were in the single superphosphate production, due to the emission of SO_x and NO_x, in the limestone production due to the emission of SO_x, NO_x, and ammonia, in the transport of organic fertilizer and the use of the tractor for the soil preparation, also due to the emission of SO_x and NO_x.

For the Terrestrial Ecotoxicity category, the hotspots were in the soil maintenance, due to the emissions of phosphorus to water and soil, in the transport of the organic fertilizer, due to the emission of metals (e.g., antimony, lead, and zinc to air, and zinc to soil), and in the production of organic fertilizer due to the emission of antimony, copper, and zinc to air, and zinc to soil.

For Water Depletion, the hotspots were in the soil maintenance and the mulberry cultivation, due to the consumption of water, and in the production of limestone and single superphosphate, for the amount of water used in their production.

While for the mulberry production the hotspots were identified in the impact categories Freshwater Ecotoxicity, Freshwater Eutrophication, Human Toxicity, Natural Land Transformation, Terrestrial Acidification, and Water Depletion. For the cocoon production, the hotspots were identified in the categories Agricultural Land Occupation, Climate Change, Human Toxicity, Natural Land Transformation, Terrestrial Acidification, Terrestrial Ecotoxicity, and Water Depletion.

Figure 4 shows the detailed analysis of impacts (by process) for cocoon production. The processes highlighted in bold blue font were the main contributors to environmental impacts.

For Agricultural Land Occupation, the hotspots were in the production of Kraft paper, used for covering the silkworms during the feeding/rearing process, and in the electricity consumption.

For Climate Change, the hotspots were in the transport of mulberry leaves to feed the silkworms, due to the emission of CO_2 and CH_4 to air, in the production of the Kraft paper used for covering the silkworms during the feeding/rearing process, once again due to emission of CO_2 and CH_4, added to the emission of dinitrogen monoxide (N_2O), and in the electricity production, due to the emission of CO_2, N_2O, and CH_4.

For Human Toxicity, the greatest hotspot was in the barn disinfection, due to the use of chlorine, which emissions go to air, water, and soil, and the grid disinfection, due to the use of formaldehyde, which is largely emitted to air.

For Natural Land Transformation, hotspots could be seen in the use of electricity, due to the transformation of the natural land necessary for obtaining the Brazilian electricity mix; the transport of mulberry leaves to feed the silkworms, and the production of Kraft paper, used for covering the silkworms during feeding/rearing.

For Terrestrial Acidification, the greatest hotspot was given to the transport of mulberry leaves to feed the silkworms, due to the emission of NO_x and SO_x to air, and the production of Kraft paper, due to the emission of SO_x, NO_x, and ammonia to air.

For Terrestrial Ecotoxicity, the greatest hotspot is in the barn disinfection, due to the use of chlorine, and its emissions to air, water and soil, followed by the grid disinfection, due to the use of formaldehyde, and its emissions to air, and the Kraft paper production, due to the emission of cypermethrin (pesticide used in tree farming).

For Water Depletion, the greatest hotspot was in the silkworm feeding/rearing, and in the barn and grid disinfection, due to the consumption of ground well water.

Identifying the hotspots within the mulberry and cocoon production was extremely important for enabling finding potential improvements for the silk cocoon production under Brazilian conditions. The next section discusses a few implications of the impacts here identified and discusses a series of suggestions to improve the environmental profile of the silk cocoon production in Brazil.

The recommendations presented in the next section comprise the potential actions the producers are able to undertake. Further suggestions were considered by the authors. Nevertheless, the producers largely rely on the yarn manufacturing company for their subsistence, and the company provides them with guidelines for both the mulberry and cocoon production. From a practical perspective, producers will only take actions towards better environmental performance if such actions (i) comply with the yarn manufacturing company's policy, and (ii) it brings them economic gains.

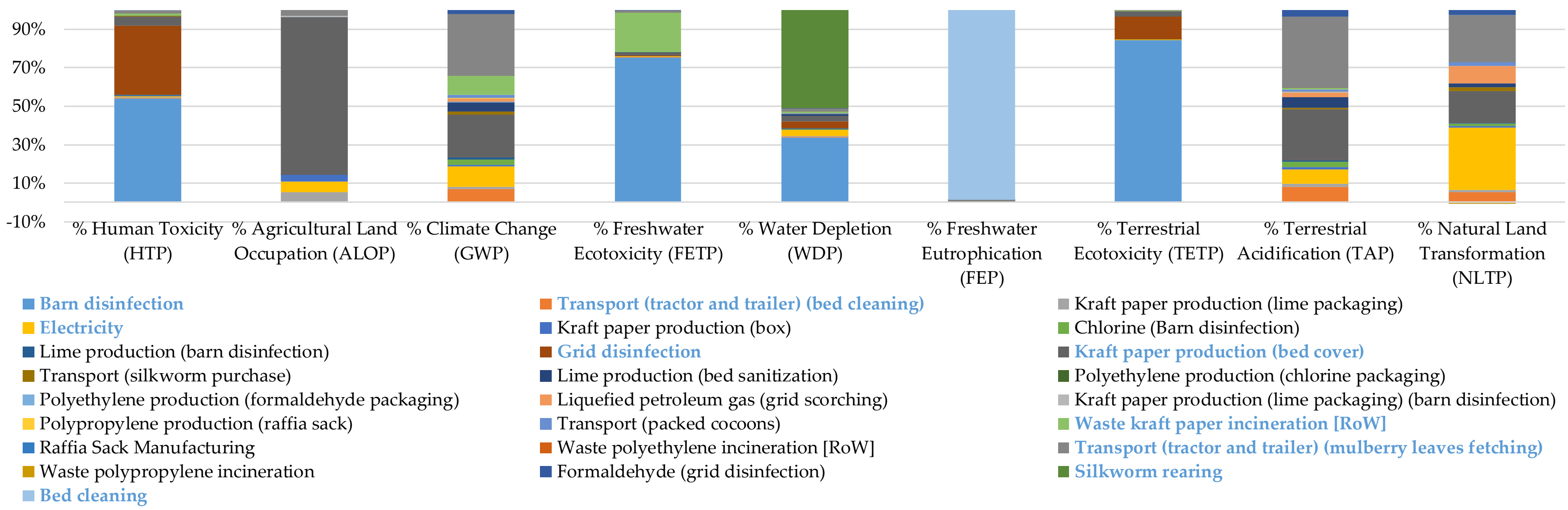

Figure 4. Impact assessment—cocoon production.

4. Discussions and Suggestions for Improving the Environmental Profile of Silk Cocoon Production in Brazil

From the results of the impact assessment, a series of suggestions aiming to improve the environmental profile of cocoon production were made. Initially, two suggestions were identified as easier to be implemented by the producers, which are presented in Scenario 1 and Scenario 2. The impacts presented in Section 3 refer to the existing practices for the presented system, thus referred to as "reference scenario".

4.1. Impact Reduction on the Cocoon Packaging

Traditionally, the cocoon producers (from the studied region) use raffia sacks to pack the cocoon for sale. Seeking a substitute for the raffia sacks, two scenarios were designed for further impact assessment.

Scenario 1. *Substitution of raffia sacks with jute sacks.*

Table 2 shows the impacts of the substitution of raffia sacks for jute sacks. A great increase of impacts in eight of the nine categories analyzed can be observed. Therefore, this option was discarded. Impacts only decreased for the category of Freshwater Ecotoxicity. Even though jute is a natural fiber, its production requires greater amounts of resources than for the raffia.

Table 2. Jute package replacing raffia package.

Category	Scenario		Impact Increase
	Reference	Scenario 1	
Agricultural Land Occupation (ALOP)	0.00001663	0.00231756	13835%
Climate Change (GWP)	0.00107066	0.00484011	352%
Freshwater Ecotoxicity (FETP)	0.00009373	0.00007937	−15%
Freshwater Eutrophication (FEP)	0.00000021	0.00000288	1285%
Human Toxicity (HTP)	0.00025955	0.00180865	597%
Natural Land Transformation (NLTP)	0.00000004	0.00000096	2512%
Terrestrial Acidification (TAP)	0.00000328	0.00003750	1045%
Terrestrial Ecotoxicity (TETP)	0.00000004	0.00000165	4031%
Water Depletion (WDP)	0.00000202	0.00024693	12114%

Scenario 1 assessed only the packaging system, considering in the reference scenario the production of polypropylene, the manufacturing of the raffia sacks, and its incineration at the end-of-life phase, in comparison to the equivalent for jute production in Scenario 1.

Scenario 2. *Substitution of raffia sacks with cotton sacks.*

Table 3, in turn, shows the impacts of the substitution of the raffia sacks with cotton ones. Once again, impacts worsened. As observed in Scenario 1, even though cotton is also a natural fiber, its production requires greater amounts of resources than those of the raffia. Therefore, this option was also discarded.

An alternative strategy to reduce the impacts related to packaging, considering the packaging for the transport of the cocoon up to the delivery point, would be to ban the use of raffia sacks and instead use the plastic boxes that are already used by the yarn manufacturer to transport the cocoons from that cocoon delivery point to the yarn manufacturing site. Those boxes can be reused for a long period of time, and they could be distributed to the producers by the yarn manufacturing company since the boxes return to the company at every rearing cycle. This practice would potentially influence impact reduction on all the impact categories analyzed. Nonetheless, adopting such practice would need oversight and assessment in order to measure its effectiveness for impact reduction.

Table 3. Cotton package replacing raffia package.

Category	Scenario		Impact Increase
	Reference	Scenario 2	
Agricultural Land Occupation (ALOP)	0.00001663	0.00278472	16645%
Climate Change (GWP)	0.00107066	0.00691869	546%
Freshwater Ecotoxicity (FETP)	0.00009373	0.00019364	107%
Freshwater Eutrophication (FEP)	0.00000021	0.00000313	1402%
Human Toxicity (HTP)	0.00025955	0.00256861	890%
Natural Land Transformation (NLTP)	0.00000004	0.00000085	2221%
Terrestrial Acidification (TAP)	0.00000328	0.00003326	915%
Terrestrial Ecotoxicity (TETP)	0.00000004	0.00006422	160515%
Water Depletion (WDP)	0.00000202	0.00061051	30098%

4.2. Reduction of the Impacts of Energy Consumption

Scenarios 1 and 2. *Replacing Incandescent Light Bulbs in the Barn with LED Ones.*

The producers in the studied region (and likely in the country), use incandescent light bulbs in their facilities, mostly because they have lower prices. Using LED light bulbs can save up to 95% energy. Considering this reduction (95%) in the energy consumption for lighting, it can be noted that 83.61% of impacts derived from energy consumption can be avoided in all impact categories, as shown in Table 4.

Table 4. Impacts of energy consumption.

Category	Scenario		Impacts Avoided
	Reference	Scenarios 1 and 2	
Agricultural Land Occupation (ALOP)	0.02009324	0.00329327	83.61%
Climate Change (GWP)	0.02598956	0.00425967	83.61%
Freshwater Ecotoxicity (FETP)	0.00015244	0.00002498	83.61%
Freshwater Eutrophication (FEP)	0.00000699	0.00000115	83.61%
Human Toxicity (HTP)	0.01046132	0.00171460	83.61%
Natural Land Transformation (NLTP)	0.00002609	0.00000428	83.61%
Terrestrial Acidification (TAP)	0.00009599	0.00001573	83.61%
Terrestrial Ecotoxicity (TETP)	0.00000388	0.00000064	83.61%
Water Depletion (WDP)	0.00025688	0.00004210	83.61%

As the same percentage of energy consumption was applied to both Scenarios 1 and 2, the same impacts of energy consumption were avoided. The substitution of the type of light bulbs is a simple practice. However, the reduction of impacts has significant representativeness, reflecting directly in the impact categories of Climate Change, Agricultural Land Occupation, and Natural Land Transformation.

A series of other suggestions are made hereafter. However, these could not be simulated using scenarios, since the inventories that would be necessary to test them accordingly either (i) were not found available in the database the researchers had access to, or (ii) do not exist yet.

4.3. Reduction of the Impacts from the Use of Kraft Paper

The Kraft paper is commonly used by producers (in the studied region) to cover the silkworms on the rearing beds, in order to maintain a stable temperature. Nevertheless, due to the great impact generated from the Kraft paper production, an alternative for a possible reduction of this impact would be substituting the Kraft paper for another type of paper and/or material. The possibilities would be newsprint, nonwoven fabric (TNT), or even a lightweight fabric with good breathability, in the latter, case reuse would also be possible. In this case, it is necessary to follow up on the use of these alternate materials and assess future impacts. The substitution of the Kraft paper could result in a significant impact reduction for the categories of Agricultural Land Occupation, Climate Change, Natural Land Transformation, Terrestrial Acidification, and Terrestrial Ecotoxicity.

4.4. Reduction of the Impacts from the Use of a Standard Tractor

(a) Replacing the diesel-driven tractor with a biogas-driven one

If the tractor used in the property were replaced with a biogas-driven one, the producer could use the silkworm litter from the rearing bed (which is currently just laid on the mulberry field, which practice has been reported to be of lesser efficiency compared to alternate handling (see Section 4.5, item b) to produce biogas and organic fertilizer (from the digestate) (see Salvador et al. [20]) that could be then still laid on the mulberry field. The biogas could be used to power the tractor, reducing/eliminating the need for diesel and consequently reducing its related impacts.

Furthermore, the economic feasibility of setting up a biodigester for such an end needs to be assessed. Nevertheless, as in the region where the study was conducted the properties are close to one another, it is worth exploring the possibility of arranging condominiums for energy recovery, where the producers could transport the rearing bed remains (silkworm litter + mulberry stems and uneaten leaves + lime residue) to a central and, from there, produce and distribute biogas and organic fertilizer.

(b) Replacing the standard tractor with a horse cart

One of the main impacts was due to the transport of mulberry leaves to feed the silkworms, and it is currently done with a standard tractor. One of the options to try to lessen the environmental impacts of this process is to use a horse cart instead of the standard tractor. Other producers in the region make use of such practice. However, currently, this is largely due to financial constraints rather than the choice of being more environmentally friendly.

(c) Replacing the standard tractor with a micro tractor

Considering the impacts of the transport of mulberry leaves from the field to the barn, one can choose to use a different tractor, in this case, a micro tractor, whose use is indicated for several soil types, including sandy and clay soil, ideal for sites of small territorial extension. This tractor has a much lower fuel consumption than the conventional tractor [36,37]. However, further assessment is needed to make sure how much this change would reduce impacts.

The alternatives above mentioned can result in significant impact reduction for the categories of Terrestrial Acidification, Climate Change, Natural Land Transformation, and Terrestrial Acidification.

4.5. Reduction of the Impacts from Both Mulberry and Silk Cocoon Production by a More Sustainable Production

(a) Organic agriculture to reduce the impacts of chemical fertilizer and herbicide

Chemical-based inputs are mostly used because of short term response and economic factors. However, chemical waste (from fertilizers, insecticides, herbicides, fungicides) can cause damage to silkworms, as mulberry leaves are the silkworm's only food. The promotion of biological or organic agriculture is necessary in order to reduce the impacts of mulberry production. Organic manure is another solution for reducing the impacts of chemical fertilizer use since physical, chemical, and biological properties of soil health are enhanced [38].

In this case, the use of biofertilizers replaces the use of pesticides in the cultivation of mulberry trees. The biofertilizer is composed of living microorganisms that assist the development, supply, and availability of primary nutrients to the plant [39].

(b) Optimizing the use of mulberry leaves waste during cutting, and the remains of the rearing beds (mulberry stems and dry leaves, and silkworm litter)

On average, 30.35% is wasted during the harvest of mulberry leaves, this green mass could be better utilized by means of improved management and planning of sericulture activities. There are also the remains of the silkworm rearing bed, with a large volume of available organic matter that can best be harnessed through strategies and/or processes considering its nutrient richness [40].

Aerobic decomposition is an opportunity to optimize the use of this material, with advantages such as faster activity of organisms and absence of unpleasant odors, it does not generate slurry and does not lose nitrogen. Another intention with composting is to reduce the C:N ratio. The result of this process is a replacement for poultry manure (organic fertilizer with considerable impact on the mulberry production). Composting aids the production of healthy plants, decreases the need for chemical fertilizers while conserving natural resources and also brings economic and social benefits. In addition, it improves the chemical, physical and biological properties of the soil, promoting root development, with higher yield and quality in cultivation [39,41].

Another alternative is vermicomposting, which involves a collective activity of earthworms and microorganisms. In addition to being rich in nutrients, enzymes, antibiotics, plant growth hormones, and large beneficial microbial populations that enhance the quality and yield of mulberry leaves, which, in turn, increases silk productivity. The product resulting from vermicomposting is rich in all the nutrients the plant needs. The use of vermicomposting also enhances a 50% reduction in the use of chemical fertilizers [38,42].

The use of green fertilizer is also a practice that adds non-compound green plant tissue to the soil in order to improve its physical structure and fertility. Green fertilizer can replace organic manure, being distributed between the mulberry rows, as it provides "additional nitrogen because of its ability to fix nitrogen from the air with the help of its root nodule bacteria" [39] (pp. 7–8), on top of preventing the growth of weeds and, consequently, abolishing the cost of getting rid of them [39].

The mentioned practices can result in significant impact reduction for the categories of Freshwater Ecotoxicity, Freshwater Eutrophication, Human Toxicity, Natural Land Transformation, Terrestrial Acidification, Terrestrial Ecotoxicity, and Water Depletion.

4.6. Reduction of the Impacts from Packaging via Reverse Logistics

Reducing the divergent socioeconomic and environmental impacts caused by waste is critical, however, there are several factors involved that make this somewhat difficult, such as social, environmental, and economic issues, including geographical boundaries and links to other sectors [43].

The great quantity and variety of packages used, result in a large number of packages disposed of in landfills, causing those not to return to their production cycle. Returning packages to their steward allows for the manufacture of new products and prevents virgin raw material from being exploited, besides further reducing costs in terms of maintaining landfills and consequently extending resource value [44]. Thus, improved reverse logistics practices could be a way out to elucidate this issue [45].

The plastic packages used for chlorine and formaldehyde, and the paper packages used for lime, could be returned to their manufacturers to be given correct disposal. A reverse logistics system could be designed where these package wastes make their way back to their manufacturer or another party who would hold stewardship. The producers could store these packages and take them to the silk yarn manufacturer (who provides those inputs to them). The silk yarn manufacturer, in turn, could forward such materials to the respective provider, until these wastes get to their primary steward for adequate reuse/disposal.

Implementation and management of packaging via a reverse logistics system can enable impact reduction on the impacts categories of Agricultural Land Occupation, Climate Change, Natural Land Transformation, Terrestrial Acidification, and Terrestrial Ecotoxicity.

5. Conclusions

From the large impact generated by the fiber and textile sector, there is a need to define strategies to reduce the impacts caused. Brazil is one of the largest silk producers in the world, and the demand for Brazilian silk is on the rise, therefore, attention is needed towards the impacts of Brazilian silk production. Hence, the objective of this study was to identify opportunities to improve the environmental profile of mulberry and silk cocoon production under Brazilian conditions. To that end, a life cycle assessment was conducted for the core processes of mulberry and silk cocoon production and upstream processes of raw material production.

Thus, it was possible to identify that the impacts of the mulberry production stood out in comparison to those of the silk cocoon production. Based on the identified impacts, several opportunities were identified towards improving the mulberry and silk production profile under Brazilian conditions. Opportunities for improvement include replacing incandescent light bulbs with LED ones, replacing Kraft paper used to cover the rearing bed, replacing the use of a standard tractor, measures for a more sustainable mulberry and cocoon production, reverse logistics of plastic and paper packaging. Although several opportunities to potentially reduce environmental impacts were identified, appropriate, tailored strategies need to be designed to overcome technical and socioeconomic barriers.

It is noteworthy that the silk yarn production needs to be included in the system boundaries to have a more complete view of the life cycle impacts of the silk production under Brazilian conditions. As of the time of this publication, the authors were trying to build a life cycle inventory of the next downstream phase, the silk yarn production. However, the contact with a company that can provide such information has not granted them this privilege thus far. Moreover, due to lack of collaboration, time, financial resources, and available inventories in the Ecoinvent database that allowed the authors to model the processes, they were unable to quantitatively test the recommendations made in Section 4.2 through Section 4.6.

For future studies, when possible, under Brazilian conditions, it is proposed to conduct a life cycle assessment study that includes the suggestions for improvement made here, in order to verify how much the reported impacts can be reduced. Moreover, research on improving the impacts of these processes not only on the environment, but also on society and the economy can be expected. Furthermore, it is also suggested to include the silk yarn production within the system boundaries for a more comprehensive picture of Brazilian silk production.

Author Contributions: Conceptualization, Methodology, S.M.B.D.B., M.d.G.G., and A.C.d.F.; software, R.S.; validation, formal analysis, investigation, writing—original draft preparation, S.M.B.D.B., R.S.; writing—review and editing, M.d.G.G. and A.C.d.F.; supervision, M.d.G.G., A.C.d.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Coordination of Improvement of Higher Education Personnel (CAPES) and the National Council for Scientific and Technological Development (CNPq).This work is financed by the ERDF through the Operational Program for Competitiveness Factors - COMPETE and national funds by FCT - Foundation for Science and Technology under the POCI-01-0145-FEDER-007136 project.

Acknowledgments: The authors would like to show their gratitude for the support provided by the Universidade Tecnológica Federal do Paraná (UTFPR) (Brazil) and the University of Minho (Portugal).

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

Appendix A. Life Cycle Inventories

Table A1. Mulberry production life cycle inventory.

Process	Input					Output		
	Name	Name Ecoinvent	Database	Quantity	Unit	Name	Quantity	Unit
Soil Correction	Limestone	lime production, milled, loose [RoW]	Ecoinvent 3.3	77.78	kg/box	Corrected Soil	2000.00	m^2/box
	Phosphorus	single superphosphate production [RoW]	Ecoinvent 3.3	1.11	kg/box	Limestone Residue	77.78	kg/box
	Tractor - Soil Correction	tractor production, 4-wheel, agricultural [RoW]	Ecoinvent 3.2	1577.78	kg.km/box	Phosphorus Residue	1.11	kg/box
Soil Preparation	Tractor - Soil Preparation	tractor production, 4-wheel, agricultural [RoW]	Ecoinvent 3.3	3974.22	kg.km/box	Prepared Soil	2000.00	m^2/box
	Corrected Soil	Corrected Soil	created	2000.00	m^2/box			
Mulberry Planting	Water (groundwell)	Water, well in ground [natural resource/in water]	Ecoinvent 3.3	22.00	L/box	Mulberry Seedlings	0.09	kg/box
	Mulberry Stems	Mulberry Stems	created	0.09	kg/box	Water	22.00	L/box
	Prepared Soil	Prepared Soil	created	2000.00	m^2/box			
Soil Maintenance	Herbicide	herbicides, at regional storehouse [RER]	Ecoinvent 3.3	0.40	L/box	Green Mass	1026.18	kg/box
	Water (groundwell)	Water, well in ground [natural resource/in water]	Ecoinvent 3.3	40.00	L/box	Herbicide Residue	0.40	L/box
	Fertilizer (poultry manure)	market for poultry manure, fresh [GLO]	Ecoinvent 3.3	1333.33	kg/box	Water	40.00	L/box
	Fertilizer Transport	transport, freight, lorry >32 metric ton, EURO4	Ecoinvent 3.3	40000.00	kg.km/box	Fertilizer Emissions (table)	1333.33	kg/box
	Rainfall	water, unspecified natural origin [natural resource/in water]	Ecoinvent 3.3	904.00	m^3/box	Rainfall	904.00	m^3/box
	Mulberry Seedlings	Mulberry Seedlings	created	0.09	Kg/box	Green Mass Waste	447.16	kg/box
Mulberry Stems Transport	Mulberry Stems Transport	transport, lorry 3.5-20t, fleet average [CH]	Ecoinvent 3.3	6.53	kg.km/box	Mulberry Stems	0.09	kg/box
	Mulberry Stems	Mulberry Stems	created	0.09	kg/box			

Table A2. Silk cocoon production life cycle inventory.

Process	Input					Output		
	Name	Name Ecoinvent	Database	Quantity	Unit	Name	Quantity	Unit/Box
Barn Disinfection	Water (groundwell)	water, well, in ground [natural resource/in water]	Ecoinvent 3.3	200.0	L/box	Disinfected Barn	1.0	unit/box
	Lime	lime production, milled, loose [RoW]	Ecoinvent 3.3	4.0	kg/box	Kraft Paper Waste	0.0	kg/box
	Chlorine	market for chlorine, liquid [GLO]	Ecoinvent 3.3	0.4	kg/box	Polyethylene Waste	0.0	kg/box
	Kraft Paper (lime packaging)	kraft paper production, unbleached [RoW]	Ecoinvent 3.3	0.0	kg/box	Water (groundwell)	200.0	
	Polyethylene (chlorine packaging)	polyethylene production, high density, granulate [RoW]	Ecoinvent 3.3	0.0	kg/box	Chlorine	0.4	
Grid Scorching	LPG	market for liquefied petroleum gas [RoW]	Ecoinvent 3.3	0.4	kg/box	Scorched Grid	390.0	grid/box
	Grid	Grid	created	390.0	grid/box			
Grid Disinfection	Formaldehyde	market for formaldehyde [GLO]	Ecoinvent 3.3	0.4	L/box	Disinfected Grid	390.0	unit/box
	Water (groundwell)	water, well, in ground [natural resource/in water]	Ecoinvent 3.3	22.2	L/box	Polyethylene Waste	0.0	kg/box
	Polyethylene (formaldehyde packaging)	polyethylene production, high density, granulate [RoW]	Ecoinvent 3.3	0.0	kg/box	Water	22.2	
	Scorched Grid	created	created	390.0	unit/box	Formaldehyde Waste	0.4	
Larvae Purchase	Green Mass	created	created	3.0	kg/box	Box	1.0	unit/box
	Kraft Paper	kraft paper production, unbleached [RoW]	Ecoinvent 3.3	0.1	kg/box			
	Larvae	created	created	0.9	kg/box			
Larvae Transport	Box	Box	created	1.0	unit/box	Box	1.0	unit/box
	Larvae Transport	transport, passenger car, large size, petrol, EURO 5 [RoW]	Ecoinvent 3.3	0.8	km/box			
Silkworm Rearing	Green Mass	Green Mass	created	1026.2	kg/box	Fed Silkworm	1.0	unit/box
	Kraft Paper (bed covering)	kraft paper production, unbleached [RoW]	Ecoinvent 3.3	3.2	kg/box	Kraft Paper Waste (bed cover)	3.2	kg/box
	Box	Box	created	1.0	unit/box	Kraft Paper Waste (lime packaging)	0.2	kg/box
	Water (groundwell)	water, well, in ground [natural resource/in water]	Ecoinvent 3.3	300.0	L/box	Rearing Bed Waste	800.0	kg/box
	Lime	lime production, milled, loose [RoW]	Ecoinvent 3.3	24.0	kg/box			
	Kraft Paper (lime packaging)	kraft paper production, unbleached [RoW]	Ecoinvent 3.3	0.2	kg/box			
	Disinfected Barn	market for transport, tractor and trailer, agricultural [GLO]	Ecoinvent 3.3	1.0	unit/box			
	Tractor (green mass fetching)	market for transport, tractor and trailer, agricultural [GLO]	Ecoinvent 3.3	14777.0	kg.km/box			

Table A2. *Cont.*

Process	Input					Output		
	Name	Name Ecoinvent	Database	Quantity	Unit	Name	Quantity	Unit/Box
Bed Cleaning	Tractor (bed cleaning)	transport, tractor and trailer, agricultural [RoW]	Ecoinvent 3.3	3200.0	kg.km/box	Clean Bed	1.0	unit/box
	Rearing Bed Waste	Rearing Bed Waste	created	800.0	kg/box	Rearing Bed Waste (see Table A4)	800.0	kg/box
Ambushing	Fed Silkworm	Fed Silkworm	created	1.0	unit /box	Silkworm in Grid	76.1	kg/box
	Disinfected Grid	Disinfected Grid	created	390.0				
Pre-selection	Silkworm in Grid	Silkworm in Grid	created	76.1	kg/box	Cocoon (1st)	74.8	kg/box
						Cocoon (2nd)	1.3	kg/box
Cocoon Cleaning	Cocoon (1st)	Cocoon (1st)	created	74.8	kg/box	Cocoon (1st) clean	74.2	kg/box
	Cocoon (2nd)	Cocoon (2nd)	created	1.3	kg/box	Cocoon (2nd) clean	1.3	kg/box
						Unreleeble Silk	0.6	kg/box
Packaging	Cocoon (1st) clean	Cocoon (1st) clean	created	74.2	kg/box	Cocoon (1st) Packed	74.2	kg/box
	Cocoon (2nd) clean	Cocoon (2nd) clean	created	1.3	kg/box	Cocoon (2nd) Packed	1.3	kg/box
	Unreleeble Silk	Unreleeble Silk	created	0.6	kg/box	Unreleeble Silk Packed	0.6	kg/box
	Polypropylene (raffia sack)	polypropylene, granulate	Ecoinvent 3.3	0.0	kg/box	Polypropylene Waste (raffia sack)	0.0	kg/box
	Raffia Sack Manufacturing	extrusion of plastic sheets and thermoforming, inline	Ecoinvent 3.3	0.0	kg/box			
Silk Cocoon Transport	Cocoon (1st) Packed	Cocoon (1st) Packed	created	74.2	kg/box	Delivered Cocoon	76.1	kg/box
	Cocoon (2nd) Packed	Cocoon (2nd) Packed	created	1.3				
	Unreleeble Silk Packed	Unreleeble Silk Packed	created	0.6				
	Packed Cocoon Transport	transport, passenger car, large size, petrol, EURO 5 [RoW]	Ecoinvent 3.3	0.8	km/box			
Electricity	Electricity	market for electricity, high voltage [BR]	Ecoinvent 3.3	10.0	kWh/box			
Incineration	Kraft Paper Waste	waste paper, unsorted	Ecoinvent 3.3	3.5	kg/box	Municipal Solid Waste	3.5	kg/box
	Polyethylene Waste	waste polyethylene	Ecoinvent 3.3	0.0	kg/box	Municipal Solid Waste	0.0	kg/box
	Polypropylene Waste	waste polypropylene	Ecoinvent 3.3	0.0	kg/box	Municipal Solid Waste	0.0	kg/box

Appendix B. Emissions of Organic Fertilizer (Poultry Manure)

Table A3. Organic fertilizer components.

Component	kg/box
Nitrogen	62.67
Phosphorus	28.00
Potassium	58.67
Calcium	21.33
Magnesium	5.33
Sodium	6.67
Copper	0.53
Manganese	0.40
Iron	1.33
Zinc	0.40
Boron	0.01
Sulphur	6.67
Cobalt	0.04
Aluminium	2.67
Molybdenum	0.11
Ashes	258.67
Moisture content	390.67
Organic matter	1074.67

Source: Based on [46]

Table A4. Rearing bed waste components.

Component	kg/box
Nitrogen	6.82400
Phosphorus	1.19200
Potassium	0.10312
Calcium	0.11728
Magnesium	0.04192
Copper	0.00001
Manganese	0.00041
Zinc	0.00007
Borum	0.00015
Organic Matter	765.68692

Source: Based on [40]

References

1. Giacomin, A.M.; Garcia, J.B., Jr.; Zonatti, W.F.; Silva-Santos, M.C.; Laktim, M.C.; Baruque-Ramos, J. Brazilian silk production: Economic and sustainability aspects. *Procedia Eng.* **2017**, *200*, 89–95. [CrossRef]
2. Wee, R.Y. World Leaders in Silk Production. WorldAtlas, 2017. Available online: https://www.worldatlas.com/articles/world-leaders-in-silk-production.html/ (accessed on 15 October 2019).
3. MDIC—Ministry of Industry, Foreign Trade and Services. Brazilian Trade Balance: Year to Date. Export 2019/2018; 2019. Available online: http://www.mdic.gov.br/index.php/comercio-exterior/estatisticas-de-comercio-exterior/balanca-comercial-brasileira-acumulado-do-ano (accessed on 29 August 2019).
4. ABIT—Brazilian Textile and Apparel Industry Association. Trade Balance. 2019. Available online: https://www.abit.org.br/uploads/arquivos/BALAN%C3%87A%20COMERCIAL%20BR%20201907.pdf (accessed on 15 October 2019).
5. Caetano, M. São Paulo Picks up the Thread. 2019. Available online: https://www.valor.com.br/agro/6216861/sao-paulo-retoma-o-fio-da-meada (accessed on 15 October 2019).
6. IAPAR—Agronomic Institute of Paraná. Technological Innovation Changes the Profile of Sericulture. 2017. Available online: http://www.iapar.br/2017/11/2273/Inovacao-tecnologica-muda-o-perfil-da-sericicultura.html (accessed on 15 October 2019).

7. IAPAR—Agronomic Institute of Paraná. Cadeia da Sericicultura Precisa de Inovação Para Crescer ("Sericulture Chain Needs Innovation to Grow"). 2019. Available online: http://www.iapar.br/2019/08/2563/Cadeia-da-sericicultura-precisa-de-inovacao-para-crescer-indica-curso-no-IAPAR-.html (accessed on 30 August 2019).
8. Mega, H.C. Silk Production in Brazil. 2016. Available online: http://www.usp.br/aunantigo/exibir?id=7780 (accessed on 30 August 2019).
9. Babu, K.M. Natural textile fibres: Animal and silk fibres. In *Textiles and Fashion*; Woodhead Publishing: Cambridge, UK, 2015; Available online: http://dx.doi.org/10.1016/B978-1-84569-931-4.00003-9 (accessed on 30 August 2019).
10. Cirio, G.M. Evolução e Condição Atual da Sericicultura no Paraná ("Evolution and Current Condition of Sericulture in Paraná"). In *Inovações na Sericicultura do Paraná: Tecnologias, Manejo Rentabilidade*; Soares Júnior, D., de Almeida, E.L.D., da Silva Pádua, O., Eds.; IAPAR: Londrina, Brazil, 2018. Available online: http://www.emater.pr.gov.br/arquivos/File/Biblioteca_Virtual/RedesReferencia/Livro_Sericicultura2018_2aED.pdf (accessed on 30 August 2019).
11. Badu, K.M. Silk reeling and silk fabric manufacture. In *Silk*, 2nd ed.; Woodhead Publishing: Cambridge, UK, 2019. [CrossRef]
12. Rana, S.; Pichandi, S.; Karunamoorthy, S.; Bhattacharyya, A.; Parveen, S.; Fangueiro, R. Carbon footprint of textile and clothing products. In *Handbook of Sustainable Apparel Production*; Muthu, S.S., Ed.; CRC Press: Boca Raton, FL, USA, 2015; pp. 141–165. Available online: https://www.researchgate.net/publication/276193965_Carbon_Footprint_of_Textile_and_Clothing_Products (accessed on 10 October 2019).
13. Vollrath, F.; Carter, R.; Rajesh, G.K.; Thalwitz, G.; Astudillo, M.F. Life cycle analysis of cumulative energy demand on sericulture in Karnataka, India. In Proceedings of the 6th BACSA International Conference: Building Value Chains in Sericulture, Padua, Italy, 7–12 April 2013; pp. 1–12.
14. Ribeiro, I.; Staduto, J.A.R.; Ribeiro, L.F.C. Panorama da Sericicultura no Estado do Parana ("Panorama of Sericulture in Parana State"). In Proceedings of the II SICAS—II Simpósio de Ciências Aplicadas à Sericicultura, Cascavel, Brazil, 26–27 August 2010.
15. Astudillo, M.F.; Thalwitz, G.; Vollrath, F. Life cycle assessment of Indian silk. *J. Clean. Prod.* **2014**, *81*, 158–167. [CrossRef]
16. Piekarski, C.M.; Puglieri, F.N.; De Carvalho Araújo, C.K.; Barros, M.V.; Salvador, R. LCA and ecodesign teaching via university-industry cooperation. *Int. J. Sustain. High. Educ.* **2019**, *20*, 1061–1079. [CrossRef]
17. Freidberg, S. Calculating sustainability in supply chain capitalism. *Econ. Soc.* **2013**, *42*, 571–596. [CrossRef]
18. Wilhelm, W.B. Incorporating product life cycle impact assessment into business coursework. *Bus. Educ. Innov. J.* **2013**, *5*, 45–52.
19. Huarachi, D.A.R.; Gonçalves, G.; de Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M. Life cycle assessment of traditional and alternative bricks: A review. *Environ. Impact Assess. Rev.* **2020**, *80*, 106335. [CrossRef]
20. Salvador, R.; Barros, M.V.; Do Rosário, J.G.D.P.; Piekarski, C.M.; da Luz, L.M.; de Francisco, A.C. Life cycle assessment of electricity from biogas: A systematic literature review. *Environ. Prog. Sustain.* **2019**, *38*, 1–8. [CrossRef]
21. Löfgren, B.; Tillman, A.M.; Rinde, B. Manufacturing actor's LCA. *J. Clean. Prod.* **2011**, *19*, 2025–2033. [CrossRef]
22. Bocken, N.M.P.; Allwood, J.M. Strategies to reduce the carbon footprint of consumer goods by influencing stakeholders. *J. Clean. Prod.* **2012**, *35*, 118–129. [CrossRef]
23. Barros, M.V.; Salvador, R.; Piekarski, C.M.; de Francisco, A.C. Mapping of main research lines concerning life cycle studies on packaging systems in Brazil and in the world. *Int. J. Life Cycle Assess.* **2019**, *24*, 1429–1443. [CrossRef]
24. ISO. *ISO 14040:2006 Environmental Management—Life Cycle Assessment: Principles and Framework*; International Standardization Organization: Geneva, Switzerland, 2006.
25. Chaabane, A.; Ramudhin, A.; Paquet, M. Design of sustainable supply chains under the emission trading scheme. *Int. J. Prod. Econ.* **2012**, *135*, 37–49. [CrossRef]
26. Edlund, A.M.; Jones, J.; Lewis, R.; Quinn, J.C. Economic feasibility and environmental impact of synthetic spider silk production from escherichia coli. *New Biotechnol.* **2018**, *42*, 12–18. [CrossRef] [PubMed]

27. ISO. *ISO 14040:2006 Environmental Management—Life Cycle Assessment: Requirement and Guidelines*; International Standardization Organization: Geneva, Switzerland, 2006.
28. Huijbregts, M.A.; Steinmann, Z.J.; Elshout, P.M.; Stam, G.; Verones, F.; Vieira, M.; van Zelm, R. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147. [CrossRef]
29. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; De Schryver, A.; Struijs, J.; VanZelm, R. *ReCiPe 2008. A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpointand the Endpoint Level*, 1st ed.; Report I: Characterisation; Ministry of Housing, Spatial Planning and the Environment: The Hague, The Netherlands, 2009.
30. Huijbregts, M.A.J.; Steinmann, Z.J.N.; Elshout, P.M.F.; Stam, G.; Verones, F.; Vieira, M.; Zijp, M.; Hollander, A.; van Zelm, R. *ReCiPe2016. A Harmonized Life Cycle imPact Assessment Method at Midpoint and Endpoint Level Report I: Characterization*; RIVM Report 2016-0104; National Institute for Human Health and the Environment: Bilthoven, The Netherlands, 2016.
31. Dekker, E.; Zijp, M.C.; van de Kamp, M.E.; Temme, E.H.; van Zelm, R. A taste of the new ReCiPe for life cycle assessment: Consequences of the updated impact assessment method on food product LCAs. *Int. J. Life Cycle Assess.* **2019**, 1–10. [CrossRef]
32. Weidema, B.P.; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Wernet, G. *Overview and Methodology: Data Quality Guideline for the Ecoinvent Database Version 3*; Swiss Centre for Life Cycle Inventories: Zurich, Switzerland, 2013.
33. Achachlouei, M.A.; Moberg, Å.; Hochschorner, E. Life Cycle Assessment of a magazine, part I: Tablet edition in emerging and mature states. *J. Ind. Ecol.* **2015**, *19*, 575–589. [CrossRef]
34. Ecoinvent. Allocation Cut-Off by Classification. 2019. Available online: http://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html (accessed on 11 October 2019).
35. Ecoinvent. What do the Shortcuts, Such as CH, RER, RoW and GLO Mean? 2019. Available online: http://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-do-the-shortcuts-such-as-ch-rer-row-and-glo-mean.html (accessed on 11 October 2019).
36. Lacerda, E.G.; Fernandes, C.H.; Simon, C.P.; Peterle, G.; Santos, L.N. Evaluation of Energy Demand and Production Costs of a Tail Tractor as a Function of Soil Tillage Speed. 2014. Available online: http://conbea14.sbea.org.br/2014/anais/R0081-3.pdf (accessed on 15 October 2019).
37. Agritech. TC Series. Affordable Solutions with High Versatility. 2019. Available online: http://www.agritech.ind.br/produtos/trator/serie-tc (accessed on 15 October 2019).
38. Karthik, T.; Rathinamoorthy, R. Sustainable silk production. In *Sustainable Fibres and Textiles*; Woodhead Publishing: Cambridge, UK, 2017.
39. Sakthivel, N.; Ravikumar, J.; Chikkanna; Kirsur, M.V.; Bindroo, B.B.; Sivaprasad, V. *Organic Farming in Mulberry: Recent Breakthrough*; Regional Sericultural Research Station, Central Silk Board, Ministry of Textiles, Government of India: Tamil Nadu, India, 2014; Available online: http://www.csrtimys.res.in/sites/default/files/ebooks/2014-7.pdf (accessed on 11 October 2019).
40. Yamaoka, R.S. Current condition and management of soil fertility in mulberry trees. In *Innovations in Paraná's Sericulture: Technologies, Profitability Management*; Soares Júnior, D., Almeida, E.L.D., Pádua, O.S., Eds.; IAPAR: Londrina, Brazil, 2018. Available online: http://www.emater.pr.gov.br/arquivos/File/Biblioteca_Virtual/RedesReferencia/Livro_Sericicultura2018_2aED.pdf (accessed on 15 October 2019).
41. Agritech. Organic Farming: Compost. Composting. 2019. Available online: http://www.agritech.tnau.ac.in/org_farm/orgfarm_composting.html# (accessed on 15 October 2019).
42. Agritech. Organic Farming: Compost. Vermicompost. 2019. Available online: http://www.agritech.tnau.ac.in/org_farm/orgfarm_vermicompost.html (accessed on 15 October 2019).
43. Taelman, S.E.; Tonini, D.; Wandl, A.; Dewulf, I.J. A Holistic Sustainability Framework for WasteManagement in European Cities: Concept development. *Sustainability* **2018**, *10*, 2184. [CrossRef]
44. Rebehy, P.C.P.W.; Lima, S.A.; dos, S.; Novi, J.C.; Salgado, A.P., Jr. Reverse logistics systems in Brazil: Comparative study and interest of multistakeholders. *J. Environ. Manag.* **2019**, *250*, 109223. [CrossRef] [PubMed]

45. Agrawal, S.; Singh, R.K. Analyzing disposition decisions for sustainable reverse logistics: Triple Bottom Line approach. *Resour. Conserv. Recycl.* **2019**, *150*, 104448. [CrossRef]
46. BeefPoint. Utilização da Cama de Frango Como Adubo Orgânico de Pastagens ("Use of Chicken Litter as a Pasture Organic Fertilizer"). 2009. Available online: https://www.beefpoint.com.br/utilizacao-da-cama-de-frango-como-adubo-organico-de-pastagens-56121/ (accessed on 15 October 2019).