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Looking for Environmental Scoring: A Case Study of a Portuguese Cotton White T-Shirt Made with Recycled Fiber

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Abstract: Promoting sustainable consumer behavior is now an obligation under new European legislation, requiring life cycle assessment (LCA) for accurate environmental impact evaluation. Portugal is a key textile producer with an edge in competitiveness in sustainable textile production, driven by electricity-reduced carbon footprints and closed-loop manufacturing. Additionally, while simple spreadsheets can estimate a product's carbon footprint, openLCA v1.11.0 software, combined with the ecoinvent database, greatly enhances environmental footprint calculations by integrating diverse impact categories that are otherwise difficult to estimate. In this study, openLCA is used to evaluate the environmental footprint of a white T-shirt made in Portugal with 50% recycled cotton from post-industrial wastes combined with 50% organic cotton from Turkey to assist in the design of environmental key performance indicators (KPI). The RECIPE and EF methods (adapted) are used to calculate the environmental impacts and allow aggregation into a single score. The KPI related to the global warming impact is validated using a spreadsheet calculator. We propose an "Envi-Score" based on an A-to-E classification for benchmarking and better communication with the buyers. E is set as the normalized environmental impact of the European benchmark for a mixture of material T-shirts encompassing cradle-to-gate boundaries. The introduction of recycled cotton produced in Portugal proves to be environmentally beneficial over organic and conventional cotton. Organic cotton proves to be beneficial in comparison with conventional cotton for most environmental categories, except for the ones affected by the lower production yield, for example, land use. The hotspots for the main impact categories are identified, and finally, a labeling scheme is proposed to clearly inform about the environmental performance of the products and avoid greenwashing with the "Envi-Score" rate, carbon footprint, land use, and water depletion.

Keywords: life cycle assessment (LCA); textiles; carbon footprint (CF); eco-labels; key performance indicators (KPI); benchmark

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Citation: Gonçalves, A.; Baêta, M.; Nagy, M.; Silva, C. Looking for Environmental Scoring: A Case Study of a Portuguese Cotton White T-Shirt Made with Recycled Fiber. *Sustainability* **2024**, *16*, 5896. https://doi.org/10.3390/su16145896

Academic Editor: Antonio Caggiano

Received: 19 May 2024
Revised: 18 June 2024
Accepted: 25 June 2024
Published: 10 July 2024

1. Introduction

The urgency of harmonized sustainability criteria is clear and pushed by European legislation. On 30 March 2022, the European Commission announced a package of proposals to make sustainable products the norm [1], boost circular business models, and empower consumers for the green transition. The European Union (EU) Strategy for Sustainable and Circular Textiles [2] is one of the sectorial initiatives also presented, including requirements for textiles to make them last longer, easier to repair and recycle, with a minimum recycled content, produced respecting social rights, clear information, and a digital product passport to tackle greenwashing, empower consumers, raise awareness about sustainable fashion, overproduction, and overconsumption, and discourage the destruction of unsold or returned textiles. Also, propose mandatory extended producer responsibility for textiles with eco-modulation of fees, address the unintentional release of microplastics from synthetic textiles, restrict the export of textile waste, promote sustainable textiles globally, incentivize circular business models, including reuse and repair sectors, and encourage companies and member states to support the objectives of the strategy. Products and inputs should be tracked from the very start of the supply chain, guaranteeing traceability for all the outputs, including information about their origin, location, and transformation process.

At the same time, the commission published a proposal for a directive empowering consumers for the green transition [3] through better protection against unfair practices and better information, including the proposal for amendment to the Unfair Commercial Practices Directive and the Consumer Rights Directive 2011/83/EU, resulting in new requirements that are highly relevant for textile products. The new EU rules will ensure that consumers are provided with information at the point of sale about a commercial guarantee of durability as well as information relevant to repair, including a reparability score, whenever this is available. General environmental claims, such as "green," "eco-friendly," and "good for the environment," will only be allowed if underpinned by recognized excellence in environmental performance, notably based on the EU Ecolabel, type I ecolabels, or specific EU legislation relevant to the claim. Voluntary sustainability labels covering environmental or social aspects must rely on third-party verification or be established by public authorities using life cycle analysis methods, including the Product Environmental Footprint (PEF) method [4]. Moreover, there will be conditions for making green claims related to future environmental performance, such as "climate neutral by 2030," and for comparing them to other products.

Parallelly, the initiative on substantiating green claims proposes to apply a standard methodology based on product and organizational environmental footprint methods to have reliable, comparable, and verifiable environmental claims and performance. The Commission Recommendation (EU) 2021/2279 of 15 December 2021 promotes the use of environmental footprint methods, such as ISO 14040 and ISO 14044 [5,6], in relevant policies and schemes related to the measurement and/or communication of the life cycle environmental performance of all kinds of products, including both goods and services and of organizations.

Nevertheless, in this actual regulation trend, there is still no consensus regarding KPIs for identifying a "sustainable fashion product" for simple and trusted communication with consumers. Although PEF already encompasses the environmental dimensions, there was a lack of harmonization in the existing studies concerning boundaries, allocation criteria, or process considerations. Another issue related to LCA studies is the difficulty of checking the results because each one is based on combined information from different and, most of the time, confidential sources [7].

European EcoScore is being pushed by a citizen's movement to offer a uniform label based on a standardized calculation for the whole European territory, avoiding confusion for the consumer-facing multiplication of environmental labels, although the methodology is not yet settled [8]. Although a methodology exists for food products, with some research proving that it can influence consumer decisions [9], it does not spread to other products. More research on defining sustainability labels for textile products is crucial to addressing environmental and social challenges. Transparent sustainability information is essential for producers to meet consumer and buyer demands. Current labeling schemes vary widely, impacting consumer trust and decision-making. Research should contribute to standardizing labeling schemes, harmonizing criteria, and enhancing the credibility of sustainability information. This will foster greater sustainability across the textile value chain, supported by international agreements and mandatory standards, positioning labeling schemes as key factors in sustainable purchasing decisions [10].

Clothing manufacturing in Portugal is ranked 4th in Europe in 2023 (out of 26 total EU countries, after Italy, France, and Germany, with an average growth of 3.2% per year between 2018 and 2023 [9], exporting mainly to other European countries. Since Portugal is focusing its differentiation strategy on sustainability, this study could be of utmost importance to highlight and demonstrate these efforts.

More than 15 kg of textile waste is generated per person in Europe every year. The largest source of textile waste is discarded clothes and home textiles from consumers, which represent 85% of the total textile waste [11]. The generation of textile waste is problematic, as incineration and landfills—both inside and outside Europe—are its primary end destinations. The Waste Directive 2008/98/EC update enforces textile recycling in a circular economy. In Portugal, there are about 13 recycling units, of which Valérius 360 is cotton-specific.

A query search at the Web of Science™ Core Collection database retrieved the results of Figure 1:

Q1 (LCA or "Life cycle a*" or "carbon footprint") and "T-shirt";
Q2 (LCA or "Life cycle a*" or "carbon footprint") and (Simapro or Gabi);
Q3 (LCA or "Life cycle a*" or "carbon footprint") and "openLCA";
Q4 (LCA or "Life cycle a*" or "carbon footprint") and (Simapro or Gabi) and "T-shirt";
Q5 (LCA or "Life cycle a*" or "carbon footprint") and "openLCA" and "T-shirt."

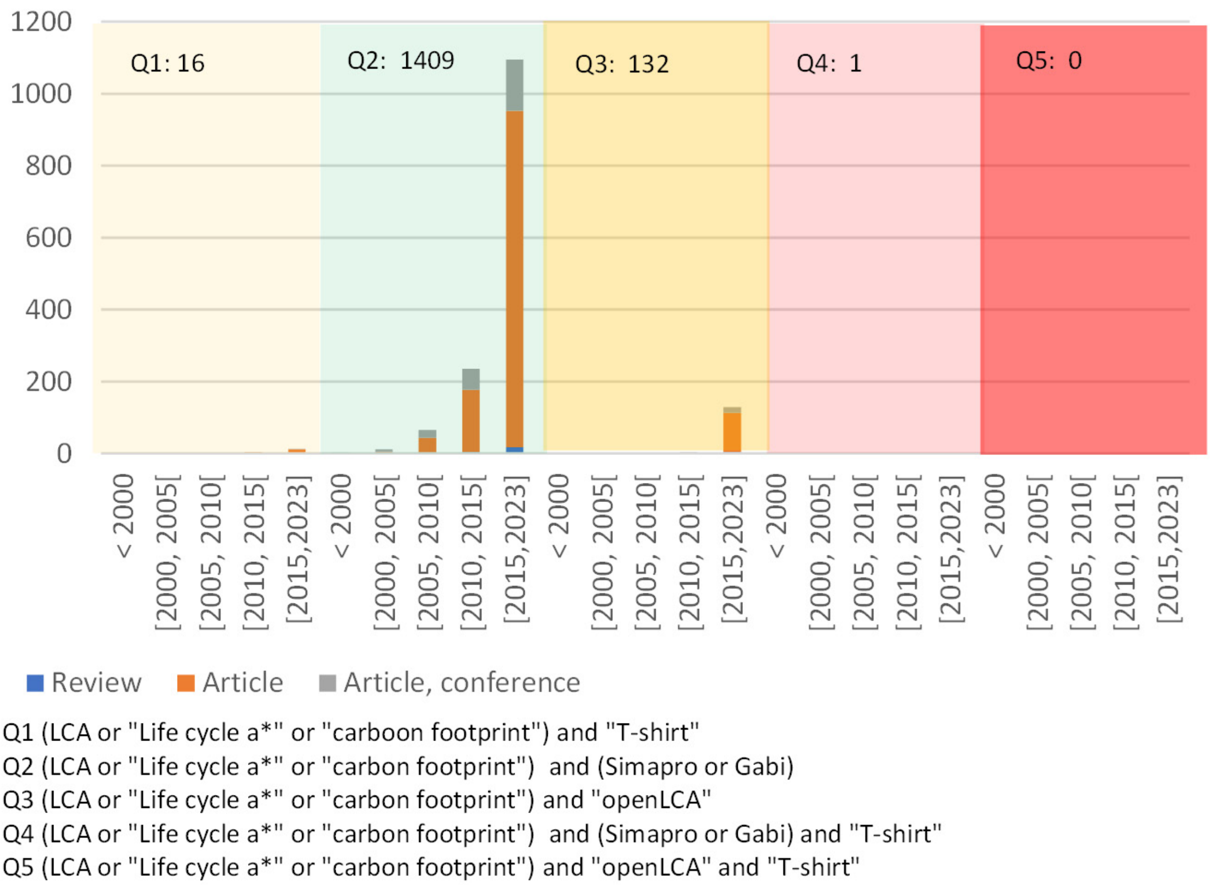

Figure 1. Outcomes of the query search in the Web of Science ™ Core collection.

The search query allows us to conclude that there is a much broader use of Simapro or GaBi proprietary LCA software than openLCA open software for any environmental LCA (e-LCA) study (Q2 and Q3). Regarding T-shirt e-LCA studies Q1, there were only sixteen identified, one of which was a review from the authors [7] and none covering recycled cotton or openLCA in a Portuguese context, which are the novelties of our approach. Recent research reveals a significant lack of LCA studies focusing on recycled cotton within the Portuguese context and emphasizes the need for future research based on industrial-scale processes, considering variables such as yield and material demand in recycling processes [12,13]. This gap is addressed by this study.

A virgin cotton study [14] in China considered a "cradle-to-grave" approach, covering cotton cultivation and cotton fiber production, irrigation, commercial fertilizers and pesticides, ginning (separation of seed and fiber), textile manufacturing including spinning, knitting, dyeing (pre-treatment, dyeing, post-treatment, and finishing) and making-up (cutting, sewing, and package), distribution, consumer use (wearing, washing, drying, and ironing, taking electricity, detergent, and wastewater emission into account), and disposal through landfill. The potential environmental impacts are evaluated using the CML2001 and USEtox methodologies built into the GaBi version 6.0 software, including climate change, abiotic depletion, acidification potential, photochemical ozone creation potential, eutrophication potential, water use, and toxicity. The distance for cotton transport by road is 3800 km. It focused on identifying hotspots; for example, water-use hotspots are used for cultivation, while hotspots for climate change (global warming potential) are used for electricity use and coal burning.

A virgin cotton study in Turkey [15] referring to textile exchange [16] for the organic cotton case study. GaBi 8.0 software with CML 2001 impact assessment methodology for global warming, acidification, and eutrophication potentials and a cradle-to-grave analysis of 1000 cotton T-shirts (250 kg). The distances between the cotton field to the yarn factory, the yarn factory to the fabric supplier, and the fabric mill to the shirt facility are 1092.4 km, 928.9 km, and 543.4 km, respectively, by road. Climate change retrieving 4.3 kg/kg T-shirt "cradle-to-gate." Water depletion is not addressed.

Within the Google Search engine, two reports (Textile Exchange [16] and Cotton Inc. [17]) were found for virgin organic and conventional cotton fiber that look at the environmental impact of climate change, water depletion, primary energy demand, acidification potential, and eutrophication potential. Both reports try to align the stages considered and assumptions to ensure a fair comparison between the two fiber production pathways. It estimated for an average market regarding China, India, Turkey, and the USA, 1.808 kg CO_2 eq/kg conventional cotton fiber and 0.978 kg CO_2 eq/kg organic fiber.

The carbon uptake at the cotton cultivation stage (1.54 kg CO_2 eq/kg fiber) is not considered; otherwise, the values could be negative, and at the end-of-life, the carbon will eventually be released as part of a short carbon cycle. Water consumption (blue water): 2740 L/kg virgin cotton and 704 L/kg organic fiber.

Moreover, only one study dealing with recycling cotton yarn was identified [18] in the context of Zhejiang province in China. It considers raw material acquisition, transportation, breaking, mixing, and spinning. The life cycle of virgin cotton yarn production was divided into raw material acquisition, transportation, mixing, and spinning. The distance between the cotton cultivation origin in Xinjiang province and the factory in Zhejiang province is assumed to be 4650 km by truck. The average distance between the factory of yarn manufacturers and the enterprises located in the local or nearby cities engaged in the recovery of waste clothes is assumed to be 100 km by truck. Both pathways obtain 1000 kg of yarn. Climate change, fossil depletion, water depletion, and human toxicity environmental impact categories were analyzed using GaBi proprietary software and ReCipe midpoint (H) impact assessment. Climate change retrieved 11 kg CO_2 eq/kg virgin conventional cotton yarn and 4.38 kg CO_2 eq/kg recycled yarn. Water depletion is retrieving 3514 m^3 of virgin yarn and 583 m^3 of recycled yarn.

It was identified in a recent master thesis concerning the life cycle assessment of a knit fabric made in Portugal with recycled cotton (60%) and conventional cotton (40%) and its comparison with a knit fabric made with conventional cotton, using the GaBi software version 10.6 and ReCipe 2016 midpoint methodology with a hierarchical approach (H) to analyze climate change, fossil depletion, terrestrial acidification, freshwater eutrophication, human toxicity, freshwater ecotoxicity, and terrestrial ecotoxicity impact categories. The life cycle considers the collection and transport of textile waste in a ratio of 20–30 km to the recycling unit, energy consumed in the recycling and spinning units, and the textile waste generated by these processes. Database figures were used for the remaining inventory inputs, including conventional cotton purchased on the global market, yarn dyeing (only for virgin yarn), and the knitting process. The production of 100 kg of knit fabric generated a climate change impact of 484.72 kg CO_2 eq recycled knit and 870.20 kg CO_2 eq virgin conventional cotton knit [19].

To better understand the limitations and the best way to harmonize criteria to benchmark environmental impacts on textile products, this study will cover a case study in Portugal that uses the "cradle-to-gate" approach to analyze the impacts of a T-shirt made with recycled cotton combined with organic cotton and compare it with another T-shirt made just with organic cotton or conventional cotton. It is based on the primary data gently shared by the Portuguese company Valérius [20], a facility able to convert cotton textile waste into new yarn after being transformed into new jersey fabrics, finally used to produce more conscious garments. This Portuguese textile company handles the final garment manufacturing process and has close partnerships with knitting and dyeing houses. Its recycling process can obtain, through a mechanical process, high-quality recycled cotton fibers with a 20 mm length, although, as usual [18], they need to be blended with other virgin fibers to expand strength and durability. Organic cotton is one of the virgin fibers frequently used and will be considered in this study. Although the recycling process is thorough, some recycled fibers are too small and cannot be used in a textile context, so the company has added another site to use them for the production of paper.

We expect to reach results that can be benchmarked with other studies and reference results, to contribute to the widespread utilization of openLCA software in the textile sector, and for a systematic methodology that can be used by the fashion industry to have a better understanding of how to create more eco-friendly products. Furthermore, it highlights the textile recycling conditions in Portugal and the environmental benefits of turning waste into new products, allowing a reduction in primary resources' consumption, land occupied to produce natural fibers, stocks from overproduction, and unsold garments, chemicals, water, and energy consumption, less greenhouse gas emissions, as well as a cutback in the total amount of textile materials discarded in landfills, which should be the last resort according to the EU waste framework directive (Directive 2008/98/EC).

2. Materials and Methods

The e-life cycle assessment will be based on ISO 14040 [5] and 14044 [6], the Product Environmental Footprint Category Rules T-shirts [21], and openLCA software [22]. openLCA is open-source and free software for sustainability and life cycle assessment that offers a large collection of data sets and databases, complemented with detailed insights into calculations and smart functionalities that make it easy to share and compare the models, which is of major importance when the objective is benchmark results.

This study uses the "cradle-to-gate" approach to analyze the environmental impact of a T-shirt made with 50% recycled cotton and 50% organic cotton. The life cycle for T-shirt production has been divided into the following stages: organic cotton fiber production (cultivation and ginning), recycled fiber production spinning, knitting, dyeing, finishing, cutting, and sewing (Figure 2). Transportation between stages of fiber production, yarn production, and cotton waste collection to the recycling unit is considered. A "cradle-to-gate" carbon footprint (ISO 14067 [23]), based on an Excel Spreadsheet input/output inventory and "open source" emission factors, was also undertaken to compare against openLCA outcomes related to climate change and global warming potential 100 years (GWP_{100}). The idea behind this approach is aligned with the GHG protocol [24], which opts to use an Excel spreadsheet approach, transparency, and open-sourcing [25]. The influence of the electricity mix of the power system in the years 2014 and 2021 is considered in the analysis, the hotspots are identified, and the results are compared with the literature.

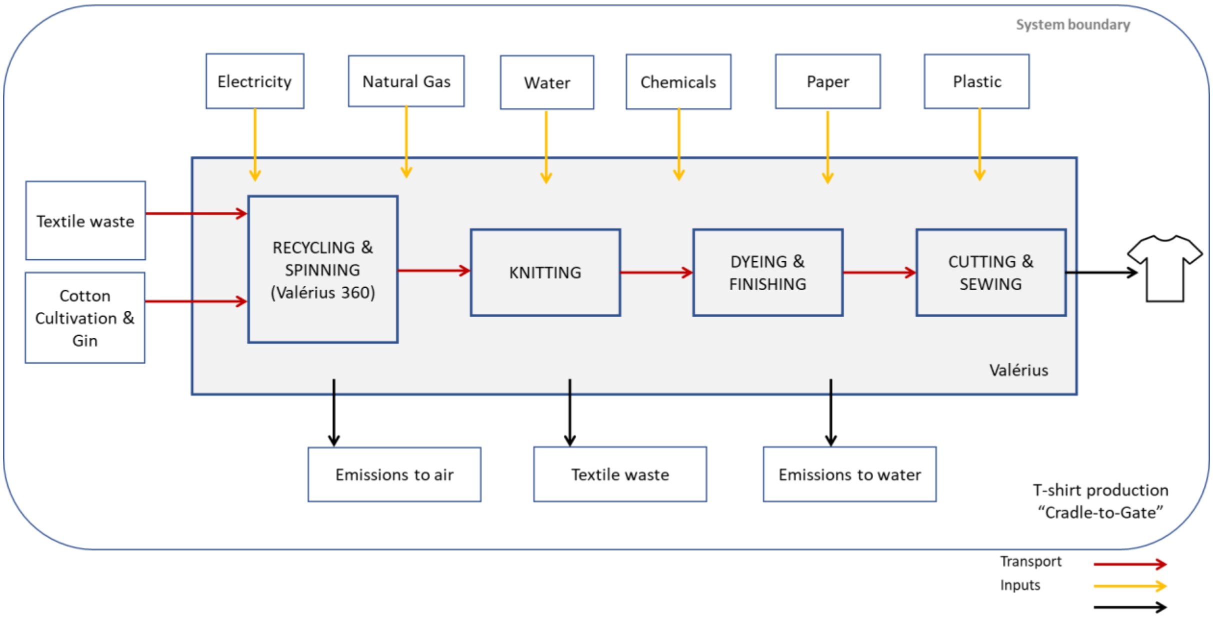

Figure 2. System diagram with the cradle-to-gate boundary considered in the study.

2.1. Goal of the Study

The goal of this study is to quantify, with openLCA, the environmental footprint of a white Jersey T-shirt made in Portugal with 50% recycled cotton mixed with 50% organic cotton (scenario 1) and compare it with a T-shirt made with 100% organic cotton (scenario 2) and another one made with 100% conventional cotton (scenario 3). This study considered the production of the T-shirt with Jersey knit (100%), with Ne30 yarn, and bleached. The objective is to be able to understand if environmental impact can be reduced when using recycled cotton instead of 100% organic cotton fibers or 100% conventional cotton, support the identification of environmental KPI's for benchmarks, and test the adequacy of openLCA for this kind of study on apparel. The outcome is validated for the GWP_{100} impact category.

2.2. Functional Unit

The functional unit (FU) of the product is going to be used as a reference to normalize all the inputs and outputs of the LCA analysis. This study considered 1 kg of a Jersey white T-shirt as the FU, and since the T-shirt does not have any other components, for the environmental footprint calculation of the final T-shirt (declared unit), it was assumed to be 1 short-sleeve white T-shirt with 200 g (considered as the average weight of a men's T-shirt size 40).

2.3. System Boundaries

This study includes all the processes "cradle-to-gate" (and their inputs and outputs), starting with the transport of the post-production textile waste from other production units until the final production of the T-shirt, including mechanical recycling, spinning, knitting, dyeing, finishing, cutting, and sewing processes (as described in Figure 2). It also includes the conventional and organic cotton production impacts based on the openLCA v1.11.0 [22] and ecoinvent v3.7.1 APOS U 20201221 database, as well as transport between processes, but does not include the T-shirt distribution, consumer use, or end-of-life since these processes are not controlled at the production stage. The three types of T-shirts are produced through the same process of spinning, knitting, dyeing, finishing, cutting, and sewing, so the difference in environmental impacts only came from fiber production.

Since this study does not include the use or disposal stage, the expected number of wears of the T-shirt [26] was not considered, nor was its end-of-life. It is assumed that the performance of virgin versus 50% recycled T-shirts is the same.

2.4. Life-Cycle Inventory

The life cycle inventory data for the T-shirt made with 50% recycled cotton and 50% organic cotton were provided by Valérius and are shown in Table 1. For the scenarios of the T-shirt made with 100% organic cotton and 100% conventional cotton, the same weight of these materials was considered to replace the total weight of fiber in the first scenario.

Table 1. Inventory of inputs and outputs of the processes considered within the study boundaries.

Process	Flow	Units	Quantity per T-Shirt kg
	INPUTS		
Recycling	Electrical Energy—grid	kWh	3.82×10^{-1}
	Water	kg	2.50×10^{-2}
	Textile Waste	kg	1.12×10^{0}
	Chemical product—Softener	kg	9.95×10^{-4}
	Transport road	km	5.00×10^{1}
Organic Cotton at Spinning Unit	Organic cotton lint	kg	9.50×10^{-1}
	Transport road	km	2.51×10^{2}
	Transport container Turkey	km	4.56×10^{3}
Spinning	Electrical Energy—grid	kWh	2.98×10^{0}
	Natural Gas	Nm^3	7.02×10^{-3}
	Chemical product—Paraffin	kg	4.47×10^{-3}
Knitting	Electrical Energy—grid	kWh	4.80×10^{-1}
	Electrical Energy—solar	kWh	2.20×10^{-1}
	Transport road	km	2.80×10^{1}
Dyeing and Finishing	Electrical Energy—grid	kWh	1.13×10^{0}
	Electrical Energy—solar	kWh	4.15×10^{-1}
	Natural Gas	Nm^3	2.26×10^{-1}
	Water	kg	1.80×10^{0}
	Transport road	km	1.50×10^{1}
	Chemical product—Organic	kg	3.24×10^{-2}
	Chemicals Product—Inorganic	kg	3.40×10^{-3}
	Chemical Product—Softener		5.25×10^{-2}
	Chemical Product—Hydroxide Peroxide	kg	1.82×10^{-2}
	Chemical Product—Sodium Hydroxide	kg	4.54×10^{-3}
	Chemical Product—Acetic Acid (80%)	kg	1.82×10^{-3}
Cutting	Electrical Energy—grid	kWh	1.69×10^{-1}
	Plastic	kg	1.35×10^{-2}
	Paper	kg	1.17×10^{-2}
	Transport road	km	5.00×10^{0}
Sewing	Electrical Energy—grid	kWh	1.92×10^{-1}
	OUTPUTS *		
Recycling	Textile waste	kg	1.70×10^{-1}
Spinning	Textile waste	kg	1.90×10^{-1}
Knitting	Textile waste	kg	3.00×10^{-2}
Dyeing and Finishing	Waste Water	kg	2.55×10^{0}
	Textile waste	kg	1.70×10^{-1}
Cutting	Textile waste	kg	2.60×10^{-1}
	Plastic	kg	1.35×10^{-1}
	Paper	kg	1.17×10^{-1}
Sewing	Textile waste	kg	2.50×10^{-1}
All	Textile Waste (total)	kg	1.07×10^{0}

* except air emissions.

The post-industrial textile waste is collected from units within a 50 km ratio and transported by 7.5-ton diesel trucks to a unit recycling unit, where the recycled cotton yarn is produced through a physical process using electrical energy, water, natural gas, and chemical products (silicone products and paraffin). The recycling process starts with the waste cutting; the small pieces are immediately soaked with a softener solution and then vacuumed into another container to rest some more time until they are soft enough to pass to the LaRoche griding process to become very loose recycled fibers, which are compressed to be stored or continue to the mixing of the recycled cotton fiber with organic cotton (or other sustainable virgin fiber) to obtain the strength characteristics to be spun into recycled yarn. It uses new open-end spinning technology that allows savings and real-time readings of energy consumption [20]. In the case of this study, the recycled yarn is mixed with organic cotton fiber produced in Turkey and transported to Portugal by container ship and truck until the spinning unit.

Recycled cotton yarns are transported to a knitting factory to produce recycled cotton knit, which is white bleached and finished in one of the company's partner dyeing houses using a jet dyeing machine and a Ramula. All these processes are sourced with electrical energy from the grid and solar panels. The dyeing house is also fed with natural gas, water, and chemical products (dyeing and finishing). The white knit is moved to a very close factory equipped with automated cutting units and capacity for T-shirt manufacturing, using only electrical energy, some paper, and plastics that are reused or sent to recycling processes.

2.5. Data Source

Valérius 360 provided primary data for their core processes; information from upstream processes, including the production of conventional and organic cotton and its transportation, was acquired by the ecoinvent v3.7.1 APOS U 20201221 database through openLCA v1.11.0 [22]. The Allocation at Point of Substitution (APOS) introduces the burden from the previous at the point where the recycled cotton is used, so it has an additional impact on the final T-shirt made with recycled cotton. The system was defined considering each supply chain tier as unit processes (U), with the quantification of their individual inputs and outputs. This study considers openLCA flows and providers, as shown in Table 2.

Table 2. openLCA flows and their providers that were considered for the study.

openLCA Flows	Providers
acetic acid, without water, in 98% solution state	acetic acid production, product in 98% solution state | acetic acid, without water, in 98% solution state | APOS, U—RER
calendering, rigid sheets	calendering, rigid sheets | calendering, rigid sheets | APOS, U—RER
chemical, inorganic	market for chemicals, inorganic | chemical, inorganic | APOS, U—GLO
chemical, organic	market for chemical, organic | chemical, organic | APOS, U—GLO
electricity, medium voltage	market for electricity, medium voltage | electricity, medium voltage | APOS, U 2021—PT
fiber, cotton, organic	fiber production, cotton, organic, ginning | fiber, cotton, organic | APOS, U—RoW
fiber, cotton	fiber production, cotton, ginning | fiber, cotton | APOS, U—RoW
hydrogen peroxide, without water, in 50% solution state	market for hydrogen peroxide, without water, in 50% solution state | hydrogen peroxide, without water, in 50% solution state | APOS, U—RER
kraft paper	market for kraft paper | kraft paper | APOS, U—RER
natural gas, low pressure	market for natural gas, low pressure | natural gas, low pressure | APOS, U—RoW
Paraffin	market for paraffin | paraffin | APOS, U—GLO
silicone product	market for silicone product | silicone product | APOS, U—RER
sodium hydroxide, without water, in a 50% solution state	market for sodium hydroxide, without water, in 50% solution state | sodium hydroxide, without water, in 50% solution state | APOS, U—GLO
tap water	market for tap water | tap water | APOS, U—Europe without Switzerland
transport, freight, lorry 3.5–7.5 metric ton, EURO6	transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | APOS, U—RoW

RER—European market. GLO—Global market. RoW—Rest of the world.

According to the data provided, to produce 1 kg of white T-shirts, we will use 1.118 kg of cotton waste, mainly from production wastes, combined with 0.95 kg of virgin cotton. The use of post-consumer textile waste is still very limited. The recycling process generates 0.17 kg of cotton lint waste, meaning an efficiency of 85% in the recycling process. Overall, the existing process leads to an efficiency of 48.3%.

The cotton waste generated was used as the input for the recycling unit through a "waste treatment process" following the openLCA material flow logic. This waste was not considered "avoided waste" because it can be used in other processes (such as producing other new products with lower value).

The ecoinvent database does not include detailed chemicals applied in the process, so it was necessary to classify some of them as inorganic or organic chemical products after applying the suitable upstream process.

Inventory data were collected between October 2020 and September 2021. For a more accurate estimate of Portuguese electricity emissions, it was considered the electricity mix in Portugal, provided by REN for 2021 [27], as presented in Table 3.

Table 3. Portuguese electricity production mix in 2021 [27] and characterization to define the openLCA providers for flow "electricity, high voltage".

Electricity Mix—Portugal 2021	GWh	%	Characterization
Renewable generation	29,526	53.0%	-
Hydro	11,607	20.8%	Reservoir: 40.16% Run of the river: 59.84% [28]
Wind	12,921	23.2%	1–3 MW Turbine: 96.37% <1 MW Turbine: 7.317% 1–3 MW Offshore: 0.04% *
Biomass			
Non-cogeneration	1837	3.30%	Wood chips, 6667 kW *
Cogeneration	1432	2.57%	Wood—GLO *
Solar	1729	3.10%	Solar tower power plant 20 MW—RoW *
Non-renewable generation	15,607	28.0%	-
Coal	694	1.25%	-
Natural Gas			
Non-cogeneration	10,976	19.7%	Combined cycle
Cogeneration	3653	6.56%	Conventional, 100 MW
Others			
Non-cogeneration	213	0.38%	Oil *
Cogeneration	71	0.13%	
Pumped stored generation	1597	2.87%	-
Import (commercial schedules)	8957	16.1%	From Spain *
TOTAL	55,687	100%	-

* based on openLCA 2014 figures, according to data available [29].

2.6. Assumptions

For the study, some assumptions had to be made since the information available was not complete or the process was not exactly equal all the time:

- Organic cotton and conventional cotton are produced in the same location in Turkey for transport distance calculations, although the "fiber, cotton, organic" and "fiber, cotton" generic flows are used for the calculations.
- It did not consider the capture of CO_2 in the fibers in the cultivation process.
- Tap water is being used for recycling, dyeing, and finishing processes, and there is no production of wastewater in the recycling unit.
- The average distance for collecting textile waste is 50 km.

- Renewable solar energy produced and used by the knitting, dyeing, and finishing units was not included in the calculations as it is considered to have negligible impact.
- Road transport is being conducted in Turkey and Portugal with EURO 6 freight lorry 3.5–7.5 metric tons (348.5 km); transport by sea in containerships from Turkey to Portugal (4559.6 km).
- Chemical products made with mixtures were grouped and classified as softeners (silicon products), "chemical, organic," and "chemical, inorganic."
- Plastic and paper used in the cutting process are considered to be reused several times, meaning the inputs are equal to the outputs.
- The yarns will be the only material used on the T-shirt, and it will not have any accessories, composition, or care label since the information will be printed inside the neck.
- On the openLCA calculation, it was not considered a cut-off; it was chosen to auto-link the default providers by unit processes.
- All the processes are the same for the different types of yarn. T-shirts without specific treatment (e.g., moisture transfer).
- The spinning machine does not use a significant quality of lubricant oil.
- At openLCA, each process was converted into a product system, choosing the options "auto-link processes," "prefer default providers," and "unit process," so the cut-off was not considered.

2.7. Limitations

The below limitations where identified:

- This study does not include the T-shirt, packaging, or downstream processes such as logistics, transport from the factory until the customer house and retail, use stage, or end-of-life.
- The appearance, quality, or durability of the T-shirt made with recycled cotton versus the T-shirt made with virgin fibers were also not considered in the comparison.
- The primary data used in the study were provided by Valérius without any further verification or measurements made by this article's authors. The allocation rules applied were not communicated, although processes are specific for this kind of production.
- Although water is used from wells and the dyeing unit uses river water, in this study, a tap water flow was applied.
- Impacts related to labor/workers were not considered.

2.8. Impact Assessment

The ReCipe 2016 mid-point (H) was used as the impact assessment method, converting emissions and resources used in the product life cycle into 18 environmental impact categories/indicators. These categories include fine particulate matter formation (kg PM2.5 eq); fossil resource scarcity (kg oil eq); freshwater ecotoxicity (kg 1,4-DCB eq); Freshwater eutrophication (kg P eq); global warming (kg CO_2 eq); human carcinogenic toxicity (kg 1,4-DCB eq); human non-carcinogenic toxicity (kg 1,4-DCB eq); ionizing radiation (kBq Co-60 eq); land use (m^2a crop eq); marine ecotoxicity (kg 1,4-DCB eq); marine eutrophication (kg N eq); mineral resource scarcity (kg Cu eq); ozone formation, human health (kg NOx eq); ozone formation, terrestrial ecosystems (kg NOx eq); stratospheric ozone depletion (kg CFC11 eq); terrestrial acidification (kg SO_2 eq); terrestrial ecotoxicity (kg 1,4-DCB eq) and water consumption (m^3). This method is frequently used in this scope and considers the hierarchist (H) perspective, which is based on the scientific consensus about the time frame (100 years) and plausibility of impact mechanisms [30]. No allocation method was considered.

At the stage of normalization, it was necessary to recalculate the impact of the three T-shirts with the EF method (adapted) based on EF method 2.0. This method retrieves impact results in compatible units with the available normalization factor per person-year [31].

2.9. Excel Spreadsheet Carbon Footprint for openLCA Validation

The carbon footprint (CF) is defined by part of an e-LCA that relates exclusively to the environmental category of climate change, metric global warming potential at 100 years, defined as GWP_{100} and measured in CO_2 eq. The inventory of each stage of the T-shirt production is in Table 1.

Each input flow (mass or energy) is multiplied by the respective emission factor (EF) and added up to give the overall CF as defined in Equation (1):

$$CF = \sum_{s=1}^{n} \sum_{i=1}^{m} m_{is} EF_i \quad (1)$$

s stands for stage (cultivation, recycling, spinning, knitting).

i stands for the flow number at stage s.

The EFs applied for the CF calculation are available in Table 4.

Table 4. Emission factors were applied for the GWP_{100} calculation.

Flow	Emission Factors	Unit [kg CO_2 eq]	Source
Electricity	0.219	/kWh	[32]
Natural gas	3.128	/kg	
Well to tank	0.528	/kg	[33,34]
Direct emissions	2.6	/kg	Equation (2)
Water	0.149	$/m^3$	[33]
Wastewater	0.272	$/m^3$	[33]
Chemicals	1.3 [a]	/kg	[34]
Transport road [b]	3.23×10^{-4}	/kg.km	
Well to tank	5.91×10^{-5}	/kg.km	[33]
Direct emissions	2.64×10^{-4}	/kg.km	
Transport Maritime [c]	1.97×10^{-5}	/kg.km	
Well to tank	3.63×10^{-6}	/kg.km	[33]
Direct emissions	1.61×10^{-5}	/kg.km	
Organic cotton lint	0.978	/kg	[16]

[a] Primary chemical. [b] Heavy goods vehicle (>3.5–7.5 Tonnes) 100%. [c] Container ship average.

In general, units were converted so that the EFs from Table 4.

Table 4 was consistent with the quantities used in the life cycle inventory, although some flows required intermediate calculations to be aligned.

The EFs found for the extraction and distribution of natural gas depended on their energy content, meaning 1.14×10^{-2} kg CO_2 eq/MJ [35]. To obtain them in terms of mass flow, it was necessary to resort to Equation (2) and the low heat value (LHV) of 46.3 MJ/kg (NG EU Mix Pipped) [36].

$$EF_{mass}\left[\frac{kgCO_2eq}{kg}\right] = LHV\left[\frac{MJ}{kg}\right] \cdot EF_{energy}\left[\frac{kgCO_2eq}{MJ}\right] \quad (2)$$

The inventory is intended to consist almost exclusively of mass flows in kilograms, except for water and electricity, which are desired in m^3 and kWh, respectively. To achieve this goal, it was sometimes necessary to convert units, as for the transformation of natural gas volumetric flows (V) into mass flows (m), to which it resorts to Equation (4). The natural gas being in a gaseous state, its properties are affected by ambient conditions, which prevents the direct application of Equation (3) because, although the consumed volume is known, the corresponding density (ρ) is unknown. However, it is possible to determine the value of ρ because natural gas is an ideal gas with 17.5 kg/kmol molecular mass (M) [36], and the pressure (P) and temperature (T) conditions considered during the volume measurement are known (1 atm and 25 °C).

$$\rho\left[\frac{kg}{m^3}\right] = \frac{P\,[kPa]\cdot M\left[\frac{kg}{kmol}\right]}{R\left[\frac{m^3\cdot kPa}{K\cdot kmol}\right]\cdot \mathrm{T}[K]} \quad (3)$$

R stands for the gas constant.

Once the density under the desired pressure and temperature conditions is known, Equation (4) can be applied.

$$m[kg] = V\left[m^3\right]\cdot\rho\left[\frac{kg}{m^3}\right] = n[kmol]\cdot M\left[\frac{kg}{kmol}\right] \quad (4)$$

n stands for the number of moles.

The total chemical quantity was calculated by adding all the different chemical products included in the process.

Transport by road and sea was converted to the unit kg.km with the quantities transported in each step.

After the harmonization of all the quantities, the initial inventory was converted into the one available in Table 5.

Table 5. Inventory for each supply chain process per 1 kg T-shirt.

Process	Electricity (kWh)	Natural Gas (kg)	Water (m^3)	Chemicals (kg)	Wastewater (m^3)	Transport Road (kg.km)	Transport Maritime (kg.km)	Org. Cotton Lint (kg)
Recycling	3.82×10^{-1}	0	2.50×10^{-5}	9.95×10^{-4}	-	5.60×10^{1}	-	9.50×10^{-1}
Organic cotton at spinning unit	-	-	-	-	-	2.38×10^{2}	4.33×10^{3}	
Spinning	2.98×10^{0}	5.02×10^{-3}	-	4.47×10^{-3}	-	-	-	
Knitting	4.80×10^{-1}	-	-	-	-	4.77×10^{1}	-	
Dyeing and finishing	1.13×10^{0}	1.62×10^{-1}	1.80×10^{-3}	1.13×10^{-1}	2.55×10^{-3}	2.52×10^{1}	-	
Cutting	1.69×10^{-1}	-	-	-	-	7.57×10^{0}	-	
Sewing	1.92×10^{-1}	-	-	-	-	-	-	
Total	5.33×10^{0}	1.67×10^{-1}	1.83×10^{-3}	1.18×10^{-1}	2.55×10^{-3}	3.74×10^{2}	4.33×10^{3}	9.50×10^{-1}

3. Results

The following section presents a summary of the results of the LCA study according to the openLCA outputs. To give visibility to the contribution of each main step or component, the environmental impacts were calculated for the Electricity Portuguese Mix in 2021, transport for the importation processes, transport along the local supply chain, each fiber, each process, and finally, for the three T-shirt scenarios.

It included some results from selected literature to give context to the results achieved and help with the interpretation.

3.1. Electricity Modeling—Portuguese Electricity Mix in 2021

Electricity has an impact on the environmental burden of products and processes, and this is recognized by European governments, which are continually implementing policies and promoting new technologies to reduce the impact of energy production. To increase accuracy, the LCA of electricity generation in Portugal during 2021 was updated at openLCA by modifying the process "market for electricity, medium voltage | electricity, medium voltage | APOS, U—PT," valid for the year 2014, from ecoinvent v3.7.1 APOS U 20201221, by using 2021 data from REN HUB [27], retrieving 237 g CO_2 eq/kWh instead of the 487 g CO_2 eq/kWh of the previous process for the Climate Change impact category. The former value was compared against the values found for the Portuguese power system (162 g CO_2 eq/kWh [22]), with coal power dismissed in January 2021, and the values of the database "OurWorld in Data" [32] (219 g CO_2 eq/kWh) accounting for imports from Spain with coal feedstock. The openLCA value is higher because it includes imports, extraction, and transport of feedstocks and infrastructure-embedded materials from PowerPlants and is thus considered to validate the outcome of the openLCA process (as shown in Table 6).

Table 6. Environmental impact for the Portuguese electricity production mix in 2021 (per kWh).

Indicator	Impact Result	Unit
Fine particulate matter formation	0.000	kg $PM_{2.5}$ eq
Ionizing radiation	0.035	kBq Co-60 eq
Fossil resource scarcity	0.080	kg oil eq
Freshwater ecotoxicity	0.004	kg 1,4-DCB
Stratospheric ozone depletion	0.000	kg CFC11 eq
Human non-carcinogenic toxicity	0.063	kg 1,4-DCB
Freshwater eutrophication	0.000	kg P eq
Marine eutrophication	0.000	kg N eq
Marine ecotoxicity	0.005	kg 1,4-DCB
Land use	0.027	m^2a crop eq
Water consumption	0.003	m^3
Terrestrial acidification	0.001	kg SO_2 eq
Terrestrial ecotoxicity	0.190	kg 1,4-DCB
Ozone formation, terrestrial ecosystems	0.001	kg NO_x eq
Human carcinogenic toxicity	0.013	kg 1,4-DCB
Ozone formation, human health	0.000	kg NO_x eq
Mineral resource scarcity	0.000	kg Cu eq
Global warming	0.237	kg CO_2 eq

3.2. Transport–Logistics

Transport was evaluated for the scenario of "50% recycled cotton + 50% organic cotton" under two perspectives: the transport used to bring the imported fiber from Turkey to the spinning unit (the same distances were used for organic cotton and conventional cotton) and the sum of the transport to bring the textile wastes from the other units to the recycling unit, with the transport between each step of the following processes (as applicable). The total environmental impact of transport on the global process is shown in Table 7, separately for the imported fiber and for local travel.

Table 7. Total environmental impact of transport on the global process (including virgin fiber importation and transportation within local production units).

Indicator	Imported Fiber	Local	Total	Unit
Fine particulate matter formation	0.000	0.000	0.000	kg $PM_{2.5}$ eq
Fossil resource scarcity	0.053	0.023	0.076	kg oil eq
Freshwater ecotoxicity	0.004	0.002	0.006	kg 1,4-DCB
Freshwater eutrophication	0.000	0.000	0.000	kg P eq
Global warming	0.162	0.070	0.232	kg CO_2 eq
Human carcinogenic toxicity	0.014	0.006	0.020	kg 1,4-DCB
Human non-carcinogenic toxicity	0.096	0.053	0.148	kg 1,4-DCB
Ionizing radiation	0.004	0.002	0.007	kBq Co-60 eq
Land use	0.004	0.002	0.006	m^2a crop eq
Marine ecotoxicity	0.006	0.003	0.009	kg 1,4-DCB
Marine eutrophication	0.000	0.000	0.000	kg N eq
Mineral resource scarcity	0.000	0.000	0.001	kg Cu eq
Ozone formation, human health	0.001	0.000	0.001	kg NO_x eq
Ozone formation, terrestrial ecosystems	0.001	0.000	0.001	kg NO_x eq
Stratospheric ozone depletion	0.000	0.000	0.000	kg CFC11 eq
Terrestrial acidification	0.001	0.000	0.001	kg SO2 eq
Terrestrial ecotoxicity	1.122	0.589	1.712	kg 1,4-DCB
Water consumption	0.000	0.000	0.000	m^3

The transport of the imported fiber contributes to the most relevant impact, so it was associated with the importation of organic cotton and conventional cotton, while the impact of the local transport was associated with each unit, as applicable.

3.3. Cotton Fibers—Recycled, Organic, and Conventional

As already referred, for the study, it was considered the generic openLCA flows for organic and conventional cotton (as identified in Table 2).

Table 8 shows the environmental impacts of the recycled lint versus the default impacts for organic cotton and conventional cotton (at the production location), and it is clear that recycled cotton fibers can bring major benefits for categories such as global warming, human non-carcinogenic toxicity, and land use.

Table 8. Environmental impact of each cotton fiber at the production location (per 1 kg of fiber).

Indicator—Cotton Fiber	Recycled	Organic	Conventional	Unit
Fine particulate matter formation	0.000	0.003	0.007	kg PM $_{2.5}$ eq
Fossil resource scarcity	0.051	0.033	0.469	kg oil eq
Freshwater ecotoxicity	0.005	0.082	0.369	kg 1,4-DCB
Freshwater eutrophication	0.000	0.012	0.002	kg P eq
Global warming	0.155	0.903	2.859	kg CO_2 eq
Human carcinogenic toxicity	0.010	0.011	0.122	kg 1,4-DCB
Human non-carcinogenic toxicity	0.064	0.004	5.573	kg 1,4-DCB
Ionizing radiation	0.018	0.045	0.067	kBq Co-60 eq
Land use	0.014	14.636	4.001	m^2a crop eq
Marine ecotoxicity	0.007	0.110	0.183	kg 1,4-DCB
Marine eutrophication	0.000	0.024	0.012	kg N eq
Mineral resource scarcity	0.000	0.001	0.011	kg Cu eq
Ozone formation, human health	0.000	0.006	0.012	kg NO_x eq
Ozone formation, terrestrial ecosystems	0.000	0.007	0.012	kg NO_x eq
Stratospheric ozone depletion	0.000	0.000	0.000	kg CFC11 eq
Terrestrial acidification	0.000	0.021	0.032	kg SO_2 eq
Terrestrial ecotoxicity	0.384	0.776	5.483	kg 1,4-DCB
Water consumption	0.002	0.014	0.757	m^3

According to the Textile Exchange 2014 study [16], the global warming potential (GWP_{100}) of organic cotton is 0.978 kg CO_2 eq per 1 kg of fiber; the main contribution was given by India with a share of 74%, while openLCA applied an estimative for RoW (Rest of the World without India).

The global average GWP_{100} of conventionally grown cotton is calculated to be 1.808 kg CO_2 eq per fiber kg as per Cotton Inc.'s study in 2012 (if not considering the capture of CO_2 in the fibers) [17].

Organic cotton makes the biggest contribution to the category of land use. The other processes' contribution is neglectable for this category, although land occupation (one of the dimensions of land use) was not included in the Textile Exchange study since this indicator is indirectly proportional to the yield, and a low yield does not necessarily result in a high environmental profile [16]. It is important to note that this impact category refers to the relative species loss caused by specific land use types (annual crops, permanent crops, mosaic agriculture, forestry, urban land, and pasture) [37].

On the other side, according to the same study, the production of conventional cotton consumes 2120 m^3 of blue water per 1000 kg of cotton fiber, while producing 1 metric ton of organic cotton requires 15,000 m^3 of water. Blue water includes all the fresh water inputs but excludes rainwater, although water consumption in the Textile Exchange study includes green water (rainwater and moisture stored in the soil and used for plant growth) [37]. This inclusion can justify the big difference when comparing this reference value for organic cotton with the openLCA results, which refer to m^3 of water consumed from m^3 of water extracted. Figure 3 shows the results for each impact category of the respective project variants. For each indicator, the maximum result is set to 100%, and the results of the other variants are displayed according to this result.

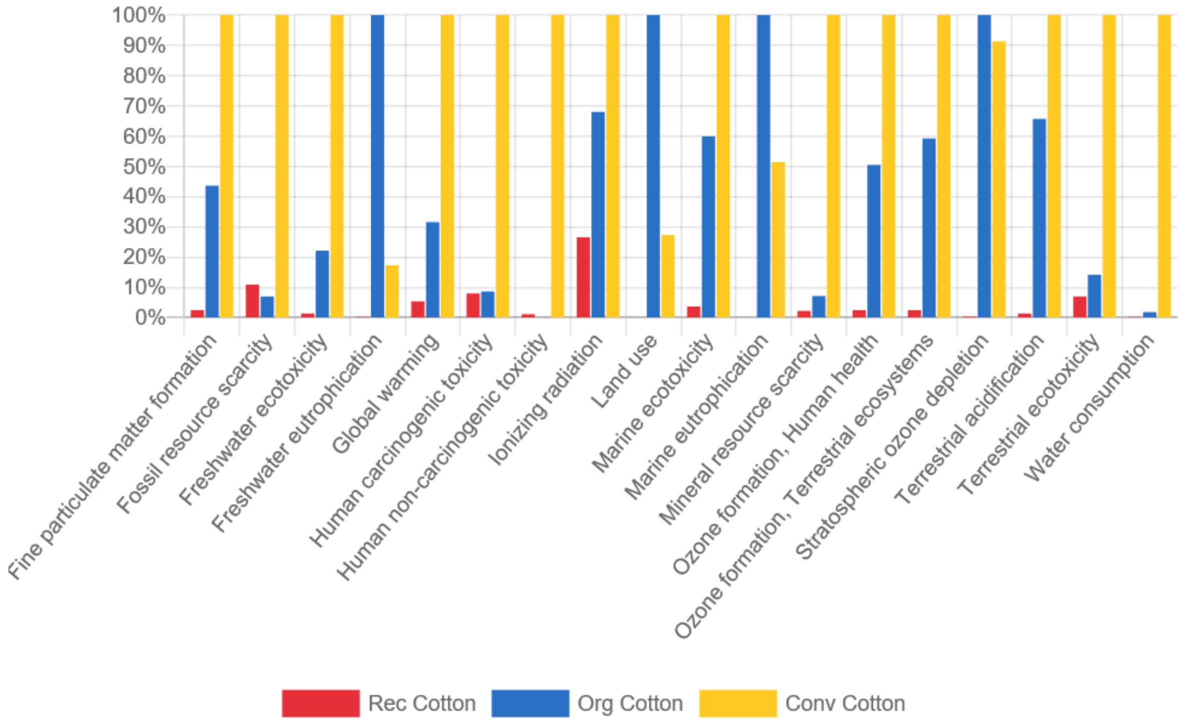

Figure 3. Relative impact category results of the respective project variants: recycled cotton fiber (Rec Cotton), organic cotton fiber (Org Cotton), and conventional cotton fiber (Conv Cotton).

Conventional cotton fiber production led to a major impact on the main parts of the categories, except for freshwater eutrophication, land use, marine eutrophication, and stratospheric ozone depletion. On the other hand, the impacts of recycled cotton fiber are far less for all the impact categories, bringing clear benefits to reducing environmental depletion.

3.4. T-Shirt Made with 50% Recycled and 50% Organic Cotton

The results of the environmental impact study of the white T-shirt under study are available in Table 9. Since LCA results are difficult to interpret on their own, the table compares the environmental impact of three variants: the white T-shirt made with 50% recycled cotton and 50% organic cotton (T-shirt 50% RC + 50% OC), a T-shirt made with 100% organic cotton (T-shirt 100% OC), and another one made with 100% conventional cotton (T-shirt 100% CC).

The recycled cotton content in the T-shirt makes a relevant contribution to relieving resources and environmental pressure in all the impact categories when compared with organic cotton (as shown in Figure 4). Freshwater eutrophication and land use show the worst performance when compared with the T-shirt made of conventional cotton, but these higher impacts come from the mixture with organic cotton and not from the recycled cotton fiber itself.

According to PEFCR [26], the most relevant impact categories for T-shirts are climate change, particulate matter, acidification, freshwater eutrophication, freshwater ecotoxicity, water use, and fossil resource use.

Table 9. This table shows the LCA results of the project variants: a T-shirt made with 50% recycled cotton (RC) and 50% organic cotton (OC), a T-shirt made with 100% organic cotton, and a T-shirt made with 100% conventional cotton (CC). Each selected LCA category is displayed in rows, and the project variants are in the columns. Values are presented per 1 kg white T-shirt.

Indicator	T-Shirt 50% RC + 50% OC	T-Shirt 100% OC	T-Shirt 100% CC	Unit
Fine particulate matter formation	0.01	0.01	0.02	kg PM $_{2.5}$ eq
Fossil resource scarcity	0.97	1.03	1.83	kg oil eq
Freshwater ecotoxicity	0.33	0.40	0.95	kg 1,4-DCB
Freshwater eutrophication	0.01	0.02	0.00	kg P eq
Global warming	3.12	4.05	7.70	kg CO_2 eq
Human carcinogenic toxicity	0.48	0.50	0.70	kg 1,4-DCB
Human non-carcinogenic toxicity	3.32	3.39	13.94	kg 1,4-DCB
Ionizing radiation	0.29	0.32	0.36	kBq Co-60 eq
Land use	14.11	28.00	7.79	m^2a crop eq
Marine ecotoxicity	0.42	0.53	0.66	kg 1,4-DCB
Marine eutrophication	0.02	0.05	0.02	kg N eq
Mineral resource scarcity	0.01	0.01	0.03	kg Cu eq
Ozone formation, human health	0.01	0.02	0.03	kg NO_x eq
Ozone formation, terrestrial ecosystems	0.01	0.02	0.03	kg NO_x eq
Stratospheric ozone depletion	0.00	0.00	0.00	kg CFC11 eq
Terrestrial acidification	0.03	0.05	0.07	kg SO_2 eq
Terrestrial ecotoxicity	4.75	6.84	15.14	kg 1,4-DCB
Water consumption	0.05	0.06	1.47	m^3

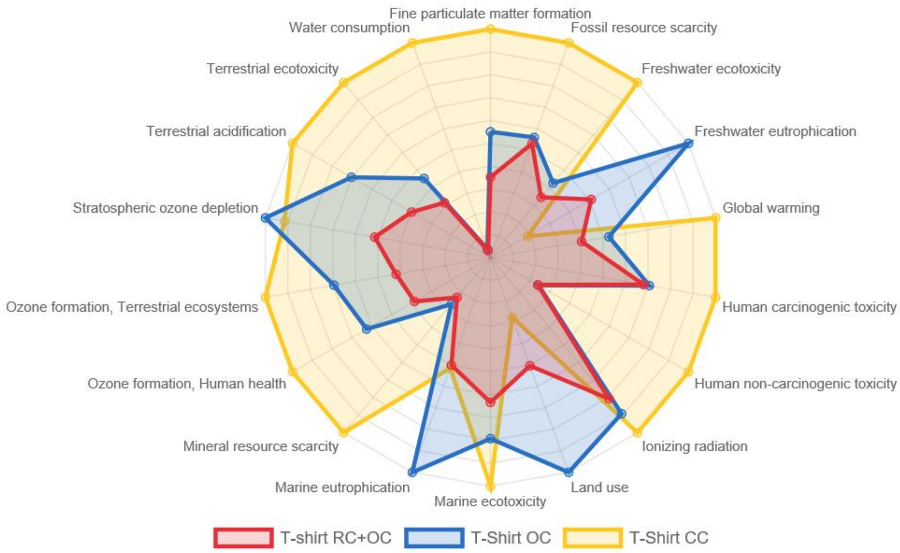

Figure 4. This figure shows the LCIA results of the project variants for each LCA impact category. For each indicator, the maximum result is set, and the results of the other variants are displayed according to this result. In the graphic, a larger area represents a higher environmental impact.

As initially defined, the white T-shirt under study is made with 200 g of 50% recycled cotton mixed with 50% organic cotton, with the following contribution to environmental depletion [16,37]:

- Climate change affects the environment on a global scale and is characterized by the global warming potential (GWP) that results from green gas emissions. The consequences include increased average global temperatures and sudden regional climatic changes. GWP quantifies the integrated infrared radiative forcing increase in greenhouse gas (GHG), expressed in kg CO_2 eq, and is the midpoint characterization factor selected for the climate change impact category [37]. The GWP resulting from the green gases emitted from the production of this T-shirt adds up to 624 g CO_2 eq, with the main contributions largely depending on cotton seed production and the Portuguese electricity production mix.

- Particulate matter considers the adverse health effects on human health caused by emissions of particulate matter (PM) and its precursors (NO_x, SO_x, and NH_3). The production of the T-shirt adds up to 1 g of $PM_{2.5}$ equivalent. The main contribution comes from organic seed cotton production.
- Acidification addresses impacts due to the release of acidifying substances in the environment related to the emissions of NO_x, SO_x, and NH_3, with an effect on the acidification of soils and water, resulting in forest decline and lake acidification. The T-shirt has an estimated impact of less than 1 g SO_2 equivalent, with organic seed cotton production accounting for a large proportion.
- Freshwater eutrophication results from the oxygen required for the degradation of dead biomass due to high levels of nutrients (mainly nitrogen and phosphorus) released from sewage outfalls and fertilized farmland and the consequent accelerated growth of algae and other vegetation. The T-shirt production has a freshwater eutrophication potential of 2 g P to freshwater equivalents, with seed cotton production as a major contributor.
- Freshwater ecotoxicity addresses the toxic impact on an ecosystem, which damages individual species and changes the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem. The freshwater ecotoxicity that results from the T-shirt production adds up to 65 g of 1,4-DCB equivalent, mainly from the disposal of wastewater from the dyeing of a finishing unit and seed cotton production.
- Water use refers to the water consumed from the water extracted (e.g., via irrigation). The water consumed while producing one t-shirt is estimated at 10 m^3 due to the electricity production from renewable sources and irrigation for the organic cotton-seed production.
- Fossil resource use is related to the increase in fossil fuel extraction, which causes an increase in costs due either to a change in production technique or to sourcing from a costlier location. The production of a T-shirt retrieves a fossil fuel potential (FFP) of 195 g of oil equivalent from the combustion of fossil fuels for electricity and transport, apart from natural gas in the spinning, dyeing, and finishing units.

The main contributors' processes (hotspots) for each impact category are identified in Figure 5. With openLCA, it was also possible to identify the main contributor processed along the supply chain.

The T-shirt made with 50% RC + 50% OC has an impact of 14 m^2a crop eq on the land user category; 98.6% of this impact comes from the organic cotton fiber used as raw material on the spinning unit.

Organic cotton lint production generates more than 50% of the impact on categories such as fine particulate matter, ozone formation, freshwater eutrophication, marine eutrophication, land use, and stratospheric ozone depletion, while dyeing and finishing give the main contribution to freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity, marine ecotoxicity, and mineral resource scarcity.

As already referred to, the transport of the organic cotton from its origin until the factory was incorporated into the organic cotton production and delivery at the spinning unit, and transport between facilities was incorporated into each process (as applicable); nevertheless, the contribution to the climate change category is less than 8%.

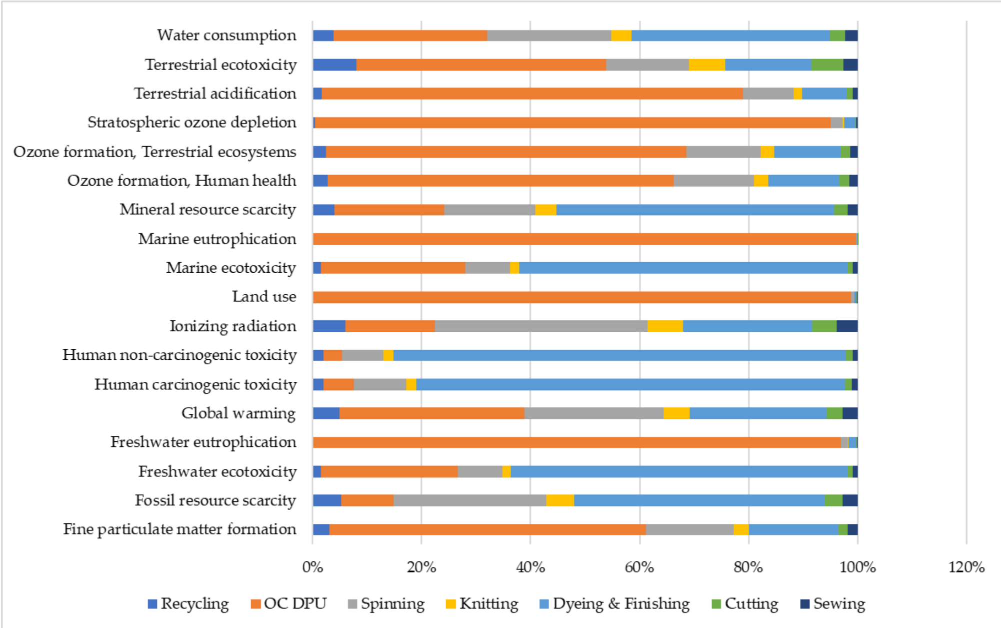

Figure 5. Impact per process of the T-shirt made with 50% recycled cotton and 50% organic cotton.

3.5. Data Quality Analysis—openLCA

LCA is a field in which commonly coupled primary data are collected in the processes under study with data bases that provide background life cycle inventory, and rarely, if ever, are the collected data a "perfect" match for representing the system being modeled [38]. The data quality assessment through a pedigree matrix supports the study's reproducibility and the results' reliability, as presented in Figure 6.

Name	Impact result	Unit	R	C	T	G	F
Fine particulate matter formation	0.00558	kg PM2.5 eq	3	3	3	4	2
Ionizing radiation	0.29227	kBq Co-60 eq	1	1	5	1	1
Fossil resource scarcity	0.97407	kg oil eq	2	2	5	2	1
Freshwater ecotoxicity	0.32694	kg 1,4-DCB	2	3	3	3	2
Stratospheric ozone depletion	2.60028E-5	kg CFC11 eq	4	5	2	5	2
Human non-carcinogenic toxicity	3.32446	kg 1,4-DCB	3	4	3	4	2
Freshwater eutrophication	0.01190	kg P eq	4	5	2	5	2
Marine eutrophication	0.02253	kg N eq	4	5	2	5	2
Marine ecotoxicity	0.42056	kg 1,4-DCB	2	3	3	3	2
Land use	14.10526	m2a crop eq	3	3	2	5	2
Water consumption	0.04793	m3	3	3	4	3	3
Terrestrial acidification	0.02711	kg SO2 eq	4	4	3	4	2
Terrestrial ecotoxicity	4.75342	kg 1,4-DCB	2	2	4	3	1
Ozone formation, Terrestrial ecosystems	0.01225	kg NOx eq	2	3	3	4	2
Human carcinogenic toxicity	0.47824	kg 1,4-DCB	1	1	5	4	3
Ozone formation, Human health	0.01103	kg NOx eq	3	3	3	4	2
Mineral resource scarcity	0.00594	kg Cu eq	2	2	4	1	1
Global warming	3.11523	kg CO2 eq	3	3	4	3	2

Figure 6. Impact analysis per 1 kg of T-shirts (5 T-shirts); Recipe 2016 Midpoint (H) with the results per category and with the data quality retrieved by openLCA.

The pedigree matrix was settled using the ecoinvent data quality system both for processes and flow, considering the following entries for primary data provided:

- Reliability: 3

- Completeness: 2
- Temporal correlation: 1
- Geographical correlation: 1
- Further technological correlation: 1

Global warming retrieved 3.12 kg CO_2 eq, with a classification of 3 for reliability, completeness, and geographic correlation, meaning most of the data came from non-verified data partly based on qualified estimates, with representative data from only some sites (<50%) relevant for the market considered or >50% of sites but from shorted periods, and data from areas with similar production conditions. For further technological correlation, we achieved a score of 2 based on data from processes and materials under study. Temporal correlation obtained the worst classification (4), meaning that it used a significant number of data with less than 15 years of difference in the time period of the data set.

3.6. Excel Spreadsheet Carbon Footprint—Results for the T-Shirt Made with 50% Recycled Cotton + 50% Organic Cotton

Validation of openLCA results was conducted by comparing the GWP_{100} result with the CF assessed based on the Excel spreadsheet calculation, which found that the impact is approximately 2.98 kg CO_2 eq per functional unit (1 kg of product) and 0.60 kg CO_2 eq per T-shirt (200 g). Information about carbon footprint contributions per process and per flow can be found in Table 10.

Table 10. Carbon footprint of 1 kg T-shirt made with 50% recycled cotton and 50% organic cotton.

GWP100 kg CO_2 eq/kg	Electricity	Natural Gas	Water	Chemicals	Wastewater	Transport Road	Transport Maritime	Org. Cotton Lint
Recycling	8.37×10^{-2}		3.73×10^{-6}	1.29×10^{-3}	-	1.81×10^{-2}	-	
Organic cotton at spinning unit	-	-	-	-	-	7.60×10^{-2}	8.55×10^{-2}	9.29×10^{-1}
Spinning	6.53×10^{-1}	1.57×10^{-2}	-	5.81×10^{-3}	-	-	-	
Knitting	1.05×10^{-1}	-	-	-	-	1.54×10^{-2}	-	
Dyeing and Finishing	2.47×10^{-1}	5.06×10^{-1}	2.68×10^{-4}	1.47×10^{-1}	6.94×10^{-4}	8.14×10^{-3}	-	
Cutting	3.70×10^{-2}	-	-	-	-	2.45×10^{-3}	-	
Sewing	4.20×10^{-2}	-	-	-	-	-	-	
Total	1.17×10^{0}	5.22×10^{-1}	2.72×10^{-4}	1.54×10^{-1}	6.04×10^{-4}	1.21×10^{-1}	8.55×10^{-2}	9.29×10^{-1}

In Figure 7, it is possible to see the percentage of the CF per flow and per process, including, in this last case, a comparison with the openLCA results.

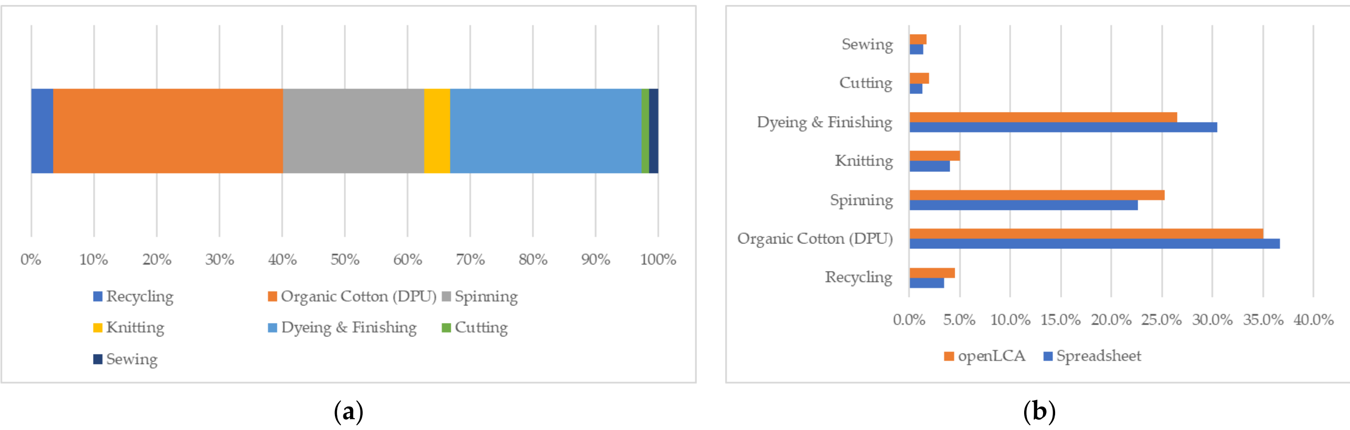

Figure 7. (**a**) Percentage of GWP_{100} impact per type per flow; (**b**) percentage of GWP_{100} impact per type per process and comparison of the spreadsheet and openLCA results. Organic cotton (DPU) represents the impact generated by organic lint cultivation, ginning, and transportation from Turkey to a recycling facility.

Electricity, organic cotton lint, and natural gas generate the major impact, being responsible for more than 85% of the total carbon emissions.

As is seen in Figure 7 above, the processes with the highest contribution are organic cotton lint production, spinning, and dyeing and finishing, responsible for 90% of the GHG emissions due to the high consumption of electricity, natural gas, and chemicals. These results are again plenty aligned with openLCA, which retrieves a global warming total impact of 85% for these three processes. This means a difference of more than 6% in the case of the results returned by the spreadsheet, mainly due to a higher impact for the organic cotton lint (37% for the spreadsheet versus 34% through openLCA) and dyeing and finishing processes (31% for the spreadsheet versus 25% through openLCA).

From the Excel spreadsheet, transport by truck represents 4% of the global footprint, compared to only 3% in container ships, which is aligned with the 7% global warming impact retrieved by openLCA.

3.7. Normalization

Environmental impacts were recalculated using the EF method (adapted) based on EF method 2.0 to enable normalization. This is the impact assessment method of the environmental footprint initiative, which considers 16 environmental categories that can be aggregated into a single score. The normalization was performed by applying the normalization factors (NF) of the JRC Technical Report 2017 [31] as presented in Figure 8. No weighting was considered for the calculation of a single score per T-shirt or comparison with the reference T-shirt on PEFC (PEF-RP).

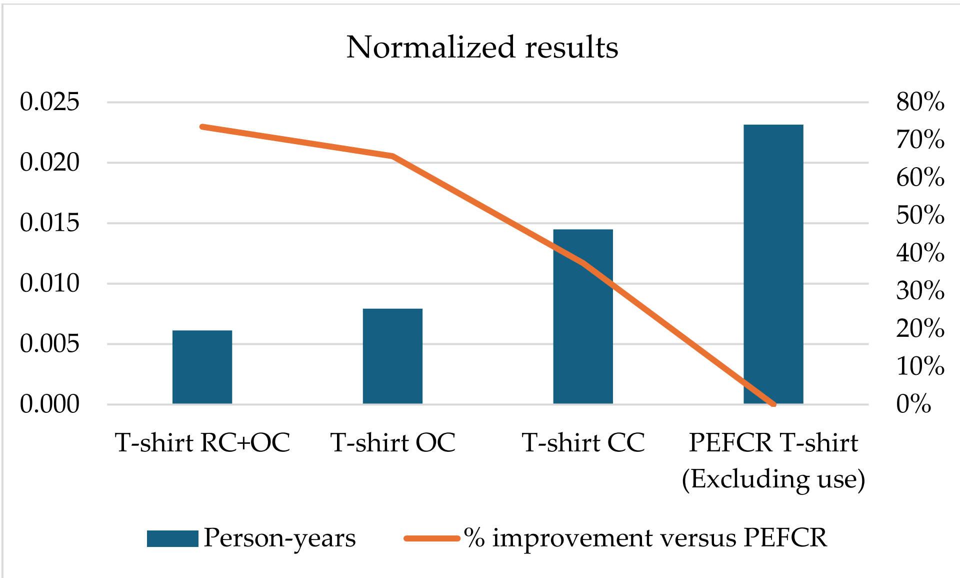

Figure 8. Single environmental score per 1 T-shirt with 200 g at the factory gate and percentage of improvement versus the PEF-RPT-Shirt (excluding use).

The normalization analysis demonstrates that the utilization of recycled cotton can lead to a 23% reduction in the environmental impact when compared to T-shirts manufactured solely with organic cotton. Furthermore, it exhibits a 58% improvement in environmental impact when contrasted with the T-shirt produced entirely from conventional cotton. These values are also compared with the PEFCR standard T-shirt, normalized for a T-shirt weighing 200 g, excluding the use phase, with emissions of 10.6 kg CO_2 eq/T-shirt and 0.0232 person-years of normalized environmental impact.

Scoring from A to E for enhanced consumer communication could be established by considering the normalized impact of the PEF-RP (person-years) as the most adverse scenario (E). This figure reflects the typical environmental impact of a T-shirt in the current phase of defining new European regulations, albeit not yet enforced. The optimal scenario (A) would hypothetically entail zero environmental impact, while B, C, and D denote incremental increases of 25% until reaching the worst-case scenario of E.

4. Discussion

Looking for KPIs to support the apparel sustainability scoring that can give accurate insights to support the consumer decision at the point of sale, it was also possible to give a contribution to valorize the use of recycled cotton, the garments production in Portugal, and openLCA as open access software for the calculation of the fashion products environmental burdens. In the study, we assumed that impacts related to use and disposal remain constant across the three scenarios, with no effect on relative results. This assumption allows us to focus on the specific changes introduced by each scenario without the confounding effects of varying use and disposal impacts, which highly depend on consumer decisions.

For the last few years, the Portuguese government has been implementing several initiatives to reduce the use of fossil resources in production, with a very positive impact on the reduction of GHG emissions. Modeling of the Portuguese electricity mix for the 2021 scenario improved the LCA results accuracy since it is a hotspot for climate change, resulting in a reduction of 51% on the CO_2 eq emission when compared with the ecoinvent default electricity flow related to the 2014 scenario. Portugal is ranked 19th in the world for low-carbon power, which monitors the transition to low-carbon energy [39].

Production with virgin conventional cotton or organic cotton in Europe implies long-distance transport since local production is very limited. Although the transport of virgin fiber only has a 5% impact on the CO_2 eq emission of the final product, this impact can be reduced to less than 3% when using the 50% of recycled fiber produced in Portugal. Comparing the impacts of each fiber at the lint gate, it is possible to verify that recycled cotton lint has far less environmental impact, with only 17% of the CO_2 eq emission of organic cotton and 5% of conventional cotton, with consequently better environmental performance for the T-shirt made with a percentage of recycled cotton fibers.

Dyeing and finishing houses have the heaviest contribution to environmental burdens in T-shirt production in the categories related to human toxicity and ecotoxicity, related to the intensive use of chemicals and processes. Some of the chemicals used were included in the existing generic flows according to their classification as inorganic or organic chemical products after applying the suitable upstream process, so there is some uncertainty in these results.

The openLCA evaluation can be complemented with the verification of the chemical products datasheets against Manufacturing Restricted Substances Lists (MRSL) and, for example, the ZDHC MRSL [40].

Referring to the openLCA assessment, each 1 kg T-shirt has a carbon footprint of 3.12 kg CO_2 eq. This value was validated by the spreadsheet calculation based on open-source emission factors, retrieving 2.98 kg CO_2 eq/kg. This 5% difference is acceptable, considering that openLCA integrates all the upstream impacts. With the validation of the GWP_{100}, it is assumed that the accuracy of the remaining impact categories will be validated.

The environmental impact of one T-shirt was calculated considering the weight of 200 g per T-shirt and is summarized in Figure 9.

The proposed "Envi-Score" (A to E) is derived from the Nutri-Score, the nutritional rating system recommended by the European Commission to showcase the overall nutritional value of food products that are well-recognized by consumers and widely adopted by retailers. It comprises five color categories (green, light green, yellow, orange, and red), correlating with the letters A (best) and E (worst), respectively. This scale aims to illustrate the environmental performance of products, facilitating quick and easy interpretation. By assigning an environmental score to each product, encompassing all environmental impacts into a single key performance indicator (KPI), consumer decision-making is simplified while also offering a comparison with a reference (PEF-RP, in this case). In this system, both T-shirts with 50% recycled cotton and 100% organic cotton achieved a B grade, while 100% conventional cotton T-shirts only got a C grade, showing lower overall environmental performance.

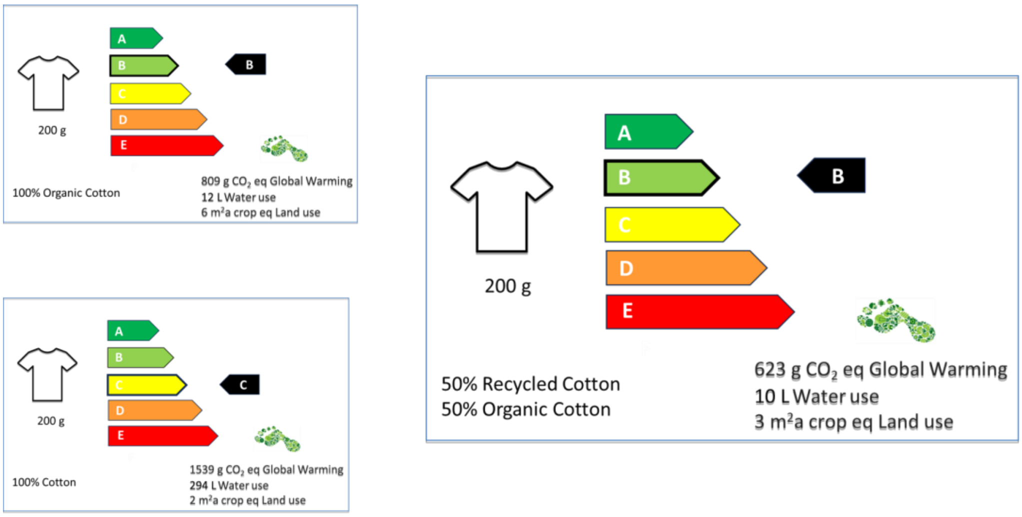

Figure 9. Proposal for product labeling to inform consumers about the environmental impact of the T-shirt through an environmental score (A to E) based on the KPI, normalized environmental impact, and the quantified KPIs carbon footprint, water use, and land use. These results are for cradle-to-gate production and do not consider the use phase.

In addition to the environmental rating system, the label provides supplementary information regarding the product's carbon footprint, water usage, and land utilization, offering additional insights for consumer decisions when the sensitivity of the scale is insufficient to differentiate products with similar environmental performance. For instance, distinguishing between a T-shirt made with recycled cotton and one made solely with organic cotton, both achieving a B score, but with a lower carbon footprint, water, and land use in the first case.

Information about composition and product mass is incorporated into the environmental label, emphasizing the impact on environmental performance. Implementing such an environmental scoring and labeling system could effectively discourage greenwashing practices, prompting companies to innovate and produce products with lower environmental footprints compared to those commonly available at the time of the latest PEF-RP study update.

5. Conclusions

This paper summarizes the life cycle assessment (LCA) calculations conducted using openLCA to examine the environmental impacts and environmental score of a T-shirt made in Portugal, containing 50% recycled cotton yarns, compared to an equivalent hypothetical T-shirt made solely with virgin cotton yarns (conventional or organic). The primary objective is to establish a set of Key Performance Indicators (KPIs) capable of summarizing the environmental performance of products for transparent communication with consumers.

Encouraging sustainable consumer behavior is not merely a suggestion but a legal requirement under new European legislation. Specifically, the legislation mandates the use of life cycle assessment (LCA) to accurately assess the environmental impact of products. In industries like textiles, known for their significant pollution levels, comprehensive consumer information is now mandated to facilitate informed decision-making. Initiatives such as the digital product passport are increasingly essential, offering consumers transparent details about a product's environmental footprint. Given the textile industry's importance in Portugal, it is imperative to swiftly adapt to these new requirements. However, Portugal also enjoys a competitive advantage in producing more sustainable textiles, thanks to factors such as reduced carbon footprints in electricity production, increasing use of solar renewable energy, and closed-loop integrated manufacturing processes covering all production stages. Virgin cotton fiber production in Portugal is limited, necessitating imports from distant regions with additional environmental footprints. This study demonstrates the potential for optimization through increased use of recycled cotton fibers.

Embracing these regulations offers Portugal an opportunity not only to meet legal requirements but also to strengthen its position as a leader in sustainable textile production. Portugal can produce recycled cotton fibers and final products, such as T-shirts, with a very low carbon footprint (0.155 kg CO_2 eq/kg for recycled cotton fiber and 3.12 kg CO_2 eq/kg for a white T-shirt) [13] and reduced overall environmental impact. This approach can help mitigate the disadvantage of not being a cotton-producing country through enhanced recyclability. This study only addresses "cradle-to-gate" environmental impacts, failing to demonstrate Portugal's advantage as a proximity producer to the European consumer market, with lower distribution impacts and small batch production tailored to demand, thus avoiding overproduction waste.

While estimating a product's impact on global warming can be conducted through a simple spreadsheet, openLCA, coupled with the ecoinvent database, significantly aids in calculating the environmental footprint of products by considering various impact categories. openLCA has proven to be an effective and readily accessible software for conducting LCA studies in the apparel industry, aiding in the democratization of these studies. However, the drawback of openLCA lies in the cost of maintaining the database and the challenge of consumer comprehension.

In conclusion, the following KPIs and a template for the environmental label (Figure 10) are proposed to summarize the environmental performance of products:

- "Envi-Score": This KPI combines environmental impacts into a single metric by normalizing different impact categories into the same units (person-years) and comparing them with the European reference defined at PEF-RP. It results in a scale from A (green) to E (red), aiming to illustrate product environmental performance for easy interpretation at the point of sale.
- Global warming potential is expressed in grams of CO_2 equivalent per product.
- Water use is expressed in liters per product.
- Land use is expressed in square meters of crop equivalent.

In the context of the energy transition, with the move towards a fully decarbonized power supply, it is crucial to draw attention to other finite resources depleted during production, such as water consumption due to the threat of water scarcity and land use often associated with deforestation. Information about the "Bill of Materials" is included in the label, emphasizing the materials' impact on environmental performance, while the product's mass facilitates easier benchmarking.

The proposed labeling initiative aims to contribute to the development of the European Eco-score methodology for apparel. It seeks to provide consumers with accurate information, helping them make more sustainable choices. Implementing such an environmental scoring and labeling system could effectively deter greenwashing practices, encouraging companies to innovate and develop products with reduced environmental footprints compared to those commonly available at the time of the latest PEF-RP study update. However, ensuring that the environmental performance of products can be accurately compared requires guaranteeing that these key performance indicators (KPIs) are calculated using the same methodology and adhere to the same minimum requirements. This necessity can lead to exploring new areas of study, justified by the interest in expanding the scope of the analysis to include "cradle-to-grave" considerations and providing concrete information about product durability in alignment with the Product Environmental Footprint Category Rules (PEFCR) to enhance the conclusions. Additionally, emphasis is placed on the importance of establishing a dedicated process for assessing the toxicity of chemicals used in production as well as addressing social aspects along the supply chain.

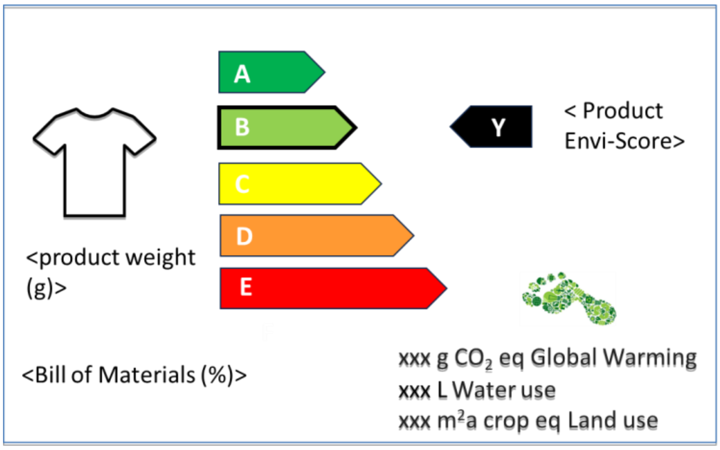

Figure 10. Proposed template for the environmental label.

Author Contributions: Conceptualization, C.S. and A.G.; Methodology, C.S. and A.G.; software, A.G.; validation, M.B., A.G. and C.S.; formal analysis, A.G. and M.B.; investigation M.N.; resources, C.S.; data curation, A.G. and M.B.; writing—original draft preparation, A.G.; writing—review and editing, A.G. and C.S.; visualization, A.G.; supervision, C.S.; project administration, C.S.; funding acquisition, C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC)—UIDB/50019/2020 (https://doi.org/10.54499/UIDB/50019/2020), UIDP/50019/2020 (https://doi.org/10.54499/UIDP/50019/2020), and LA/P/0068/2020 (https://doi.org/10.54499/LA/P/0068/2020).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

Acknowledgments: Special thanks to the data provided by Valérius 360, which is crucial for the life cycle inventory specific to Portugal.

Conflicts of Interest: Author Miklós Nagy was employed by the company Valérius 360. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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