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A Comparative Life Cycle Assessment of T-Shirt Production Using from Viscose, Lyocell, Cotton, and Polyester

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Abstract

This study presents the first cradle-to-gate life cycle assessment (LCA) of T-shirt production using viscose and Lyocell fibers, benchmarked against cotton and polyester under consistent system boundaries. The analysis covers spinning, knitting, wet processing, garment assembly, and regionalized energy supply. Results show that cotton T-shirts exhibit the lowest global warming potential (14.1 kg CO_2eq/kg) but the highest water demand (2.9 m^3/kg) in China. Polyester garments, although less water-intensive, contribute significantly to plastic accumulation (1.0 kg/kg shirt) compared to cellulose-based fibers (0.1 kg/kg shirt). Within man-made cellulose fibers, Lyocell generally outperforms viscose in toxicity-related categories—reducing freshwater ecotoxicity by 35% and human non-carcinogenic toxicity by 62%—thanks to its closed-loop solvent recovery. However, Lyocell also shows the highest carbon footprint (21.6 kg CO_2eq/kg) unless produced in regions with cleaner energy mixes. Regional sensitivity analysis indicates that shifting production from China to Brazil could reduce global warming impacts by up to 38%. Overall, these results highlight the trade-offs across fiber types and demonstrate the importance of both material choice and production geography in driving sustainability within textile supply chains.

Keywords: man-made cellulose fibers; textile sustainability; life cycle assessment; natural fibers; synthetic fibers

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1. Introduction

Population growth, lifestyle changes, and human activities have significantly impacted the planet's climate. From 2011 to 2020, global surface temperatures were 1.1 °C higher than between 1850 and 1900, with projections ranging from a 1.5 °C increase in the best-case scenario to 4.5 °C in extreme cases [1]. This temperature rise could put 3–14% of terrestrial species at risk of extinction and lead to the disappearance of 70–90% of coral reefs [1]. In 2022, global carbon dioxide emissions reached 36.1 Gt, a 1.5% increase from 2021 [2], with clothing and footwear production responsible for an estimated 10% of global emissions [3,4].

Within this context, textile fibers fall into two categories: natural (like cotton, linen, silk, and wool) and man-made. Natural fibers are produced from plants or animals and are processed into yarn through mechanical treatment. Man-made fibers are created from synthetic polymers or natural polymers like cellulose [5].

In 2024, 128 million tons of textile fibers were produced worldwide; this figure is expected to grow to 149 million tons in 2030 [6]. Of the total fiber production, 60% is polyester, 19% is cotton, 6% is man-made cellulose fibers, 5% is nylon, 1% is wool, and 9% other fibers [7]. Moreover, pre- and post-consumer recycled textiles represent less than 1% of the total market [6].

Polyester is a fossil-based, non-biodegradable polymer widely used in clothing due to its rapid drying, strength, low cost, and versatility [4]. However, its contribution to microplastic pollution is concerning, accounting for 35% of microplastics in oceans, affecting marine life and soil microbial diversity [8–10]. While polyester can be recycled, it made up only 14.8% of the fiber market in 2021 [6].

Cotton, on the other hand, is the natural fiber with the highest contribution to the fashion industry. Its production is highly carbon-intensive due to the extensive use of land, fertilizers, pesticides, and water [4,11]. Although some techniques have been applied to reduce the environmental impact of cotton production, such as organic cotton, cotton alone cannot meet the increasing demand for textile fibers.

Man-made cellulose fibers (MMCFs) are plant-based materials derived from dissolving-grade pulp and processed into fibers through either derivatization or direct dissolution routes. MMCFs are expected to reach 8.6 million tons by 2027, with over 80% produced in Asia and 60% in China [12,13]. Viscose dominates MMCFs production (~80%), followed by acetate (13%), Lyocell (4%), and modal (3%) [6,14].

Viscose, Lyocell, cotton, and polyester fibers were estimated to be produced at rates of 6.4, 0.7, 26.4, and 90 million tons in 2024, respectively (Figure 1) [15–17]. While MMCFs represent a relatively small share of total fiber production (~7.1 million tons), their role is expanding due to their renewable origin and potential to complement cotton supply.

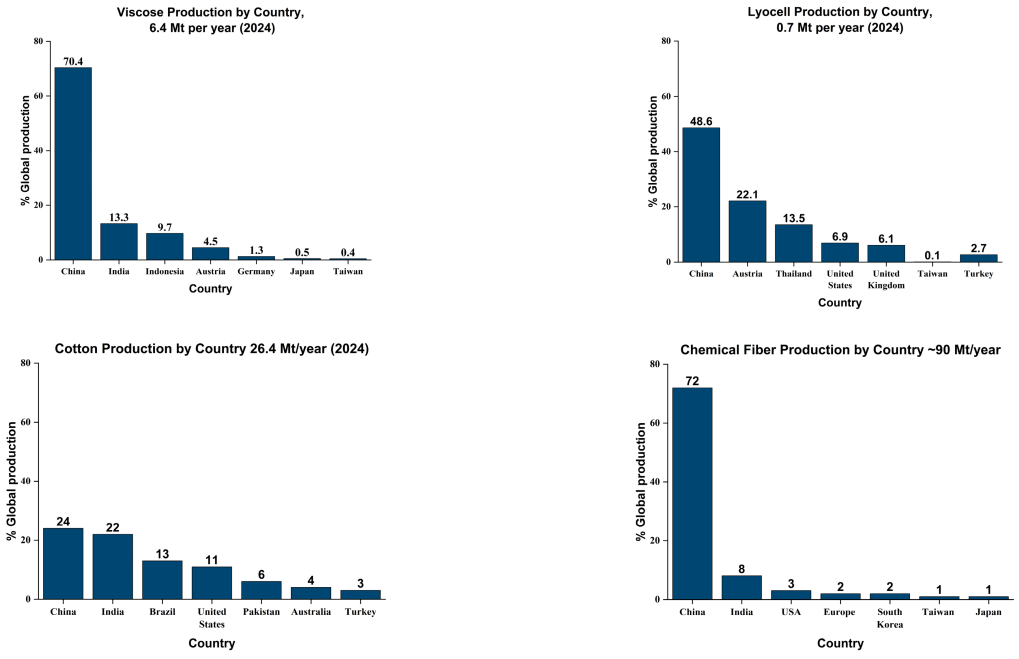


Figure 1. Global production of viscose, Lyocell, cotton, and polyester fibers for 2024 [15–17].

Viscose fibers are produced through a chemical derivatization process in which cellulose is treated with sodium hydroxide and carbon disulfide (CS_2) to form cellulose xanthate, which is subsequently regenerated into fibers in an acidic coagulation bath (Figure S1) [13,18,19]. This process is associated with significant chemical consumption and potential emissions, particularly related to CS_2, which contribute to its environmental

profile [20]. Viscose is the dominant man-made cellulosic fiber, with a global production of approximately 6.4 million tons per year, representing around 80% of MMCFs (Figure S2).

Lyocell fibers are produced via a direct dissolution process in which cellulose is solubilized in N-methylmorpholine-N-oxide (NMMO) and regenerated into fibers without chemical derivatization (Figure S3) [18]. The process operates in a closed-loop system with high solvent recovery rates, which reduces chemical emissions but requires higher energy input for solvent recovery and purification [21]. In contrast to viscose, Lyocell accounts for a much smaller share of MMCF production, with a global output of approximately 0.7 million tons per year (Figure S4).

A limited number of life cycle assessment (LCA) studies have evaluated the environmental performance of textile fibers. However, existing research on MMCFs has predominantly focused on upstream processes, particularly the production of staple fibers [22–24]. Similarly, comparative LCAs involving commercial fibers such as cotton and polyester have been mainly confined to cradle-to-fiber or cradle-to-yarn system boundaries [25–29]. As a result, the environmental implications of garment manufacturing for MMCFs remain underexplored in the scientific literature.

This study aims to quantify and compare the environmental impacts of T-shirt production from viscose, Lyocell, cotton, and polyester using a cradle-to-gate life cycle assessment. In doing so, it addresses a critical gap by incorporating the full manufacturing process for man-made cellulose fibers—including spinning, knitting, wet processing, and garment assembly—under consistent methodological assumptions. The analysis incorporates primary and secondary data, regionalized energy supply scenarios, and a comprehensive impact assessment using the ReCiPe 2016 (H) method, along with a midpoint indicator for plastic pollution. This integrated approach enables a robust comparison of fiber choices at the product level, offering decision-relevant insights for sustainable textile supply chains.

2. Materials and Methods

The methodology of this study follows the standard LCA framework defined by ISO 14040 [30] and ISO 14044 [31], including goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The following sections describe the system boundary (Section 2.1), data collection procedures (Section 2.2), modeling assumptions, impact assessment methods (Section 2.3), and geography selection (Sections 2.4 and 2.5) to ensure a consistent comparison across fiber types and regions.

2.1. System Boundary

Figure 2 illustrates the cradle-to-gate system boundary (SB) and mass balances required to produce one kilogram of cotton, polyester, viscose, and Lyocell shirts. Contributions from raw material production (cotton lint, resin, and eucalyptus chips) are also included in the calculations (Figure S5). The cumulative total losses for producing a cotton shirt add to 31%, while a polyester shirt is 27% due to more conservative losses during the knitting and wet processing/finishing stages. For viscose and Lyocell, losses are 31% if tracked from the spinning stage and 73.8% if tracked from the eucalyptus chips used for DP production. All textile-related waste is assumed to be incinerated without energy recovery, with no CO_2 release for natural fibers and MMCFs to be considered as biogenic, and emissions of 2.31 kg CO_2 per kg of synthetic fibers.

2.2. Data Collection

Data collection was performed to support the defined system boundary, covering raw material production, fiber processing, textile manufacturing, and garment assembly (Figure 2). This study is based on a modeling approach using secondary data and pro-

cess simulation; no experimental or industrial-scale production was conducted as part of this work.

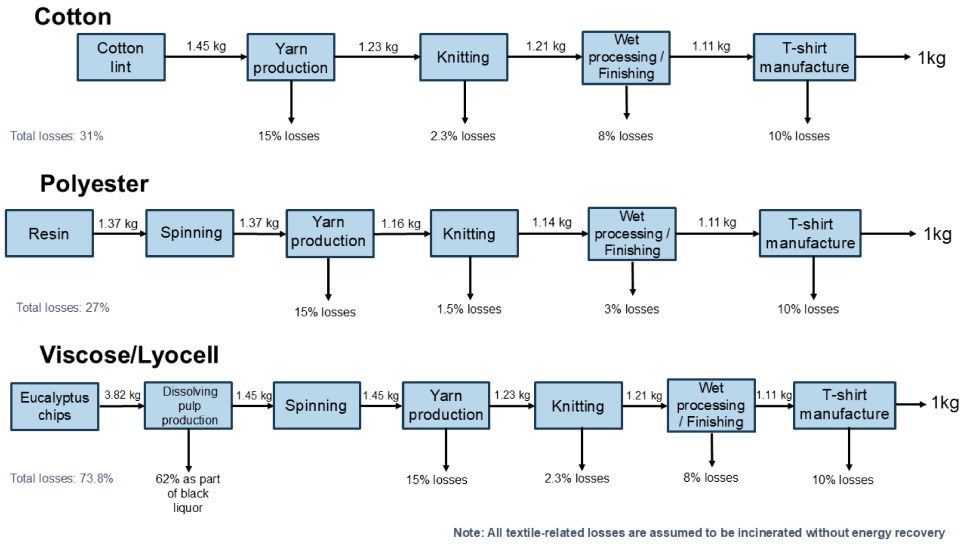


Figure 2. Cradle-to-gate system boundary to produce 1 kg of shirts made of cotton, polyester, viscose, and Lyocell fibers.

For the construction of the life cycle inventory company reports, scientific articles, and theses were used to track information regarding the inputs and outputs for the process. The search was not limited to LCA analysis, as some studies were focused on LCI development only, rather than LCA. Particularly for dissolving pulp production, a computational model was developed in this article and is explained in Section Dissolving Pulp Production.

For the central analysis, average values for the variables were selected. Moreover, a Monte Carlo analysis was conducted to evaluate the variability of the life cycle inventory parameters. Input variables were modeled using uniform probability distributions, with lower and upper bounds defined by the minimum and maximum values reported in the literature ranges. A total of 1000 iterations were performed using the Monte Carlo simulation module in openLCA (version 2.6.1). This number of iterations was selected to ensure stable results while maintaining computational efficiency. Simulations were executed on a standard workstation without the need for parallel computing. The use of uniform distributions was considered appropriate due to the limited availability of detailed statistical data for most input parameters.

As China is the largest country producer, data collection was primarily focused on Chinese practices, isolating the regional effect and making the comparison by fiber type more accurate (Figure S6, Section 2.4). Further analysis examined changes in the region where the raw-material processing takes place (from spinning to T-shirt manufacture) to the geographies of the USA, Europe, and Brazil (Section 2.5).

Dissolving Pulp Production

Approximately 1.2 million tons of viscose-grade dissolving pulp are produced in China, the largest producer. Approximately 90.5% of the Chinese viscose-grade DP is produced using pre-hydrolysis kraft (PHK), with 58% of the production coming from eucalyptus biomass [32].

To create our model, a comprehensive data collection was conducted for each Chinese PHK mill, encompassing its operational conditions, location, and annual production. Then, weighted factors were calculated based on each mill's productivity, and an average operational model was created using WinGEMS© Version 5.4, a specialized software for the pulp and paper industry. Average operational conditions are summarized in Table 1, while the LCI is detailed in Table S1.

Table 1. Average operational conditions for Chinese viscose-grade DP (PHK) based on productivity-weighted factors [32].

Parameter	Value
Power self-sufficiency (%)	88.6
Pre-hydrolysis yield (%)	84.1
Digester yield (%)	41.4
Total mill yield (%)	36.3
Fuel composition, power boiler (%)	Coal: 90 Sludge: 10
Mill's power self-sufficiency (%)	87.3
Digester type	Continuous
Fuel composition, lime kiln (%)	Coal: 100
Oxygen delignification stage	Yes
Bleaching sequence	O-D-Eo-D-D
ClO_2 generator type	SVP-lite
Total energy consumption (GJ/air-dry ton pulp)	23.1

2.3. Life Cycle Assessment

This study aims to quantify the LCA of 1 kg of T-shirts produced with either cotton, polyester, Lyocell, or viscose. The system boundary follows a cradle-to-gate approach (Figure 2). To address the inherent differences among fibers, results based on the tenacity of the yarn fibers will be presented throughout the manuscript and in the Supplementary Materials. A basic weight of 250 g for a medium-size cotton shirt was used as a baseline, resulting in a force limit of 3,725 g·cN/tex. According to the yarn tenacity values provided in Table 2, the equivalent T-shirt masses required to withstand the same level of force are 115 g for polyester, 153 g for Lyocell, 250 g for viscose, and 250 g for cotton. Therefore, fibers with higher tenacity, such as polyester and Lyocell, can achieve the required strength at a lighter weight.

Table 2. Mechanical properties of selected MMCFs and benchmarks [33].

Fiber	Mean Density of the Yarn (g/cm^3)	Tenacity (cN/tex)	Breaking Elongation (%)
Lyocell	0.63	24.3	8.8
Viscose	0.53	14.9	14.7
Cotton	0.44	14.9	6.1
Polyester	0.55	32.5	11.8

The LCI comprises two parts. First, the DP production, which encompasses all relevant inputs and outputs from cradle to mill gate, was simulated utilizing WinGEMs' simulation package Version 5.4 (Section Dissolving Pulp Production). Second, data was collected on the raw material production, spinning, knitting, wet processing, finishing, and T-shirt manufacture (Figure 2) and summarized in Tables 3–5. For the LCIA, the open-source openLCA software Version 2.6.1, with access to the Ecoinvent 3.10 database, was utilized. ReCiPe (hierarchical) was set as the methodology for its comprehensive evaluation across eighteen impact categories, including global warming potential (GWP). This study used a 100-year time horizon as its base. A key limitation of existing LCA methodologies is the quantification of plastic pollution effects. Consequently, this article employs a simplified model to address this variable, which is examined in greater detail in Section Plastic Pollution.

Allocation selection was not needed for Lyocell staple fiber production due to the absence of by-products. In contrast, viscose staple fiber production generates sodium sulfate as a by-product at a rate of 0.6 kg per kg of fiber, with a 50% recovery efficiency [20]. Since viscose fibers are the primary product and sodium sulfate has a much lower revenue, environmental impacts were allocated based on economic partitioning. Viscose fibers were priced at USD 2000 per ton, while sodium sulfate was valued at USD 180 per ton [34,35]. Consequently, 97.4% of the environmental burdens were assigned to viscose fibers, and 2.6% to sodium sulfate.

Table 3. Life cycle inventory to produce a cotton T-shirt.

Stage	Parameter	Value	Range	Unit	Reference	Notes
Cotton cultivation	Yield cotton lint	2.33	-	t/ha	[17]	The yield selected corresponds to 2024/2025
	Yield cotton seed	2.9	-	t/ha	[17]	The yield selected corresponds to 2024/2025
	Nitrogen fertilizer	116.3	68.4–176.8	kg N/t cotton lint	[25–27,36–39]	
	Phosphate fertilizer	77.4	20.2–118.1	kg P_2O_5/t cotton lint		
	Potassium fertilizer	49.4	20.2–124.0	kg K_2O/t cotton lint		
	Pesticides	5	1.4–10.0	kg/t cotton lint		
	Herbicides	1.3	0.3–2.0	kg/t cotton lint		
	Diesel	60.6	8.0–81.8	kg/t cotton lint		
	Electricity	657.3	253.8–1070.0	kWh/t cotton lint		
	Agricultural film	30.6	26.6–34.0	kg/t cotton lint		
	Seeds	22	12.6–32.8	kg/t cotton lint		
	Irrigation water	2310	15–2821	m^3/t cotton lint	[40]	The average value corresponds to the Xinjiang region. The lowest and upper values correspond to the Hebei and Gansu regions, according to the mentioned reference
	Rail transportation of cotton lint	4002	-	Km	This study	Transportation from Xinjiang to Zhejiang of cotton lint
Yarn production, ring spin	Electricity consumption	3.2	1.7–5.0	kWh/kg undyed yarn	[38,41–48]	
	Water consumption	8.7	8.3–9.1	L/kg undyed yarn		
	Losses in spinning	14.9	-	% incoming material		
Knitting	Electricity	0.56	0.09–1.39	kWh/kg undyed fabric	[41,42,48]	
	Losses in knitting	2.3	-	% incoming material		

Table 3. *Cont.*

Stage	Parameter	Value	Range	Unit	Reference	Notes
Wet processing/Finishing	Electric power	0.76		kWh/kg dyed fabric	[41]	A single reference for wet processing was selected to avoid chemical's double accounting
	Steam	24.1		MJ/kg dyed fabric		
	Water	159.6		L/kg dyed fabric		
	Wetting agent	1.1		g/kg dyed fabric		
	Desizing enzyme	0.3		g/kg dyed fabric		
	Acetic acid	4.3		g/kg dyed fabric		
	Sequestering agent	2.1		g/kg dyed fabric		
	Salt	74.5		g/kg dyed fabric		
	Soda ash	21.3		g/kg dyed fabric		
	Dyestuff	4.4		g/kg dyed fabric		
	Soap	1.1		g/kg dyed fabric		
	Cationic softener	2.1		g/kg dyed fabric		
	Silicon	1.1		g/kg dyed fabric		
	Antigrease agent	1.1		g/kg dyed fabric		
	Caustic soda	2.7		g/kg dyed fabric		
	Hydrogen peroxide	2.7		g/kg dyed fabric		
	Oil-removing agent	0.5		g/kg dyed fabric		
	Stabilizer	0.5		g/kg dyed fabric		
	Sodium thiosulphate	1.1		g/kg dyed fabric		
	Losses	8		% incoming material		
T-shirt manufacture	Electricity	0.56		kWh/kg shirt	[41]	
	Losses in T-shirt manufacture	10		%		

Table 4. Life cycle inventory to produce a polyester T-shirt.

Stage	Parameter	Value	Range	Unit	Reference	Note
Resin	Polyethylene terephthalate	1	-	kg/kg staple fiber	[49]	
	Rail transportation of PET resin	1329	-	Km	This study	Transportation from Guangdong to Zhejiang of PET
Staple fibers production	Electricity	0.66	0.64–0.69	kWh/kg undyed yarn	[22,50,51]	
	Heat	4.9	4.8–5.0	MJ/kg undyed yarn		
	Losses in spinning	15	-	% incoming material	[52]	
Knitting	Electricity	0.35	-	kWh/kg undyed fabric	[51]	
	Heat	0.19	-	MJ/kg undyed fabric		
	Losses in knitting	1.5	-	%	[52]	
Wet processing/Finishing	Electricity	0.47	-	kWh/kg dyed fabric	[53]	
	Steam	22.9	-	MJ/kg dyed fabric		
	Sodium carbonate	0.1	-	g/kg dyed fabric		
	Sodium dithionite	0.7	-	g/kg dyed fabric		
	Stabilizing	1	-	g/kg dyed fabric		
	Detergent	2.3	-	g/kg dyed fabric		
	Disperse dye	2.2	-	g/kg dyed fabric		
	Water	28	-	L/kg dyed fabric		
	Losses	3	-	% incoming material	[52]	
T-shirt manufacture	Electricity	0.56	-	kWh/kg shirt	[41]	
	Losses in T-shirt manufacture	10	-	%		

The process for yarn production (ring spin) is assumed to be the same as the one presented in Table 3.

Table 5. Life cycle inventory to produce a viscose or Lyocell T-shirt.

Stage	Parameter	Value	Range	Unit	Reference	Notes
Eucalyptus cultivation	Nitrogen	5	-	kg/m^3 harvested timber	[54]	
	Phosphate fertilizer	2.8	-	kg P_2O_5/m^3 harvested timber		
	Potassium fertilizer	2.4	-	kg K_2O/m^3 harvested timber		
	Gasoline, chainsaw	0.12	-	kg/m^3 harvested timber		
Eucalyptus chips	Eucalyptus logs	1.11	-	m^3/m^3 chips		
	Diesel	1	-	kg/m^3 chips		
	Land transportation of chips (rail)	711	-	Km	This study	Transportation from Forests to Shandong port, and from Qingdao port to the pulp mill
	Ship transportation of eucalyptus chips	2307	-	Km	This study	From Shandong port to Qingdao port
Dissolving pulp production	Eucalyptus chips	2.48	-	kg/kg dissolving pulp (90% solids)	This study	Inputs were calculated as part of the process simulation for Chinese dissolving pulp mills. For a more detailed LCI on DP production, see Supplementary Materials (Table S1).
	NaOH	52.2	-	g/kg dissolving pulp (90% solids)		
	Na_2SO_4	32.9	-	g/kg dissolving pulp (90% solids)		
	CaO	17.8	-	g/kg dissolving pulp (90% solids)		
	H_2O_2	1.9	-	g/kg dissolving pulp (90% solids)		
	H_2SO_4	22.6	-	g/kg dissolving pulp (90% solids)		
	O_2	24.7	-	g/kg dissolving pulp (90% solids)		
	$NaClO_3$	27.1	-	g/kg dissolving pulp (90% solids)		
	CH_3OH	2.8	-	g/kg dissolving pulp (90% solids)		
	Coal	175.2	-	g/kg dissolving pulp (90% solids)		
	Electricity	186.2	-	Wh/kg dissolving pulp (90% solids)		
	Water	26.5	-	L/kg dissolving pulp (90% solids)		
Viscose staple fibers (stand-alone facilities)	Viscose-grade dissolving pulp	1	-	kg/kg viscose staple fiber	[20,24,55–58]	
	Rail transportation of DP to the pulp mill	914	-	Km		Transportation from the pulp mill to Jiangxi
	Electricity	0.97	0.74–1.15	kWh/kg viscose staple fiber		

Table 5. *Cont.*

Stage	Parameter	Value	Range	Unit	Reference	Notes
Viscose staple fibers (stand-alone facilities)	Steam	21.5	19.4–25.5	MJ/kg viscose staple fiber	[20,24,55–58]	
	Water consumption	50.9	29.7–130.0	L/kg viscose staple fiber		
	CS_2	85.7	60.0–100.0	g/kg viscose staple fiber		
	H_2SO_4	0.77	0.60–1.03	kg/kg viscose staple fiber		
	NaOH	0.55	0.40–0.70	kg/kg viscose staple fiber		
	Zn	12.2	3.0–33.2	g/kg viscose staple fiber		
	Spin finish	4.3	-	g/kg viscose staple fiber		
	NaOCl	33.3	0–50.0	g/kg viscose staple fiber		
Viscose staple fibers	Rail transportation of viscose staple fibers	587		Km	This study	Transportation from Jiangxi to Zhejiang
Lyocell staple fibers (stand-alone facilities)	Viscose-grade dissolving pulp	1	-	kg/kg Lyocell staple fibers	[24,59,60]	
	Rail transportation of DP to the pulp mill	467	-	Km		Transportation from the pulp mill to Jiangsu
	Electricity	1.6	1.4–1.8	kWh/kg Lyocell staple fibers		
	Steam	24.4	21.3–27.4	MJ/kg Lyocell staple fibers		
	Water consumption	14.8	10.3–19.4	L/kg Lyocell staple fibers		
	NMMO *	54.3	40.0–68.6	g/kg Lyocell staple fibers		The life cycle inventory was generated based on the study of Righi et al. and is summarized in the Supplementary Materials (Tables S1 and S2).
	Spin finish	1.5	-	g/kg Lyocell staple fibers		
	H_2O_2	42.3	-	g/kg Lyocell staple fibers		
	HCl	214.1	150.0–278.3	g/kg Lyocell staple fibers		
	NaOH	158.4	116.8–200.0	g/kg Lyocell staple fibers		
	Propyl gallate	1.8	-	g/kg Lyocell staple fibers		
	Hydroxylamine	0.9	-	g/kg Lyocell staple fibers		
Lyocell staple fibers	Rail transportation of Lyocell staple fibers	316	-	Km	This study	Transportation from Jiangsu to Zhejiang

Note: Stages for yarn production (ring spinning), knitting, wet processing/finishing, and T-shirt manufacture are approximated to those of cotton (Table 3). * The LCI for NMMO production was collected from the literature and are reported in the Supplementary Materials (Table S2).

Plastic Pollution

Several recent studies have made efforts to integrate plastic pollution metrics into LCAs, acknowledging the environmental burden posed by microplastic and fiber emissions, including those from textiles. Notably, there has been progress in proposing fate-based characterization factors and frameworks to capture the persistence and distribution of plastic pollutants in the environment [61].

However, as highlighted by Sabate and Kendall (2024), there is currently no standardized or widely accepted methodology within LCA to consistently account for plastic emissions, particularly those related to losses during use or disposal stages, such as fiber shedding from textiles [62].

The lack of harmonized impact indicators and the variability in data on degradation, exposure, and ecological effects contribute to this gap, underscoring the urgent need for methodological consensus in incorporating plastic pollution into LCIA models.

A simplified approach was employed in this article, building upon the previous work of Echeverria et al. (2021) [63]. Based on the relative aquatic and soil biodegradability, a plastic accumulation potential (PAP) was defined (Table 6). Cellulose-based fibers show approximately 90% biodegradation in water and soil environments [64,65], while some other studies report 100% biodegradation for wood-based cellulose fabrics in the marine environment [66]. Therefore, out of 1 kg, it is estimated that 10% will remain in the environment for longer than 100 years. Comparatively, polyester fibers are non-biodegradable, and therefore their PAP is 1 kg/kg shirt. PAP was added as an additional midpoint category, alongside the ReCiPe categories.

Table 6. Parameters for the calculation of plastic pollution as a midpoint category [63].

Raw Material	Relative Aquatic Biodegradability (%) [65]	Weight Loss in Soil (%) [64]	Plastic Accumulation Potential (kg/kg Shirt)
Cotton	90	90	0.1
Viscose	88	90	0.1
Lyocell	88	90	0.1
Polyester	0	0	1.0

Although this study presents the endpoint categories for ReCiPe—ecosystem quality, natural resources, and human health—there is no direct translation for plastic pollution from a midpoint category to an endpoint category. As a result, plastic pollution was not included in the ReCiPe endpoint categories.

2.4. Chinese Scenario

As discussed in previous sections, the production of market textile fibers predominantly occurs in China (Figure 1). Therefore, a specific case study focusing on the Chinese context was developed. The power requirements in this scenario are met using the average Chinese grid-based electricity, as modeled in the Ecoinvent 3.10 dataset. Steam requirements are assumed to be fulfilled through internal production processes.

The fuel mix for steam sourcing was established based on data from the International Energy Agency (IEA) for China's total energy supply by source. The distribution was set as follows: 67.7% coal, 8.9% natural gas, 20.2% biofuels and waste, and 3.2% oil [67].

To evaluate the influence of geographic variability, additional scenarios were developed by modifying the regional Chinese energy supply while keeping process parameters constant, which are further discussed in Section 2.5.

2.5. Sensitivity Analysis: Region of Processing

To analyze global production, the United States, Europe, and Brazil were chosen to examine how the Global Warming Potential (GWP) varies with changes in processing regions. Therefore, the raw materials (dissolving pulp, PET resin, and cotton lint) remain as studied in Section 2.4, and the remaining operations within the system boundary were performed in the other selected regions.

The selection of these countries/regions was based on their contrasting energy mixes and relevance to the global textile market. These regions represent a spectrum from carbon-intensive systems (e.g., China) to lower-carbon systems with higher shares of renewable energy (e.g., Brazil and Europe), with the United States as an intermediate case. This enables a structured sensitivity analysis to isolate the effect of regional energy supply on environmental impacts while maintaining consistent process assumptions. The power supply was tailored to each region, utilizing region-specific electricity grid data from the Ecoinvent 3.10 database. Steam generation was regionalized based on the IEA dataset, revealing a distribution for the United States of 11.7% coal, 41.0% natural gas, 5.1% biofuels and waste, and 42.2% oil; for Europe, it was 16.7% coal, 30.4% natural gas, 13.1% biofuels and waste, and 39.8% oil; and for Brazil, it was 5.4% coal, 10.2% natural gas, 40% biofuels and waste, and 44.5% oil [67].

3. Results and Discussion

3.1. Chinese Scenario

In the Chinese scenario, Lyocell fibers exhibit a higher carbon footprint compared to viscose fibers, as depicted in Figure 3A. The primary differences in GWP arise from variations in energy consumption during staple fiber production, where Lyocell production requires higher heat and electricity inputs due to the energy-intensive solvent recovery and purification stages (Tables S3 and S4). Although chemical-related emissions are higher for viscose than for Lyocell T-shirts (2.99 kg CO_2eq/kg vs. 3.85 kg CO_2eq/kg), these are mainly associated with the use of carbon disulfide (CS_2), sulfuric acid, and other chemicals during the spinning process.

These differences reflect the underlying dissolution mechanisms: viscose relies on a derivatization route involving CS_2, leading to higher chemical intensity and associated emissions, whereas Lyocell uses a non-derivatizing NMMO-based process with high solvent recovery, resulting in lower toxicity impacts but higher energy demand.

Cotton T-shirts have the lowest GWP due to the absence of a spinning stage, where the cotton lint, similar to staple fibers, is sent directly to yarn production (Table S5). Polyester T-shirts exhibit the highest GWP contribution from raw material production (resin production) but benefit from a more streamlined melt-spinning process compared with viscose and Lyocell fibers (Table S6). In addition, polyester wet processing and finishing require lower chemical inputs compared with cellulose-based fibers [41,53].

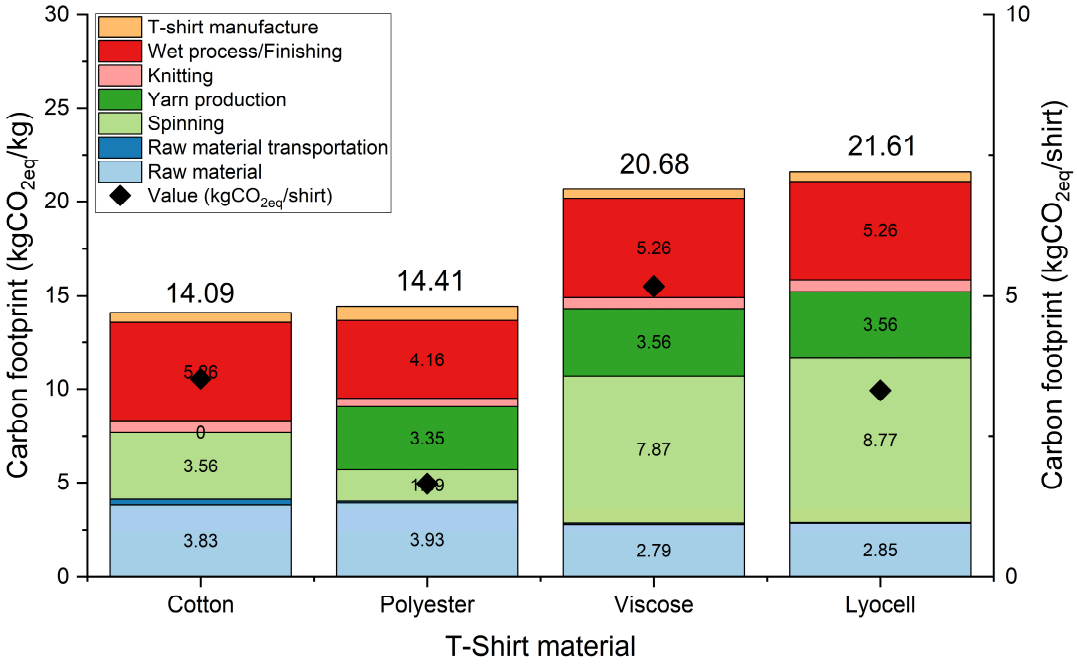
When accounting for fiber tenacity, polyester and Lyocell require less material to achieve equivalent mechanical performance, resulting in lower GWP per functional unit. In this regard, the GWP profile ranks viscose as the highest, followed by cotton, Lyocell, and then polyester. Accordingly, mass-based comparisons should be interpreted with caution.

The GWP reported on Figure 3 does not account for the carbon embedded in the T-shirt, estimated to be 1.8 kg CO_2eq/kg shirt. If considered, the GWP for cotton, viscose, and Lyocell T-shirts drops to 12.3, 18.9, and 19.8 kg CO_2eq/kg, respectively.

Cotton T-shirt production presents the highest normalized impacts in six of the eighteen ReCiPe midpoint categories, particularly those related to ozone formation, terrestrial ecotoxicity, water consumption, and land use (Figure 3B). These impacts are primarily

associated with irrigation requirements, intensive fertilizer and pesticide application, and relatively low lint yield per hectare.

(A)



(B)

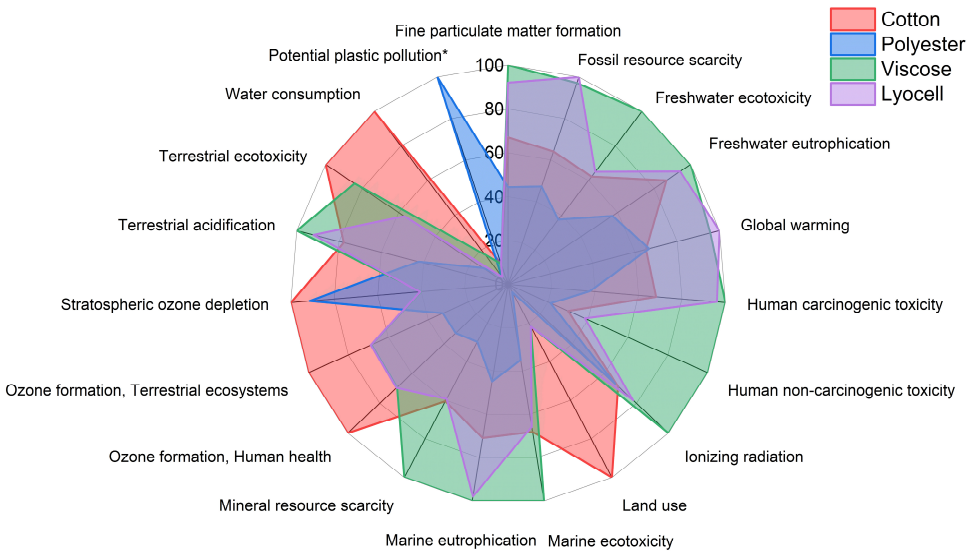


Figure 3. LCA to produce one kilogram of cotton, polyester, viscose, and Lyocell T-shirts (Chinese case scenario). (**A**) GWP values. (**B**) Normalized midpoint environmental categories; the asterisk in the potential plastic pollution category denotes that this is an impact calculated by the authors and does not belong to the ReCiPe methodology (Table S7).

Viscose T-shirts exhibit the highest normalized impacts in ten of the eighteen midpoint categories, primarily due to chemical-intensive processing during the spinning stage. The use of CS_2 and other sulfur-based chemicals during the spinning stage contributes significantly to human toxicity and freshwater ecotoxicity.

Polyester T-shirts present the highest potential for plastic pollution, reflecting the non-biodegradable nature of PET and its persistence in environmental compartments. In contrast, Lyocell T-shirts show higher impacts in global warming potential and fossil

resource scarcity, which are directly linked to the elevated energy demand associated with solvent recovery and purification.

The normalized LCA results for producing cotton, polyester, viscose, and Lyocell shirts based on equivalent tenacity are presented in Figure S7.

When emissions are broken down by stage, staple fibers production holds a GWP of 2.8, 3.1, 5.9, and 6.1 kg CO_2eq/kg for cotton, polyester, viscose, and Lyocell, respectively. Previous studies have reported that Chinese cotton staple fibers' GWP is 1.0–5.2 kg CO_2eq/kg [25–29,39,42]. Polyester staple fibers have been cited as having a GWP of 4.1 kg CO_2eq/kg [22,68].

Chinese viscose staple fibers have been reported to have a carbon footprint ranging from 4.9 to 9.9 kg CO_2eq/kg [22,23]. This study estimates direct emissions of 2.4 kg CO_2eq/kg for viscose staple fiber production, which aligns reasonably well with the value reported by the Chinese Alliance for Sustainable Development of Viscose at 2.6 kg CO_2eq/kg [20].

Emissions data for Lyocell fiber production remains limited in the literature, with most studies focusing on European systems [22,23]. However, the study by Guo et al. (2021) reports that Lyocell staple fibers possess higher GWP, acidification potential, and primary energy demand than viscose fibers [24].

The literature is limited to comparisons of T-shirt manufacturing using different types of fibers. A Chinese cotton T-shirt has been reported to have a GWP of 32 kg CO_2eq/kg, while this study estimates that it is 14.1 kg CO_2eq/kg [48]. A polyester T-shirt was reported to have a GWP between 19.6 and 78.3 kg CO_2eq/kg [52,69].

3.2. Region Sensitivity

The Chinese scenario consistently shows the highest GWP across all fiber types (Figure 4), reflecting the carbon intensity of its energy mix. In contrast, Brazil and Europe exhibit lower GWP values due to cleaner electricity and steam generation systems.

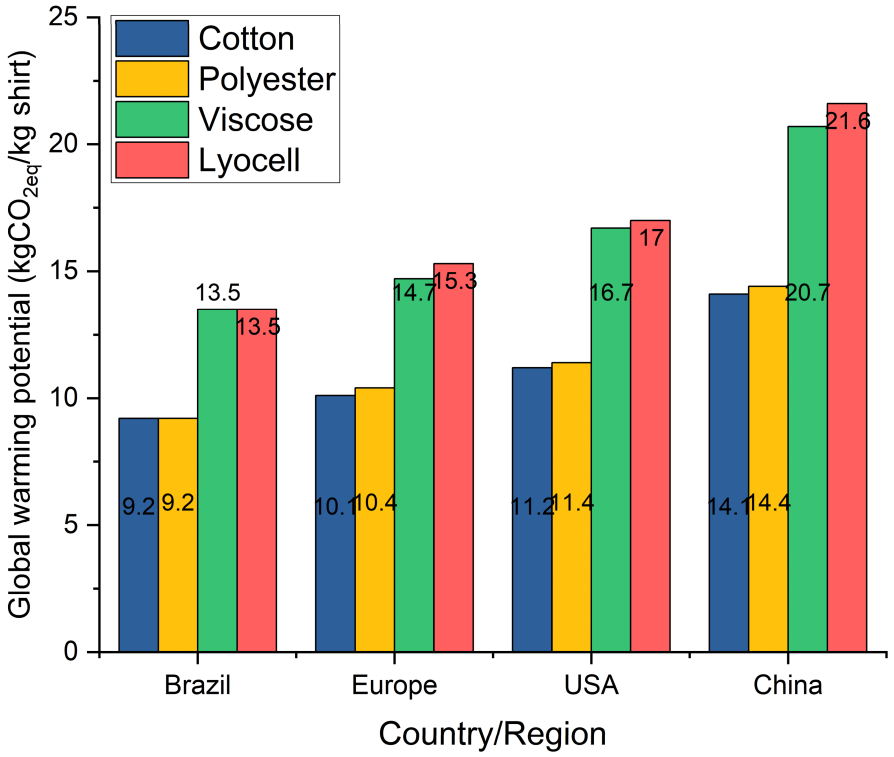


Figure 4. Region sensitivity analysis. GWP of producing 1 kg of polyester, cotton, Lyocell, and viscose T-shirts.

Austria, which accounts for 4.5% and 22.1% of the global viscose and Lyocell production, could potentially present GWP values of 14.7 and 15.3 kg CO_2eq/kg for viscose and Lyocell T-shirts, competitive with the values obtained for Chinese cotton and polyester T-shirts.

The ReCiPe endpoint categories per kg of shirt type and region are given in Tables S8–S11 of the Supplementary Materials, while the probabilistic results derived from Monte Carlo simulations are presented as violin plots in Figure 5, providing a holistic understanding of the variability associated with each fiber-region scenario across key environmental endpoints. Among the fibers evaluated, viscose—particularly in the Chinese context—exhibited the widest distributions and notable positive skewness in both human health and ecosystem quality indicators. This behavior reflects the high sensitivity of viscose production to variations in chemical consumption, solvent recovery efficiency, and energy use.

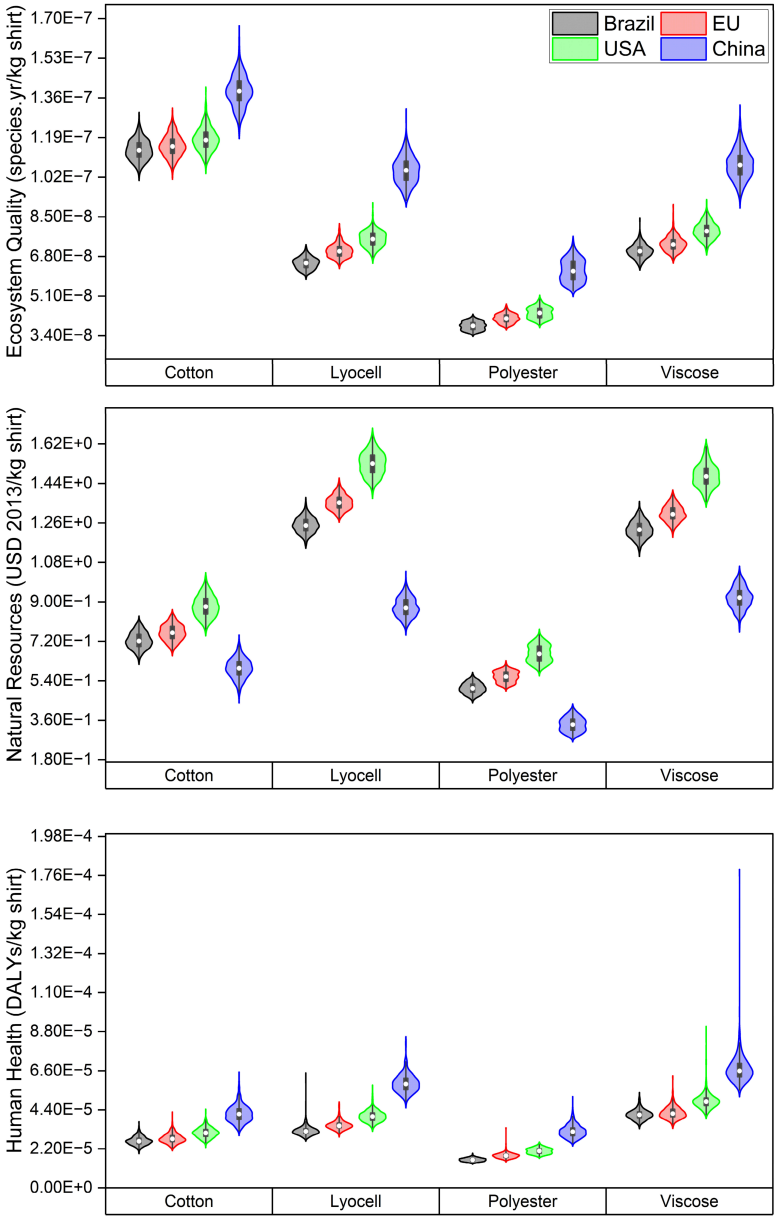


Figure 5. Endpoint ReCiPe categories for producing one kg of cotton, Lyocell, polyester, and viscose T-shirts. Violin plots reflect the probability density of 1000 Monte Carlo iterations per scenario. White dot = median; thick bar = interquartile range; thin line = 95% confidence interval.

Cotton also displayed considerable variability, primarily in ecosystem quality, which is associated with variability in agricultural inputs, including irrigation, fertilizer application, and land-use practices. Conversely, Lyocell and polyester demonstrated more compact and symmetrical distributions, indicating comparatively lower variability in environmental performance. The narrower ranges for polyester reflect the relative consistency of fossil-based resin production and melt spinning, while Lyocell's performance benefits from its controlled, closed-loop processing—despite remaining sensitive to regional energy sources.

Regional differences influence both the central tendency and variability of the results. Scenarios modeled for China consistently showed broader distributions and higher median values across the endpoint categories (except for natural resources depletion), underscoring the influence of a coal-dominant electricity grid and relatively limited emission control infrastructure. In contrast, Brazil and the European Union displayed narrower distributions and lower impact magnitudes, driven by cleaner energy mixes and potentially stricter environmental regulations. These findings underscore the importance of accounting for geographic variability in LCA, as fiber environmental performance is not only material-dependent, but also highly contingent on local production conditions.

Notably, the degree of distributional overlap observed among fibers within and across regions highlights the need for caution when interpreting median values in isolation. Decision-making processes informed by LCA results should therefore consider both the expected environmental performance and its associated uncertainty, enabling more robust and evidence-based sustainability decisions. The Monte Carlo results for producing cotton, polyester, viscose, and Lyocell shirts based on equivalent tenacity are presented in Figure S8.

3.3. Limitations

This study presents a cradle-to-gate life cycle assessment of T-shirt production using four major fiber types; however, several limitations should be acknowledged.

First, while a detailed life cycle inventory was developed, some data relied on secondary sources, introducing uncertainty in the results despite the application of Monte Carlo analysis. In particular, process-specific uncertainties related to chemical recovery and purification systems may influence the results. For Lyocell production, variations in NMMO solvent recovery efficiency, degradation reactions, and associated purification energy demand can significantly affect environmental impacts, especially in energy-related categories.

Similarly, viscose production is highly sensitive to CS_2 recovery efficiency and emission control practices. Variability in solvent recovery rates across facilities can lead to substantial differences in toxicity-related impacts, particularly those associated with human health and freshwater ecotoxicity.

In addition, fluctuations in chemical usage during bleaching and wet processing stages—such as hydrogen peroxide, caustic soda, and auxiliary agent usage—can introduce variability in several midpoint categories. These variations depend on process configurations, fabric specifications, and operational conditions, which are not always consistently reported in the literature.

Second, the analysis is limited to cradle-to-gate system boundaries and does not include use-phase or end-of-life impacts, which can significantly influence overall environmental performance. For example, laundering frequency and conditions affect the life cycle energy demand of cotton garments, while the persistence of polyester contributes to long-term environmental accumulation.

Finally, although the inclusion of a plastic pollution indicator provides additional insight, the lack of standardized characterization methods requires cautious interpretation of this metric.

4. Conclusions

This study presents the first cradle-to-gate LCA of T-shirt production that includes all manufacturing processes for MMCFs, specifically viscose and Lyocell, alongside cotton and polyester. By extending system boundaries to encompass spinning, knitting, wet processing, garment assembly, and transport, and by applying consistent modeling assumptions with regionalized energy scenarios, this work provides a robust comparative evaluation at the product level.

The results demonstrate that 1 kg of cotton T-shirts exhibits the lowest GWP under a Chinese energy context. However, this advantage comes at the cost of high impacts in categories such as water consumption, land use, and toxicity. Polyester T-shirts, which require less water and land, carry a distinct burden related to plastic pollution due to their inability to biodegrade.

Within the MMCF category, viscose and Lyocell show markedly different environmental profiles due to their distinct manufacturing processes. Viscose production, which relies on CS_2 and other chemical-intensive steps, exhibits higher impacts in categories such as human toxicity and freshwater ecotoxicity. In contrast, Lyocell, which uses a closed-loop NMMO solvent system, generally outperforms viscose across most midpoint indicators, especially in toxicity-related categories, despite higher GWP under specific regional energy mixes. These findings underscore the significance of solvent recovery and process design in achieving sustainability when using MMCFs.

This study also shows that consideration of intrinsic fiber properties, such as yarn tenacity, can significantly alter the comparative environmental performance of garments. When results are expressed per kilogram of fiber, polyester and Lyocell appear less favorable than cotton. However, once garment mass is adjusted to achieve equivalent tensile strengths, their relative performance improves, underscoring that higher-tenacity fibers can deliver the same functionality with less material. This finding highlights the importance of linking LCA results not only to mass-based units, but also to functional garment properties, since performance-driven adjustments can meaningfully reshape sustainability conclusions at the product level.

Region-specific analysis reveals that the energy mix has a significant influence on environmental outcomes. Cleaner electricity grids in Brazil and the EU substantially lower GWP for energy-intensive fibers such as Lyocell and viscose, underlining the potential of geographic selection in reducing environmental burdens.

This study demonstrates that the environmental profile of textiles cannot be adequately captured by generalized fiber rankings. Life cycle outcomes vary substantially depending on regional energy supply, chemical recovery efficiency, and garment-level functional properties. Policies and eco-labeling schemes that rely on static or mass-based classifications risk producing misleading signals; instead, performance-adjusted and context-sensitive criteria are needed to guide meaningful sustainability transitions in the textile sector.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18084070/s1, Figure S1: Gate-to-gate system boundary for viscose fiber production. Figure S2: Global viscose staple fiber production in 2023. Figure S3: Gate-to-gate system boundary for Lyocell fiber production. Figure S4: Global Lyocell staple fiber production in 2023. Figure S5: Geographical representation of the Chinese case study. Figure S6: Global viscose-grade dissolving pulp production. Figure S7: Normalized LCA results for T-shirts based on equivalent tenacity. Figure S8: ReCiPe endpoint Monte Carlo distributions for fiber scenarios. Table S1: Life cycle

inventory for dissolving pulp production. Table S2: Simplified LCI for NMMO production. Table S3: Hotspot categories for viscose T-shirt production. Table S4: Hotspot categories for Lyocell T-shirt production. Table S5: Hotspot categories for cotton T-shirt production. Table S6: Hotspot categories for polyester T-shirt production. Table S7: ReCiPe midpoint impact results. Table S8: ReCiPe endpoint results for viscose T-shirts. Table S9: ReCiPe endpoint results for Lyocell T-shirts. Table S10: ReCiPe endpoint results for cotton T-shirts. Table S11: ReCiPe endpoint results for polyester T-shirts.

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Abbreviations

The following abbreviations are used in this manuscript:

AS	Acid sulfite
CS_2	Carbon disulfide
DALY	Disability-adjusted life year
DP	Dissolving pulp
GWP	Global warming potential
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MMCF	Man-made cellulosic fiber
NMMO	N-methylmorpholine-N-oxide
PAP	Plastic accumulation potential
PET	Polyethylene terephthalate
PHK	Pre-hydrolysis kraft
SAFI	Sustainable & Alternative Fibers Initiative
VSF	Viscose staple fiber

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