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ORIGINAL PAPER

Carbon footprint calculator for the Portuguese textile and clothing industry: development, application and validation

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Abstract

This study aimed to develop, implement, and validate a carbon footprint (CF) calculator to estimate greenhouse gas (GHG) emissions generated by Portugal´s Textile and Clothing Sector (TCS). To achieve this, the GHG Protocol and life cycle assessment (LCA) methodology were applied to develop the CF and analyse two textile and clothing companies (A and B). Validation was conducted using a self-assessment method that employed 2 online calculators and a LCA software. The CF calculator enables the quantification of the 3 scopes of GHG emissions. Scope 1 includes direct emissions from sources that are owned or controlled by the company, such as on-site energy, transportation of raw materials, finished products and personnel, as well as water usage. Scope 2 comprises indirect emissions from the use of purchased energy and Scope 3 includes emissions that occur across the supply chain, such as public water usage, wastewater, transportation, employee business travel, waste disposal and the end-of-life treatment of sold products. Avoided emissions and carbon offsetting measures and carbon sequestration strategies, were included. For Company A, energy consumption was the largest contributor to the CF, accounting for 76% of the contributions. In Company B, the waste component had the greatest impact on the CF, accounted for 38% of the contributions. In the validation process, the electricity and fuel consumption components yielded values that are consistent with those from other calculators. The calculator is a tool that TCS companies can use to quantify their emissions and define measures to reduce or offset their CF.

Keywords Calculator · Carbon footprint · GHG emissions · Life cycle assessment · Textile and clothing sector · Validation

Introduction

Climate change is the most pressing issue of our time, and stands as one of the greatest environmental, social, and economic threats. The Textile and Clothing Industry (TCI) is the fourth largest contributor to environmental degradation and climate change (Roth et al. 2023), increasing strongly their impact on the climate, water, and resources if the production and consumption of textile products continue to grow.

Global textile production nearly doubled between 2000 and 2015 (Morlet et al. 2017), while clothing and footwear consumption is expected to grow by 63% by 2030, increasing from 62 million tonnes to 102 million tonnes (EEA 2019). According to Euratex (2021), the TCI holds an important position in the European economy, accounting for 5% of its workforce and representing nearly 10% of all existing companies (EURATEX 2021; Roth et al. 2023).

In Portugal, the TCI is one of the oldest and most traditional industries, as well as one of the largest and most important sectors of the national economy. According to

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official data from the National Institute of Statistics, in 2021, the TCI in Portugal comprised 11 835 companies (3 527 textiles and 8 308 clothing companies) and employed 126 940 workers, which represents a 16.5% increase compared to the previous year (INE 2021).

The primary objective of this industrial sector is the transformation of fibres into yarns, yarns into fabrics, and fabrics into garments, textiles or materials for technical application (seat belts, airbags, etc.), with a highly diverse manufacturing processes and their stakeholders in the textile industry are highly diverse and vary depending on the final product (Morlet et al. 2017).

Currently, textile consumption in the European Union (EU) ranks fourth in terms of negative impact on the environment and climate change, third in terms of water and land use from a global life cycle perspective, and fifth in terms of primary raw material consumption and greenhouse gas emissions (Costa et al. 2023; Roth et al. 2023). Each year, around 5.8 million tonnes of textiles are discarded in the EU, which represents approximately 11 kg per person (EEA 2019), as result of the linear economic model adopted by this sector (Costa et al. 2023). This model is characterized by high resource consumption and low rates of recycling, reuse and repair of raw materials and finished products. Additionally, the emission of microplastics into the oceans, resulting from washing processes, is a critical aspect of the production process (Aitex 2021) that greatly contributes to the sector's carbon footprint (Morlet et al. 2017).

Should this current trend persist, the negative impacts of this industrial sector could become catastrophic and, by 2050, the TCI will be responsible for consuming 26% of the world's carbon budget, severely jeopardising the goals set by the Paris Agreement in 2015 (APA 2021a, b). The Textile and Clothing Sector (TCS) must urgently address this issue, as decarbonization is essential to achieve the objectives outlined in the Roadmap for Carbon Neutrality 2050 and the National Energy and Climate Plan 2030 (Council of Ministers Resolution No. 53/2020). The 2020 Circular Economy Action Plan and the 2021 update to the European Industrial Strategy identify textiles as a key product value chain with an urgent need and strong potential for the transition to sustainable and circular production, consumption and business models (CE 2020, 2021a). Being aware of the TCS environmental impact will help optimise processes, reduce resource consuming, and ensure the quality and characteristics of the manufactured goods. The energy consumption required by the entire production process of the textile industry – covering the full life cycle from fiber processing to clothing products- is approximately 4.84 tons of standard coal/ton of fiber (Zhang et al. 2020). In the face of the drastic rise in global warming, the textile industry urgently needs to curb the energy-intensive and high-pollution practices, eliminate outdated production facilities, adjust its industrial structure, and embrace sustainable development. Therefore, research focusing on the evaluation of the carbon footprint of a textile industry using a whole life cycle assessment (LCA) is of great importance to the development of energy conservation and emission reduction strategies. While some studies use LCA to estimate carbon emissions across the design, production, sales, and recovery stages, they often lack a detailed analysis of the carbon footprint sources created throughout the life cycle or fail to define the sector's system boundary for carbon accounts. Chen et al. (2023) provide a comprehensive review of the textile sector's carbon footprint, focusing particularly on the life cycle environmental impact of cotton textiles. The authors highlight that significant emissions occur at various stages of production, from fiber cultivation- which is resource-intensive, particularly in terms of water and fertilizers- to the manufacturing, dyeing, and finishing processes that consume considerable energy and chemicals. Additionally, transportation and disposal stages contribute significantly to the sector's overall carbon footprint. Key findings suggest that the adoption of sustainable practices, such as recycling cotton, optimizing production processes, and transitioning to renewable energy sources, can significantly reduce emissions in the textile sector. The study emphasizes that systemic changes toward a circular economy model, combined with a shift in consumer behavior, are essential to mitigate the environmental impact of TCI (Chen et al 2023). Zhang et al. (2020) highlight the variability in carbon footprint data across studies, often caused by differences in accounting methods and boundaries. They suggest that the standardisation of assessment methods, particularly through LCA, could improve comparability and accuracy in evaluating and reducing emissions within the textile industry.

The motivation for this study stems from two major factors: to understand how to make the textile sector more environmentally sustainable and improve its environmental performance, and how to address global and local demands in compliance with institutional agreements and legal requirements.

The main objective of this work was to develop a carbon footprint (CF) calculator for the Portuguese Textile and Clothing Sector, based on the GHG Protocol standards and built using Microsoft Excel, which will enable the evaluation and classification of its activities and/or products based on their environmental impact. Moreover, the aim was to apply the CF calculator to two real-world cases, one from the textile sector and the other from the clothing sector, and validate the tool using a self-assessment method.

Materials and methods

To achieve the goals set for this study, a carbon footprint calculator was developed, applied and validated. It considered the temporal and spatial boundaries of textile products and the GHG emissions emitted during their life cycle. The whole life cycle of the textile industry is quite extensive. Based on the activities of the textile industry, three stages were defined for this cycle: the first, the agricultural production, involves the cultivation of textile raw materials; the second, the manufacturing stage, encompasses the production and processing of textiles; and the third, the sales stage, includes the transportation and distribution of textiles (Zhang et al. 2020).

Calculator development

The CF calculator was developed in strict compliance with the GHG Protocol standards and uses a comprehensive LCA of the product. It was built using Microsoft Excel to ensure accessibility and adaptability for industry stakeholders. According to Zhang et al. (2020), the evaluation steps of the LCA method for carbon footprint include establishing a product manufacturing flow chart, determining system boundaries, collecting data, calculating the carbon footprint, and testing the results. Based on this information and on GHG Protocol, the CF calculator development followed six phases, namely:

Phase 1: defining organizational boundaries

The company is fully responsible for the GHG emissions resulting from its operations and the management of its industrial activities.

Phase 2: defining operational boundaries

The system boundaries and the emissions associated with textile production were defined. Direct emissions were categorised as Scope 1, while indirect emissions were classified as Scope 2 and 3. It should also be noted that the diverse nature of sub-sectors and their products adds significant complexity to the calculation of GHG emissions throughout the textile product life cycle. For this reason, in this first version of the calculator, only emissions associated with on-site energy (including cogeneration processes), transportation of raw materials, finished products, and personnel, and water usage were considered as Scope 1 emissions. Scope 2 are indirect emissions associated with the use of purchased energy. Scope 3 encompasses all emissions associated with the use of public water, wastewater, transportation, employee business travel (including overnight stays), waste disposal and end-of-life treatment of products. Avoided emissions and carbon offsetting can also be quantified. Avoided emissions are associated with the use of renewable sources (e.g. photovoltaic technologies) for electricity production and waste recovery/reuse, while carbon offsetting involves carbon sequestration strategies, such as tree plantation.

Phase 3: selecting the calculation methodology and emission factors

Before selecting the calculation methodology, it was necessary to identify the components and indicators to be considered and that typically contribute the most to the carbon footprint. Then, the emission factors (EFs) for each indicator were selected. The EFs used for each indicator were directly taken from bibliography, except for those related to on-site energy, use of purchased energy, waste and wastewater disposal, and end-of-life treatment, which were provided by the enterprises under study. Most of the factors used to achieve the defined objectives were derived from national databases. Table 1 shows the components, indicators, and equations utilised in the CF calculator.

The calculator considers avoided emissions associated with the waste and electricity components, as well as offsetting emissions achieved through tree plantation, using references from calculators available online.

Once the components, indicators, and EFs were selected, the next step was to define the most suitable methodology for calculating GHG emissions. The IPCC 2006 guidelines provide a wide range of methodologies and techniques for emissions calculation, ranging from direct monitoring to the application of EFs. Generally, emissions are calculated by applying EFs to a set of activity data (indicators) (IPCC 2006). The evaluation of GHG emissions is typically carried out according to Eq. 1.

$$GHG\ Emissions = Activity\ Data\ xEmission\ Factor\ (EFs) \tag{1}$$

For the air travel and fugitive emissions components, the following online calculators were used*:* ICAO Carbon Emissions Calculator (ICAO 2023) and the Portuguese Environment Agency tool (APA 2023).

Phase 4: collecting data on activities with significant impact on GHG emissions

Table 1 Components, indicators, and equations used in the carbon footprint calculator

Life cycle phase	Component		Indicator	Scope	Calculation equation	References
Cultivation and extraction	Raw material		Amount of raw material used	3	Quantity x EF	Niinimäki et al. (2020) and Sandin et al. (2019)
Raw material Transportation	Raw material		Fuel Consumption/ Distance Travelled	3	Consumption x EF	GOV.UK (2022)
Production	Waste		Amount of waste produced	3	Quantity x EF	Pereira et al. (2023) Su et al. (2020) Hillman et al. (2015)
			Amount of waste recovered	Avoided emission		–
	Water		Drinking water consumption	3	Consumption x EF	EBC (2021)
			Capture and treatment	1		
	On-site Energy		Electricity consumption	2		EDP (2022) Endesa (2021) Yes Energy (2021) APREN (2021) Iberdrola (2021) G9 Energy (2021) Galp (2021)
			Electricity production through renewable energies	Avoided emission		–
			Fuel consumption used in stationary combustion	1		Pereira et al. (2023)
			Consumption of energy (electricity and heat/steam) produced by the cogeneration process	1	Consumption x EF Production x EF	Portgás (2023)
	Industrial process		Fugitive emissions	1	APA Calculator	APA (2023)
	Wastewater		The volume of wastewater produced	3	Quantity x EF	Costa et al. (2023) Pereira et al. (2023)
Transport	Employee Business travel	Car Airplane Train	Fuel Consumption/Distance Travelled (Cars)	1 & 3	Consumption x EF ICAO Calculator Distance x EF	GOV.UK (2022) Gimbert (2022) ICAO (2023) CP (2020) IPCC (2006)
	Business Travel	Hotel overnights	Nº of nights/person	3	Nº nights x EF	GOV.UK (2022)
	Employee Travel (Home-work)		Fuel Consumption		Consumption x EF	GOV.UK (2022) Gimbert (2022)
	Transportation and distribution of finished product			1 & 3		GOV.UK (2022)
End of life	End- of-life treatment of the finished product		End-of-life product destination	3	Quantity x EF	Pereira et al. (2023)

Table 2 Activities data for the two study cases—companies A and B

Life cycle phase	Component		Indicator	Unit	Company A	Company B
Production	Water		Drinking water consumption	m^3	36 865	3 068
			Capture and treatment		303 834	–
	On-site Energy		Electricity consumption	kWh	7 722 395	405 148
			Fuel consumption used in stationary combustion - Natural gas	m^3	2 805 901	–
			Fuel consumption used in stationary combustion - Biomass	Kg	2 762 874	–
			Consumption of energy (electricity and heat/steam) produced by the cogeneration process	kWh	4 952 796	–
	Waste		Amount of waste produced	kg	201 892	78 570
			Amount of waste recovered		38 860	–
	Wastewater		The volume of wastewater produced	m^3	278 233	2454
Transport	Employee business travel	Airplane	Distance Travelled	km	56 202	34 956
		Hotel overnight stays	N° of nights/person	number	31	–
	Employee Transportation		Distance Travelled (Cars)	km	73 073	12 200

The calculator was applied to two case studies: one company from the textile sector (A) and another from the clothing sector (B). Due to limitations in data availability from the companies, only the production and transportation phases of the life cycle were considered. Raw material and end-of-life stages were not considered. The data pertains to 2022 and provide relevant insight into the Scope 1, 2 and 3 emissions components (Table 2). Company A produced a total of 4 209 219 units of finished product. Company B did not provide information on that matter.

Phase 5: calculating emissions

The CF was calculated using the data provided by Company A and Company B for the year 2022.

Phase 6: preparing the GHG emissions report

After gathering data and evaluating the results for each company, it was possible to measure the contribution of each Scope to the carbon footprint. For Company A, the carbon footprint per unit produced could be calculated, however, this was not possible for Company B, due to insufficient data. An example of the report is presented in the next section.

Calculator validation

The calculator was validated using a self-assessment method, which involved comparing the results obtained with those provided by two existing online calculators: the Greenhouse Gas Emissions Calculator (GGEC), developed by the United Nations Climate Change (UNCC 2022), and the Huella de Carbono de Una Organización (HCO), developed by the Spanish Ministry for Ecological Transition (OECC 2023). A LCA software was also utilised in this process. It was possible to compare the on-site energy, transportation (products and personnel) and use of purchased energy components with the results provided by both calculators. However, the GGEC calculator was the calculator used to compare the components related to water usage, wastewater, raw materials, and employee business travel (plane trips and overnight stays). The LCA software was used exclusively to validate the results for company A.

The LCA methodology applied followed the technical specifications detailed in ISO/TS 14072 (ISO 2014), which provides additional requirements and guidelines for an effective application of ISO 14040:2006 (ISO 2006a) and ISO 14044:2006 (ISO 2006b) to organizations. The background processes and data used in the LCA are illustrated in Table 3.

Table 3 SimaPro PhD equivalent processes with inputs and outputs for the functional unit

Input and output	Unit	Value
Heat, central or small-scale, natural gas {Europe, excluding Switzerland}| market for heat, central or small-scale, natural gas | APOS, U	MJ	99 855 844
Heat, central or small-scale, other than natural gas {RoW}| heat production, hardwood chips from forest, at furnace 50 kW | APOS, U	MJ	41 443 110
Cooling energy {GLO}| market for | APOS, U	kWh	4 952 796
Electricity, low voltage {PT}| market for electricity, low voltage | Cut-off, U	kWh	7 722 395
Tap water {Europe, excluding Switzerland}| tap water production, underground water without treatment | APOS, U	t	303 834
Tap water {Europe, excluding Switzerland}| market for | APOS, U	t	36 865
Transport, passenger car, medium size, diesel, EURO 5 {GLO}| market for | APOS, U	km	1 315 311
Transport, passenger aircraft, medium haul {GLO}| market for transport, passenger aircraft, medium haul | APOS, U	Personnel.km	95 055
Building operation, budget hotel {GLO}| market for building operation, budget hotel | APOS, U	Guest.night	50
MSW deposition, landfill incl. landfill gas utilization and leachate treatment, ES, GR, PT mix EU-27	kg	201 892
Wastewater, average {Europe, excluding Switzerland}| market for wastewater, average | APOS, U	m^3	278 233
Wood ash mixture, pure {Europe, excluding Switzerland}| treatment of wood ash mixture, pure, landfarming | APOS, U	kg	38 860

The reporting unit was defined as the company's annual production and the system studied was divided into 12 activities, covering the company's responsibility scope.

As the results of this LCA (gate-to-gate analysis) study were to be compared with those provided by the footprint calculator—which does not account for raw materials- these were also excluded from the process. SimaPro 9.6 PhD was the LCA software used and the IPCC 2021 GWP100 V1.03 was the life cycle impact assessment method chosen.

Results and discussion

The components considered in the CF calculator were those that contribute the most to GHG emissions and include on-site energy (including cogeneration), water usage, use of purchased energy, transportation (road and air), raw materials, fugitive emissions, waste, wastewater, and the product end-of-life treatment. For each component, Portuguese EFs were considered whenever available.

One of the most challenging aspects of creating the calculator was the collection of data for all the components considered. Some data were unavailable, while other data were not specific to a particular piece of equipment or operational unit. This fact highlighted the need for improved data collection processes and data management by the companies. The equivalent GHG emissions for the cases under study are shown in Table 4. The two companies differ in several aspects, namely in the type of goods manufactured, production capacity, and process stages. In the case of Company B only the manufacturing stage was included.

The total carbon footprint for Company A was approximately 10 000 t CO_2e and 0.40 kg CO_2e per unit of product, while for Company B the total carbon footprint was estimated to be 188 t CO_2e. Since the number of units produced in 2022 by Company B was not available, it was not possible to estimate the carbon footprint per unit produced by this company. Studies have quantified the carbon footprint of textile manufacturing, revealing the existence of significant emissions. For instance, a facility in India reported emissions of 42 868 tCO_2e in 2014 (Akhtar et al. 2017), while another facility recorded an annual output of 10 598 tCO_2e (Mohan and Oke 2020). The results clearly demonstrate stark differences in emissions, which are influenced by factors such as facility size, production scale, and operational efficiency.

In Company A, energy consumption (natural gas, biomass, heat, and steam) during the production was the largest contributor to the carbon footprint. It accounted for a total annual emission of 7 958 t CO_2e, which represents 76% of the company's total footprint. In Company B, the waste component was the largest contributor to the carbon footprint, with total emissions of 72 t CO_2e and accounting for 38% of the company's total footprint (Fig. 1). Data highlight the need for a paradigm shift within the sector, as companies can no longer afford to overlook Scope 3 emissions. The highest contribution of Scope 3 emissions has also been observed in similar enterprises within the clothing sector (Wren 2022). This observation is further corroborated by Imran et al. (2023), who examined the carbon footprint of Pakistan's textile industry and found a gate-to-gate textile product carbon footprint of 42 624.115 $MTCO_2$e, with an indirect CFP of 42 619.207 $MTCO_2$e. These results clearly

Table 4 GHG results for Company A and Company B per component

Category		Emission source		Company A		Company B	
				kg CO_2e	%	kg CO_2e	%
Cooperative - Scope 1 and 2; Value Chain - Scope 3	Scope 1	Direct emissions from owned or controlled stationary sources that use fossil fuels and/or produce fugitive emissions	Energy- natural gas	6 161 927	75	–	-
			Energy - Biomass	82 886	1	–	-
			F-gases	–	0	–	-
		Emissions from on-site electricity, heat, steam generation	Heat and steam	1 713 667	21	–	-
		Direct emissions from own or controlled mobile sources	Road transport	175 160	2	29 244	100
		Direct emissions associated with the capture and treatment of water used in the industrial process	Water capture	42 537	1	–	-
		Total Emissions Scope 1		**8 176 177**	**78**	**29 244**	**16**
	Scope 2	Emissions associated with the use of purchased energy	Electricity	1 541 390	100	66 444	100
		Total Emissions Scope 2		**1 541 390**	**100**	**66 444**	**35**
	Scope 3	Waste produced	Wastewater treatment	372 832	49	3 278	4
			Miscellaneous waste	369 380	49	72 075	78
		Purchased Goods	Water	5 161	1	430	0.5
			Raw material	–	0	–	0
		Employee business travel	Airplane	9 229	1	16 646	18
			Train	-	-	–	-
			Overnight stays	913	0.1	–	-
		Freight forwarding	Freight transport	–	-	–	-
		Staff travel		–	-	–	-
		Total Emissions Scope 3		**757 516**	**7**	**92 429**	**49**
Avoided emissions				21 606		0	
Scope Emissions 1 + 2 + 3				10 475 083		188 117	
Total emissions				10 453 477		188 117	
Carbon footprint/ units of product (kg CO_2e/unit of product)				0.40		–	

The bold value in table indicate the total emissions for each Scope

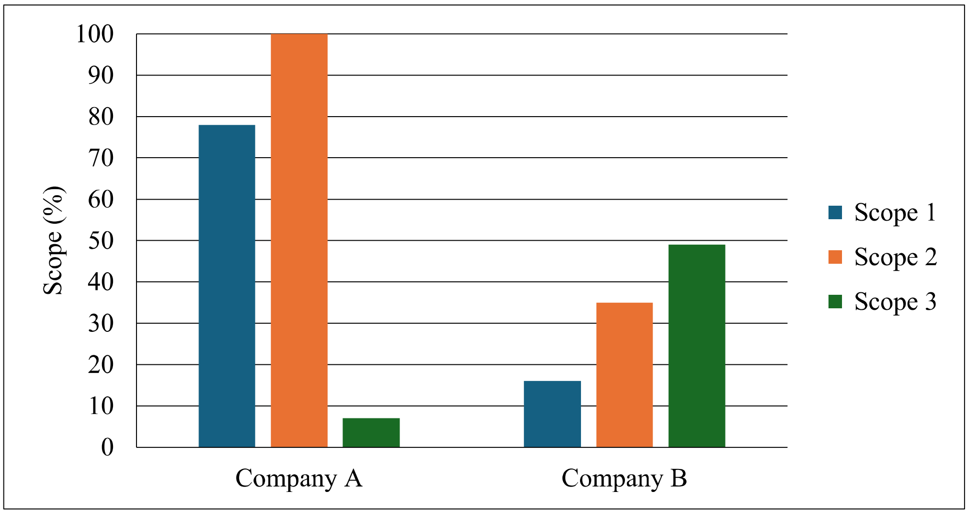


Fig. 1 Carbon footprint per scope for Company A and Company B in 2022

demonstrate the importance of stakeholders gaining a clear understanding of their emissions and the need for policies to encourage synergetic changes across the sector.

Energy consumption in the TCS varies considerably depending on the type of company and the energy sources and fuels used. Generally, most company groups, except those operating in the clothing sector, exhibit high energy consumption and are classified as energy-intensive consumers (Niinimäki et al. 2020). The research concluded that, for Company A, the use of purchased energy component accounted for 15% of the total carbon footprint (1541 t CO_2e). In contrast, for Company B this component represented 35% of the total footprint (66 t CO_2e). The behaviour displayed by Company A aligns with that of vertically integrated companies, which perform chemical processes that consume more natural gas than electricity. In those companies, natural gas consumption represents 96% of total Scope 1 emissions. The results obtained are consistent with those reported by Farhana et al. (2022). Additionally, the studies conducted by Li et al. (2019) and Sandin et al. (2019) corroborate the observation that energy consumption is one of the primary contributors to the high carbon footprint of the textile and clothing industry. Liu et al. (2020) evaluated the CF of the manufacturing process of melange yarn and identified electricity as the primary CF contributor, accounting for 61.7% of total carbon emissions. Steam, Na_2SO_4, and $FeSO_4$ were found to be other major contributors, particularly during the dyeing stage.

As a way to reduce costs and its carbon footprint, Company A has been increasing its capacity to produce its own energy and heat through a cogeneration process, using biomass as fuel. Biomass is particularly suitable for this type of company, as it is considered CO_2 neutral due to its biogenic origin, which significantly contributes to reducing the company's overall carbon footprint. For Scope 1 emissions, Company B provided data solely on road transportation carried out by its vehicles, which contributed 16% (29 t CO_2e) to its total footprint. In contrast, this component accounted for 2% (175 t CO_2e) of Company A's Scope 1 emissions.

According to Luo et al. (2022), water consumption and wastewater generation are two critical environmental challenges posed by the textile and clothing industry, which reflect its long-standing history of surface water pollution. The water used by Company A in the production process comes from surface water sources (streams) and from the public water supply, traditionally used for domestic purposes. The latter is used by both companies. Due to the scarcity of sector-specific information, the same emission factor was applied to both water from the public supply and groundwater from private extraction. As a result, the difference in emissions lies solely in the volumes of water used from each source. In the case of Company A, private water extraction contributes 1% (approximately 43 t CO_2e) to Scope 1 emissions and 0.4% to the total carbon footprint. Water consumption from the public supply contributes 1% (5 t CO_2e) to Scope 3 emissions and 0.05% to the total carbon footprint. In Company B, the contribution of water consumption from the public water supply network was approximately 430 kg CO_2e, accounting for 0.5% of the total footprint.

The data also shows that the volume of wastewater produced was different for both companies. For Company A, the volume of wastewater was quantified, as these effluents are discharged to a municipal wastewater treatment plant.

For Company B, since the wastewater generated is comparable to domestic usage, the volume of effluent produced was estimated to be 80% of the company's water consumption. For Company A, wastewater treatment contributes to 49% of Scope 3 emissions and 4% to the total carbon footprint, which amounts to approximately 373 t CO_2e. For Company B, wastewater treatment accounts for 4% (3 t CO_2e) of Scope 3 emissions and 2% of the total carbon footprint. As expected, water consumption in Company A, a vertically integrated company, was much higher compared to Company B, a clothing company that does not require water in its production process. The results obtained align with the findings of Luo et al. (2022). In their study, they used a linear method to demonstrate the impact of cotton jeans production on the water footprint and underscore the sector's contribution to both water depletion and pollution.

The low rates of recycling, reuse, and repair of raw materials and clothing are major concerns for the sector. According to the European Environment Agency, in 2020, the average consumption of textiles per EU citizen required the use of 400 m^2 of land, 9 m^3 of water, and 391 kg of raw materials (EEA 2023). The lack of information from waste management operators regarding waste management operations posed a challenge when time came to upload this information in the calculator, as it is essential to determine the EFs for each waste type according to its assigned code. Currently, there is still a significant discrepancy between the amount of valorised waste and the amount that is sent for disposal. Data on waste production for the sector demonstrate that, in general, there is a high quantity and variety of waste, and that only a small portion of this waste is considered hazardous. Additionally, the data also report that companies typically forward their waste to waste management operators, but unfortunately, its final destination is often unknown.

Data analysis also revealed that the types of waste most commonly generated by Company A were paper and cardboard packaging (European waste code (EWC): 15 01 01), unprocessed textile fibre waste (EWC: 04 02 22), wooden packaging (EWC: 15 01 03), and clothing waste (EWC: 04 02 09). In Company B, according to the information provided, the waste produced and managed included unprocessed textile fibres (EWC: 04 02 21), paper and cardboard packaging (EWC: 15 01 01), and plastic (EWC: 20 01 39). It was not possible to estimate the emissions associated with each type of waste, due to the aforementioned challenges. This seems to suggest that the emissions quantification might be somewhat lower than the actual value. In Company A, waste accounted for 49% of Scope 3 emissions and 4% to the total carbon footprint, corresponding to 369 t CO_2e. In Company B, it contributed to 78% of Scope 3 emissions and 38% of the total emissions, amounting to 72 t CO_2e.

Given the structural differences between the two organizations under study, it is evident that the vertically integrated company (A) generates a higher volume of waste, both in total and in terms of hazardous waste.

However, its impact on the overall carbon footprint is less relevant compared to Company B, where the waste produced emerges as the largest contributor to the total carbon footprint. Shirvanimoghaddam et al. (2020) stated that the high production and subsequent disposal of textiles have severe environmental consequences, such as excessive energy and water consumption, chemical water pollution, and soil degradation. Consequently, it is imperative for companies to promptly adopt strategies that may facilitate the recovery/reuse of the waste they produce, and to dispose of only those materials that cannot be recovered or recycled. Allwood et al. (2006) identified the amount of waste produced as one of the most pressing environmental challenges facing the textile industry.

The carbon emissions associated with trips made by each company vary significantly. For Company A, this component accounts for 1% of Scope 3 emissions and 0.1% of total emissions, corresponding to 9 t CO_2e. For Company B, these emissions represent 18% of Scope 3 emissions and 9% to total emissions, amounting to approximately 17 t CO_2e. The trips made by Company A were primarily driven by business strategies, such as participations in international exhibitions, whereas for Company B they involved corporate visits to supplier factories in Cabo Verde. This component had greater representation in Company A. As for the overnight stays associated with corporate travels, emissions were only quantifiable for Company A, as EFs for Cabo Verde hotels were not included in the CF calculator. For this company, overnight stays contributed 0.1% to Scope 3 emissions and 0.01% to total emissions, amounting to 913 kg CO_2e.

The CF calculator generates a comprehensive GHG emissions report, enabling companies to easily identify the primary components and scopes responsible for their emissions (Fig. 2).

The global warming potential (GWP) values resulting from the LCA applied to company A are illustrated in Fig. 3. The GWP values from the textile industry, as assessed through LCA, reveal significant environmental impacts across various stages of production. Analysis reveals that the primary contributor to the company's GWP is the use of fuel (natural gas) in stationary combustion, followed by electricity consumption (Fig. 3). The impact of the use of purchased energy component on the GWP is consistent with findings from other studies. For textile and yarn production, raw cotton consumption and electricity use represent critical environmental challenges (Jain et al. 2022). Bio-recycling of textile waste holds promise, but pre-treatment remains the most energy-intensive and environmentally impactful step in the process (Subramanian et al. 2020). These studies highlight the urgent need for more energy-efficient processes and sustainable practices throughout the textile industry's life cycle to reduce its environmental footprint.

The IPCC method includes three GWP indicators: Global Warming Potential Fossil Fuels (GWP-fossil), Global Warming Potential Land Use and Land Use Change (GWP- luluc) and Global Warming Potential Biogenic (GWP -biogenic. The GWP-fossil indicator considers the GHG emissions and sequestration in all media resulting from the oxidation or reduction of fossil fuels or fossil carbon through transformation or degradation processes (e.g. combustion, incineration, landfilling, etc.). The GWP-biogenic indicator considers the amount of GHG emissions released as a result of the combustion or decomposition of organic material. The GWP-luluc indicator takes into account the GHG emissions and bounds originating from changes in the specified carbon stocks as a result of land use and land-use changes associated with the declared/functional unit. This indicator includes biogenic carbon exchanges resulting, for instance, from deforestation or other soil activities (including soil carbon emissions). Considering the three GWP indicators, fuel consumption is the primary contributor to the GWP-fossil indicator, biomass consumption contributes to the GWP-biogenic indicator, and electricity consumption was a major contributor to the GWP-luluc (Fig. 4). This fact suggests that the energy component is the most significant factor when it comes to reducing GWP. In their study, Liu et al. (2017) examined the environmental impact of biomass energy. They found that the calculated GWP-biogenic factors ranged from 0.13 to 0.32, indicating that biomass can be regarded as a more environmentally attractive energy resource compared to fossil fuels. Additionally, short-rotation and fast-growing biomass sources, as well as the use of long-lived wood products generate lower GWP-biogenic values. This reduction is attributed to enhanced regrowth potential and higher CO_2 absorption capacity (Liu et al. 2017).

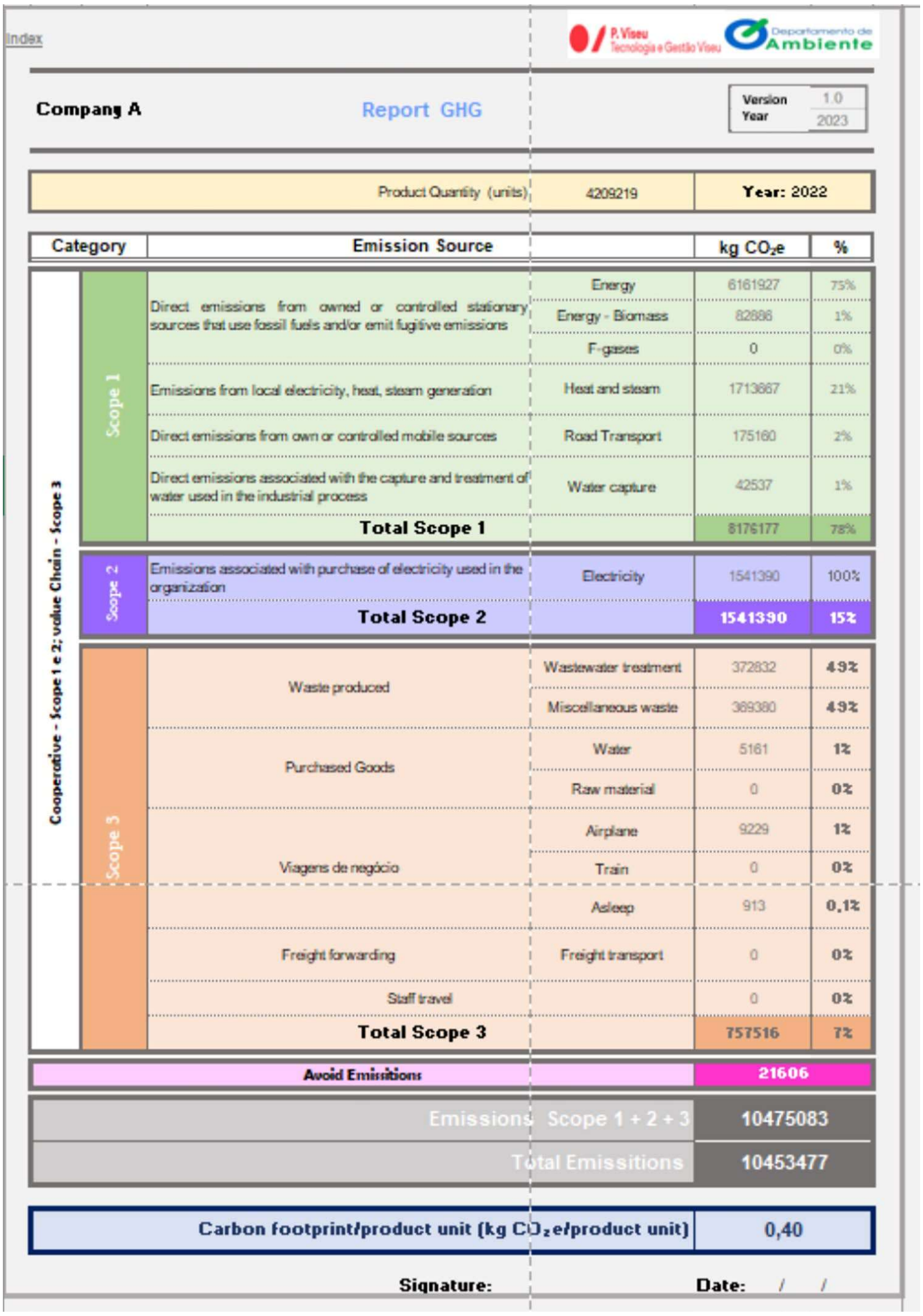
Therefore, the type and amount of energy consumed by companies are crucial factors in achieving sustainability. According to Chen et al. (2024), decarbonization practices within the textile supply chain can be organized into four key phases: production, distribution, use, and disposal/recycling. Each phase corresponds to distinct stages of the supply chain. Four primary strategies have been identified to specifically decarbonize production: the implementation of general environmental precautions, the adoption of eco-design principles, the incorporation of clean technologies, and the minimization of waste generation from raw materials. General environmental precautions involve the implementation of measures such as biological substitutions and energy optimisation throughout the production process, with the aim of reducing the overall environmental impact. According to Xu et al. (2023), green technology innovation efficiency is inversely correlated with government subsidies, but positively associated with net profit and asset size of enterprises.

Validation

The validation of the CF calculator was conducted using a self-assessment approach. This method involves comparing the results obtained from the CF calculator with those provided by several other calculators available online. For validation purposes, the GGEC and HCO calculators were chosen, as they adhere to the same methodology as the CF calculator (GHG Protocol). Additionally, for Company A the results were also compared with LCA outcomes obtained using the SimaPro PhD software. During the self-assessment process, a similarity was observed between the data provided by the HCO calculator and the CF calculator for both companies, particularly in terms of transportation emissions (Table 5).

A key advantage of the CF calculator lies in its capacity to generate results that are not provided by the GGEC and HCO calculators, which makes it a more comprehensive tool. For components such as electricity and energy (biomass), it was possible to compare the results obtained from all three calculators. However, the results for the natural gas component were compared exclusively with those provided using the GGEC calculator, while diesel consumption results were compared solely with those derived from the HCO calculator. For components such as water, wastewater, raw materials, air travel, and overnight stays, the values obtained from the CF calculator could only be compared with those from the GGEC calculator, as these components were not included in the HCO calculator or any of the other calculators available online.

Regarding the results obtained, electricity-related emissions exhibited the closest values across all three calculators. The most significant discrepancies were observed for the biomass component, due to differences in the EFs used. The CF calculator relied on locally collected data from 2022,



Index

P. Viseu Tecnologia e Gestão Viseu — Departamento de Ambiente

Company A Report GHG

Version 1.0
Year 2023

		Product Quantity (units)	4209219	Year: 2022	
Category		**Emission Source**		**kg CO₂e**	**%**
Cooperative - Scope 1 e 2; value Chain - Scope 3	Scope 1	Direct emissions from owned or controlled stationary sources that use fossil fuels and/or emit fugitive emissions	Energy	6161927	75%
			Energy - Biomass	82886	1%
			F-gases	0	0%
		Emissions from local electricity, heat, steam generation	Heat and steam	1713667	21%
		Direct emissions from own or controlled mobile sources	Road Transport	175160	2%
		Direct emissions associated with the capture and treatment of water used in the industrial process	Water capture	42537	1%
		Total Scope 1		8176177	78%
	Scope 2	Emissions associated with purchase of electricity used in the organization	Electricity	1541390	100%
		Total Scope 2		**1541390**	**15%**
	Scope 3	Waste produced	Wastewater treatment	372832	49%
			Miscellaneous waste	369380	49%
		Purchased Goods	Water	5161	1%
			Raw material	0	0%
		Viagens de negócio	Airplane	9229	1%
			Train	0	0%
			Asleep	913	0,1%
		Freight forwarding	Freight transport	0	0%
		Staff travel		0	0%
		Total Scope 3		757516	7%
		Avoid Emissitions		21606	
		Emissions Scope 1 + 2 + 3		10475083	
		Total Emissitions		10453477	
		Carbon footprint/product unit (kg CO₂e/product unit)		0,40	

Signature: **Date:** / /

Fig. 2 Layout of the GHG emissions report generated by the CF calculator

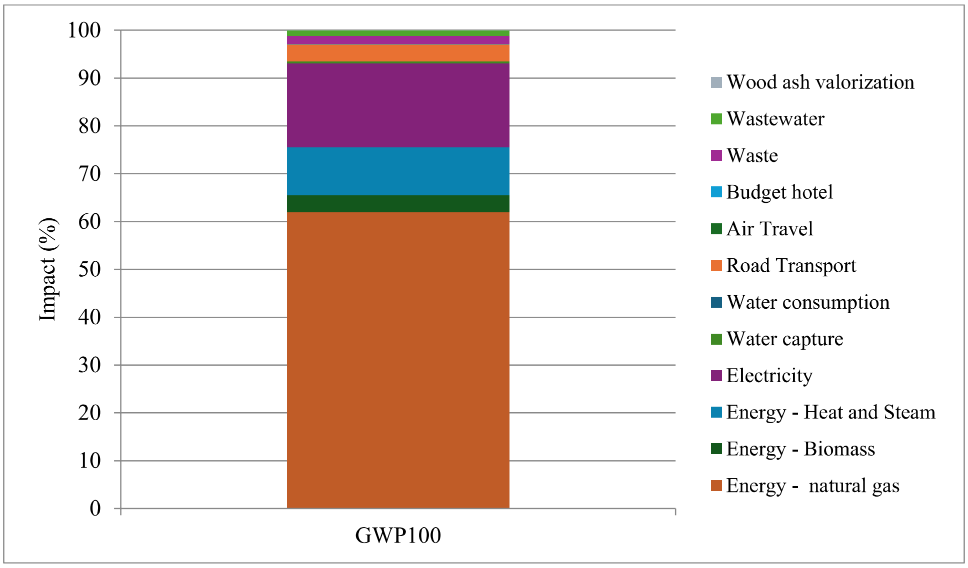


Fig. 3 Global Warming Potential (GWP) results per activity of Company A using the IPCC 2021 GWP100 method

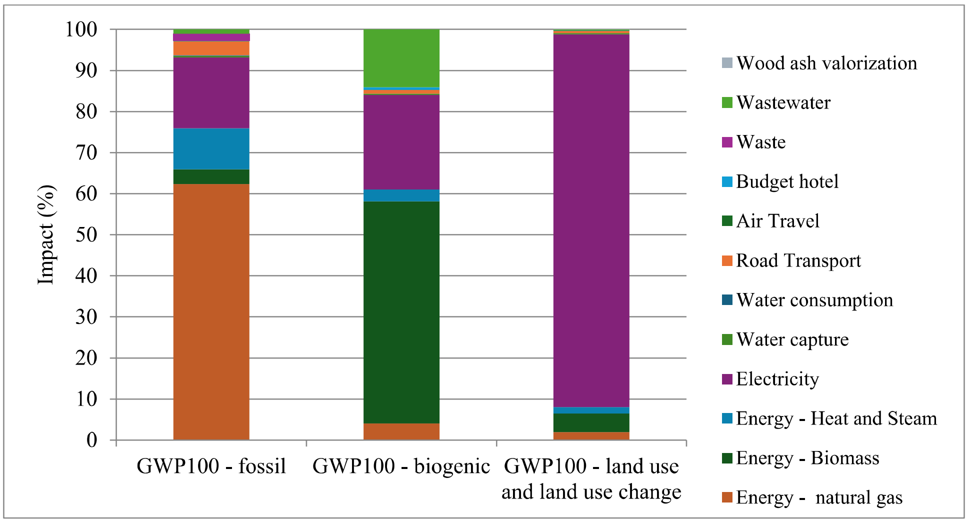


Fig. 4 Global Warming Potential (GWP) fossil, biogenic, and land use and land use change results per activity of Company A

while the GGEC and HCO calculators used outdated EFs from 2020 and 2021, respectively. The values related to the water usage component were quite similar between the two calculators, as the EFs employed were nearly identical. However, significant differences were observed for the wastewater production component. The LCA results for Scope 1 and 2 emissions were higher than those calculated using the other tools. The most notable discrepancies were observed for the electricity emissions factors, which were based on data from 2020 in the LCA software and 2022 in the CF calculator. Despite these differences, the total GHG emissions were similar (1.0 and 1.2×10^7 kg CO_2 equivalent for the CF calculator and the LCA software, respectively).

The variations in equivalent carbon dioxide emissions calculated by all three calculators can be attributed to the distinct EFs used by each tool. A crucial concern of the CF calculator is the use of updated and specific data from the Portuguese Textile and Clothing Sector, which ensures an accurate representation of the carbon footprint of each company. In a market increasingly driven by environmental consciousness, where consumers prioritise environmental issues, the implementation of measures to protect the environment will undoubtedly enhance a brand's reputation.

Table 5 Quantification of the CO_2 equivalent calculated using the tools analysed, for the components under study

Component		Emissions (kg CO_2e/year)			
		CF Calculator	GGEC	HCO	LCA
Company A					
Energy	Natural gas	6 161 927	5 671 708	–	7 483 790
	Biomass	82 886	170 794	377 591	439 372
	Heat and steam	1 713 667	–	–	1 208 077
Road Transport	Diesel	175 160	–	165 573	409 315
Electricity		1 541 390	1 758 718	1 953 766	2 115 285
Water		47 698	50 764	–	60 570
Wastewater		372 832	75 679	–	134 784
Waste		369 380	–	–	211 016
Air travel		9 229	9 229	–	9 497
Overnight stays		913	1 457	–	436
Company B					
Road Transport	Diesel	29 244	–	27 643	–
Electricity		66 444	92 270	68 470	–
Water		430	457	–	–
Wastewater		3 278	668	–	–
Air travel		16 646	16 646	–	–

CF – Carbon Footprint; GGEC - Green House Gas Emissions Calculator; HCO - Huella de Carbono de Una Organización; LCA – Life Cycle Assessment

The analysis and comparison of the aforementioned four carbon emission calculation methods highlight the pressing need for an improved carbon footprint methodology to accurately calculate product carbon emissions. The calculator's validation results for electricity and diesel consumption showed strong alignment with existing online tools, which confirms its accuracy. For other components, such as water and waste, the calculator provided more localized results that better reflect the specific context of the Portuguese TCS. This highlights its value as a tailored emissions assessment tool for the region. A critical approach to reducing the CF involves the use of eco-friendly materials, such as organic fibers and recycled inputs, which significantly reduce GHG emissions during production (Sawant et al. 2024). Additionally, innovative technologies such as carbon dioxide dyeing and ozone-based treatments help minimize chemical usage and energy consumption, further contributing to emissions reduction (Nayak et al. 2024) and building retrofitting for energy consumption reduction purposes (do Nascimento Ferreira et al. 2025). Implementing effective waste management strategies, guided by lean production principles, helps conserve resources and reduce pollution throughout the production cycle (Nayak et al. 2024; Rahaman et al. 2024). Compensation measures should be considered as a last resort and should be implemented only after all possible emission reduction and mitigation measures have been exhausted. An impactful compensation measure for Portuguese companies involves actively contributing to reforestation projects in areas devastated by wildfires.

Conclusion

Developing, applying, and validating a carbon footprint calculator provides an essential framework for TCS companies to quantify their Scopes 1, 2, and 3 GHG emissions. However, a major challenge in the development and implementation of CF calculations is the collection of accurate data from company activities. The results obtained using the CF calculator revealed lower CO_2 equivalent emissions compared to other existing calculators, with exceptions observed for the energy component (natural gas consumption) and wastewater. This stems from the fact that the EFs considered for most components (natural gas, electricity, waste, end-of-life treatment, wastewater) were calculated using Portuguese data, providing a more realistic and context-specific output. The self-assessment conducted confirmed that the EFs used significantly influence the carbon footprint results. As the fourth largest sector in the world with the greatest environmental impact, the TCS urgently needs to implement measures to reduce and mitigate these impacts to avoid worse consequences. In this context, the CF calculator emerges as a practical and versatile tool for TCS companies to estimate, monitor, and strategically manage their carbon emissions, while providing results that accurately reflect national contexts. This holistic approach empowers companies to pinpoint high-emission activities and implement targeted mitigation strategies. By providing detailed emissions data across different scopes, the calculator facilitates the adoption of reduction and offsetting measures, aligning the sector with both national and global sustainability goals. Future improvements to the calculator should focus on refining data inputs and broadening its applicability to other industrial sectors.

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Author contribution Claúdia Duarte (CD) and Maria Elisabete F. Silva (MEFS) contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by CD. José Vicente Ferreira conducted the LCA study. The first draft of the article was written by MEFS, CD and Isabel Paula Lopes Brás. All authors provided comments on previous versions of the manuscript and approved its final version.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication All authors consent to the submission of the manuscript.

References

Aitex (2021) The six most important environmental impacts that companies in the textiles sector should seek to reduce. Sustainability and the circular economy. https://www.aitex.es/the-six-most-important-environmental-impacts-that-companies-in-the-textile-sector-should-seek-to-reduce/?lang=en

Akhtar S, Baig SF, Saif S, Mahmood A, Ahmad SR (2017) Five year carbon footprint of a textile industry: a podium to incorporate sustainability. Nat Environ Pollut Technol 16:125–132

Allwood J, Laursen S, Rodríguez C, Bocken N (2006) Well dressed? The present and future sustainability of clothing and textiles in the United Kingdom. University of Cambridge, Institute for Manufacturing University of Cambridge, UK.

APA a- Agência Portuguesa do Ambiente (2021) Acordo de Paris | Agência Portuguesa do Ambiente. https://apambiente.pt/clima/acordo-de-paris

APA b- Agência Portuguesa do Ambiente (2021) Emissões de Gases com Efeito de Estufa | Relatório do Estado do Ambiente. https://rea.apambiente.pt/content/emiss%C3%B5es-de-gases-com-efeito-de-estufa

APA - Agência Portuguesa do Ambiente (2023) Conversor de gases fluorados. https://gfconversor.apambiente.pt/

APREN - Associação de Energias Renováveis (2021) Boletim eletricidade renovável. https://www.apren.pt/contents/publicationsreportcarditems/boletim-renovaveis-dezembro-2021.pdf

Chen S, Zhu L, Sun L, Huang Q, Zhang Y, Li X, Ye X, Li Y, Wang L (2023) A systematic review of the life cycle environmental performance of cotton textile products. Sci Total Environ 883:163659. https://doi.org/10.1016/j.scitotenv.2023.163659

Chen X, Cheng X, Zhang T, Chen H-W, Wang Y (2024) Decarbonization practices in the textile supply chain: towards an integrated conceptual framework. J Clean Prod. https://doi.org/10.1016/j.jclepro.2023.140452

CE - Comissão Europeia (2021) Ciclos do carbono sustentáveis. https://eur-lex.europa.eu/legal-content/PT/TXT/PDF/?uri=CELEX:52021DC0800

CE - Comissão Europeia (2020) Um novo Plano de Ação para a Economia Circular Para uma Europa mais limpa e competitiva. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b73501aa75ed71a1.0022.02/DOC_1&format=PDF

Costa A, Catarino AR, Cardoso J, Rosa J, Rodrigues R, Rodrigues S (2023) Relatório Anual dos Serviços de Águas e Resíduos em Portugal 2022 Volume 1 – Caraterização do setor de águas e resíduos. https://www.ersar.pt/pt/site-publicacoes/Paginas/edicoes-anuais-do-RASARP.aspx

CP – Comboios de Portugal (2020) Relatório de sustentabilidade 2020. https://www.cp.pt/StaticFiles/Institucional/2_gestao_sustentavel/1_RelatoriosSustentabilidade/relatorio-de-sustentabilidade-2020.pdf

Do Nascimento Ferreira V, De Cocito Araujo LO, Linhares Qualharini E, Vazquez EG, Chaer I, Najjar MK (2025) Building retrofit for energy efficiency in existing buildings: a case study of a social residential building in France. DYSONA Appl Sci 6(1):223–238. https://doi.org/10.30493/das.2024.486918

EBC - European Benchmarking Co-operation (2021). https://demo.waterbenchmark.org/

EEA - European Environment Agency (2019) Textiles in Europe's circular economy [Briefing]. https://www.eea.europa.eu/publications/textiles-in-europes-circular-economy

EEA - European Environment Agency (2023) Annual European Union greenhouse gas inventory 1990–2021 and inventory report 2023. https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-2

Endesa (2021) Origem de Energia. https://www.endesa.pt/particulares/quemsomos/Origem-de-Energia

EDP - Energia de Portugal (2022) Relatório Sustentabilidade EDP - 2021. https://www.edp.com/sites/default/files/202303/Relatório%20de%20Sustentabilidade%20EDP%202021.pdf

EURATEX (2021) A New EU Strategy for Textiles & Clothing. https://euratex.eu/wp-content/uploads/EURATEX-Vision-on-EU-Textile-Strategy-fin.pdf

Farhana K, Kadirgama K, Mahamude ASF, Mica MT (2022) Energy consumption, environmental impact, and implementation of renewable energy resources in global textile industries: an overview towards circularity and sustainability. Mater Circ Econ 4(1):15. https://doi.org/10.1007/s42824-022-00059-1

G9 Energy (2021) InfoAnual.pdf. https://public.g9energy.pt/g9energy/InfoAnual.pdf

Galp (2021) Casa Galp. https://casa.galp.pt/energias/origem-da-energia,%20obtido%20a%2031/01/2023

Gimbert Y (2022) How much CO_2 can electric cars really save? Transport & Environment. https://www.transportenvironment.org/discover/how-clean-are-electric-cars/

GOV.UK (2022) Greenhouse gas reporting: Conversion factors. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

Hillman K, Damgaard A, Eriksoon O, Jonsson D, Fluck L (2015) Climate benefits of material recycling. Inventory Ave Greenh Gas Emiss Den Nor Swed. https://doi.org/10.6027/TN2015-547

Iberdrola (2021) Rotulagem da Energia—Iberdrola. https://www.iberdrola.pt/sobre-nos/iberdrola-portugal/mercado-eletrico

ICAO - International Civil Aviation Organization (2023) https://applications.icao.int/icec/Home/Index

Imran S, Mujtaba MA, Zafar MM, Hussain A, Mehmood A, Farwa UE, Korakianitis T, Kalam MA, Fayaz H, Saleel CA (2023) Assessing the potential of GHG emissions for the textile sector: a baseline study. Heliyon. https://doi.org/10.1016/j.heliyon.2023.e22404

INE - Instituto Nacional de Estatística (2021) Indicadores económicos-ambientais - Contas das emissões atmosféricas 1995-2019. https://www.ine.pt

IPPC - Intergovernmental Panel on Climate Change (2006) National Greenhouse Gas Inventories, Volume 2 - Energy. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html

ISO (2006a) Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization. Geneve, Switzerland

ISO (2006b) Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization. Geneve, Switzerland

ISO (2014) Environmental management — Life cycle assessment — Requirements and guidelines for organizational life cycle assessment. International Organization for Standardization. Geneve, Switzerland.

Jain T, Jain JK, Agrawal R, Johri S (2022) Investigation of environmental potentials on supply chain of textile and yarn industry using smart and sustainable life cycle assessment. Manag Environ Qual 34:902–925. https://doi.org/10.1108/MEQ-03-2022-0062

Li X, Chen L, Ding X (2019) Allocation methodology of process-level carbon footprint calculation in textile and apparel products. Sustainability. https://doi.org/10.3390/su11164471

Liu W, Zhang Z, Xie X et al (2017) Analysis of the global warming potential of biogenic CO_2 emission in life cycle assessments. Sci Rep. https://doi.org/10.1038/srep39857

Liu Y, Huang H, Ren F, Wang Y, Liu Z, Ke Q, Li X, Zhang L (2020) Cradle-to-gate water and carbon footprint assessment of melange yarns manufacturing. Procedia CIRP 90:198–202. https://doi.org/10.1016/j.procir.2020.01.051

Luo Y, Wu X, Ding X (2022) Carbon and water footprints assessment of cotton jeans using the method based on modularity: a full life cycle perspective. J Clean Prod. https://doi.org/10.1016/j.jclepro.2021.130042

Mohan S, Oke N (2020) Waste Management in Textile Industry—A Novel Application of Carbon Footprint Analysis. In: Reddy KR, Agnihotri AK, Yukselen-Aksoy Y, Dubey BK, Bansal A (ed) Sustainable Environmental Geotechnics. Lecture Notes in Civil Engineering, vol 89. Springer, Cham, pp 125–130. https://doi.org/10.1007/978-3-030-51350-4_14

Morlet A, Opsomer R, Herrmann S, Balmond L, Gillet C, Fuchs L (2017) A New Textiles Economy.pdf. https://archive.ellenmacarthurfoundation.org/assets/downloads/A-New-Textiles-Economy.pdf

Nayak R, Panwar T, Grover T, Singh A (2024). Recent Trends in Sustainable Clothing and Textile Manufacturing. In: Muthu SS (eds), Sustainable Manufacturing Practices in the Textiles and Fashion Sector. Sustainable Textiles Production, Processing, Manufacturing & Chemistry. Springer, Cham, pp 75–93. https://doi.org/10.1007/978-3-031-51362-6_4

Niinimäki K, Peters G, Dahlbo H, Perry P, Rissanen T, Gwilt A (2020) The environmental price of fast fashion. Nat Rev Earth Environ 1(4):189–200. https://doi.org/10.1038/s43017-020-0039-9

OECC (2023) Calculadora de huella de carbono de organizacióm. https://www.miteco.gob.es/es/cambio-climatico/temas/mitigacionpoliticas-y-medidas/calculadoras.html#huella-de-carbono-de-un-ayuntamiento_- alcance-1_2. Accessed 26 June 2022

Pereira TC, Amaro A, Borges M, Silva R, Seabra T, Canaveira P (2023) Portuguese National Inventory Report on Greenhouse Gases, 1990–2021. https://apambiente.pt/sites/default/files/_Clima/Inventarios/20230404/NIR202315%20April.pdf

Portgás (2023) Equivalências Energéticas | Profissionais| Portgás. Portgás Website. https://www.portgas.pt/profissionais/apoio/equivalencias-energeticas/

Rahaman T, Pranta AD, Repon R, Ahmed S, Islam T (2024) Green production and consumption of textiles and apparel: Importance, fabrication, challenges and future prospects. J Open Innov Technol Mark Complex. https://doi.org/10.1016/j.joitmc.2024.100280

Roth J, Zerger B, De Geeter D, Gómez Benavides J, Roudier S (2023) Best available techniques (BAT) reference document for the textiles industry. Office Eur Union Luxemb. https://doi.org/10.2760/355887

Sandin G, Roos S, Spak B, Zamani B, Peters G (2019) Environmental assessment of Swedish clothing consumption – six garments, sustainable futures. https://doi.org/10.13140/RG.2.2.30502.27205

Sawant J, Guru R, Grewal D, Talekar S C, Kulkarni S P (2024) Sustainability in textiles: a critical review of eco-friendly practices and materials. ShodhKosh: Journal of Visual and Performing Arts. https://doi.org/10.29121/shodhkosh.v5.i2.2024.891.

Shirvanimoghaddam K, Motamed B, Ramakrishna S, Naebe M (2020) Death by waste: fashion and textile circular economy case. Sci

Total Environ 718:137317. https://doi.org/10.1016/j.scitotenv.2020.137317

Su Y, Duan H, Wang Z, Song G, Kang P, Chen D (2020) Characterizing the environmental impact of packaging materials for express delivery via life cycle assessment. J Clean Prod 274:122961. https://doi.org/10.1016/j.jclepro.2020.122961

Subramanian K, Chopra S, Cakin E, Li X, Lin C (2020) Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup. Resour Conserv Recycl. https://doi.org/10.1016/j.resconrec.2020.104989

UNCC (2022) GHG_emissions_calculator_ver02.6.xlsx. de https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Funfccc.int% 2Fsites%2Fdefault%2Ffiles%2Fresource%2FGHG_emissions_calculator_ver02.6.x lsx&wdOrigin=BROWSELINK.

Wren B (2022) Sustainable supply chain management in the fast fashion Industry: a comparative study of current efforts and best practices to address the climate crisis. Clean Logist Supply Chain 4:100032. https://doi.org/10.1016/j.clscn.2022.100032

Xu X, Cui X, Zhang Y, Chen X, Li W (2023) Carbon neutrality and green technology innovation efficiency in Chinese textile industry. J Clean Prod. https://doi.org/10.1016/j.jclepro.2023.136453

Yes Energy (2021) Impactes Ambientais—Yes Energy. https://www.yesenergy.pt/informacao-util-impactes-ambientais

Zhang J, Qian X, Feng J (2020) Review of carbon footprint assessment in textile industry. Ecofeminism Climate Change 1(1):51–56. https://doi.org/10.1108/EFCC-03-2020-0006