
From Field to Fabric: Carbon Emissions of Cotton T-Shirts in Pakistan

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Abstract:

The research study evaluates the cradle-to-grave carbon footprint of a cotton T-shirt in Pakistan by using a Life Cycle Assessment (LCA) framework. However, this research also shares the environmental impact associated with clothing production and consumption, especially in the textile sector, because it is a huge contributor to global greenhouse gas emissions.

The methods that have been used are Open LCA 2.6.1, BAFU 2025, and IPCC 2021 GWP100. The structure of the methodology follows the rules of ISO 14040 and ISO 14044 standards. Therefore, by considering the typical conditions in Pakistan, the functional unit is defined as a single 100% cotton T-shirt weighing 200g/50 washing cycles. The research article covers all the major life cycle stages, beginning from cotton cultivation, extending through ginning, spinning, knitting, dyeing, finishing, cut-make-trim (CMT) processes, distribution, consumer use, and final end-of-life disposal. However, due to limited primary industrial data, the research is derived from the published literature, combined with the BAFU database. During the process, the ginning stage, mass allocation was applied between cotton lint and cottonseed. In line with IPCC guidelines, biogenic carbon was treated as climate-neutral over the 100-year GWP time horizon, and the total carbon footprint of the functional unit was calculated as 5.19 kg CO₂-eq, which falls within the range reported in previously published literature cradle-to-grave studies of cotton T-shirts (approximately 4.25–8.44 kg CO₂-eq). However, the usability stage of the T-shirt is the most significant, accounting for 79.43%, followed by spinning (9.30%) and dyeing and finishing (5.70%). Together, these three stages accounted for more than 94% of the overall impact. In the comparison with cotton cultivation, knitting, CMT processes, distribution, ginning, and end-of-life disposal contributed relatively minor shares.

The results clearly indicate that the primary hotspots are both consumer behaviours, laundry practices, and energy-intensive textiles

These results clearly indicate that both consumer behaviour—particularly laundering practices and energy-intensive textile manufacturing processes—are acting as primary environmental hotspots. From a mitigation perspective, the research findings suggest that substantial reductions in carbon emissions could be achieved through improved efficiency in textile processing, transition towards cleaner electricity sources in industrial operations, and more sustainable consumer washing habits.

Overall, this study contributes a Pakistan-specific perspective to the existing body of LCA literature on cotton apparel. It also highlights the importance of regionalised assessment approaches in understanding product-level environmental impacts. The results should, however, be interpreted as modelled estimates based on literature-derived and secondary data inputs rather than direct primary industrial measurements.

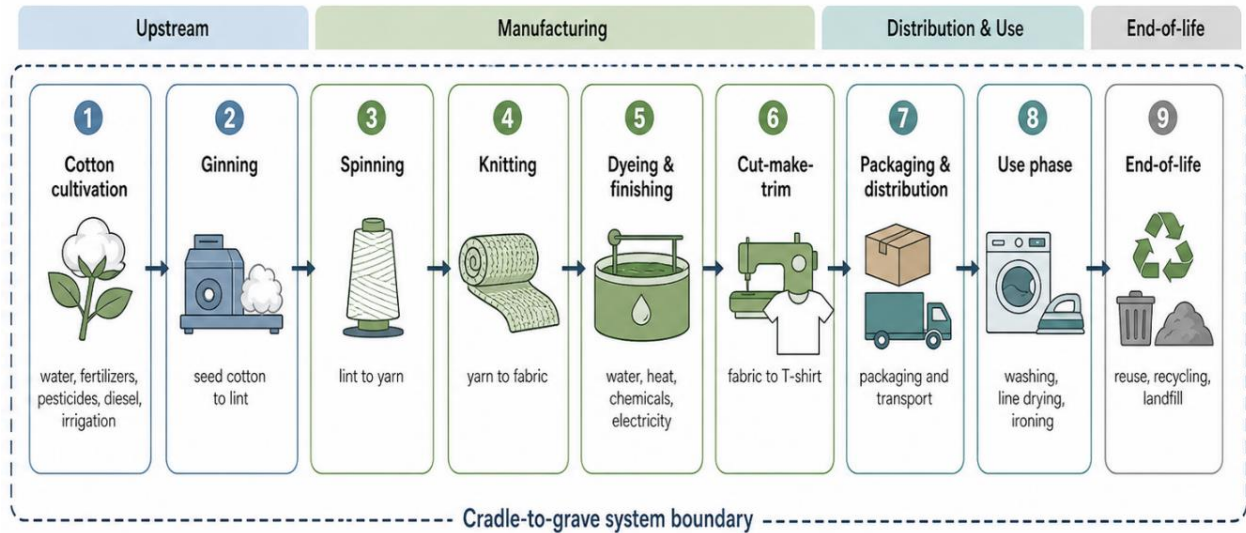
Keywords: Life Cycle Assessment (LCA); Carbon Footprint; Cotton T-Shirt; Cradle-to-Grave; Pakistan Textile Industry; ISO 14067; ISO 14040/14044; IPCC 2021 GWP100; open LCA 2.6.1; BAFU 2025 Database; Use Phase Emissions; Textile Sustainability.

1. Introduction:

The textile and apparel sector represents one of the largest global manufacturing systems and a significant source of environmental pressure. Recent sectoral assessments estimate that the apparel industry emitted approximately 944 million tonnes of CO₂-eq in 2023, accounting for around 1.78% of total global greenhouse gas emissions. In parallel, global fibre production reached 124 million tonnes in the same year, reflecting the continued expansion of textile consumption worldwide. Cotton is one of the most important natural fibres used in apparel production; its relative share has gradually declined due to increasing competition from synthetic fibres. However, it is important in the global fibre mix, and it is widely used in everyday garments, particularly products such as T-shirts [1], [2], [3], [4].

In LCA language, the environmental cotton T-shirt profile is based on and connected with a series of steps including cotton cultivation, ginning, spinning, fabric production through knitting or weaving, dyeing and finishing, garment manufacturing, distribution, consumer use, and end-of-life treatment. The same system is commonly used in evaluating cotton apparel systems across different geographical contexts [3], [5]. Therefore, Figure 1 explains the conceptual model of this ecosystem.

Figure 1: Standard global life cycle stages of a cotton T-Shirt



After observing the multiple stages of this system, it clearly shows that the energy distribution is different in life cycle stages. All stages has their relations i.e. Cotton cultivation is associated with fertiliser use, irrigation demand, diesel consumption, and field emissions; textile processing stages such as spinning, dyeing, and finishing are often electricity- and heat-intensive; and the use phase can become a major hotspot depending on assumptions related to washing frequency, machine efficiency, ironing, and drying behaviour[3], [5], [6], [7].

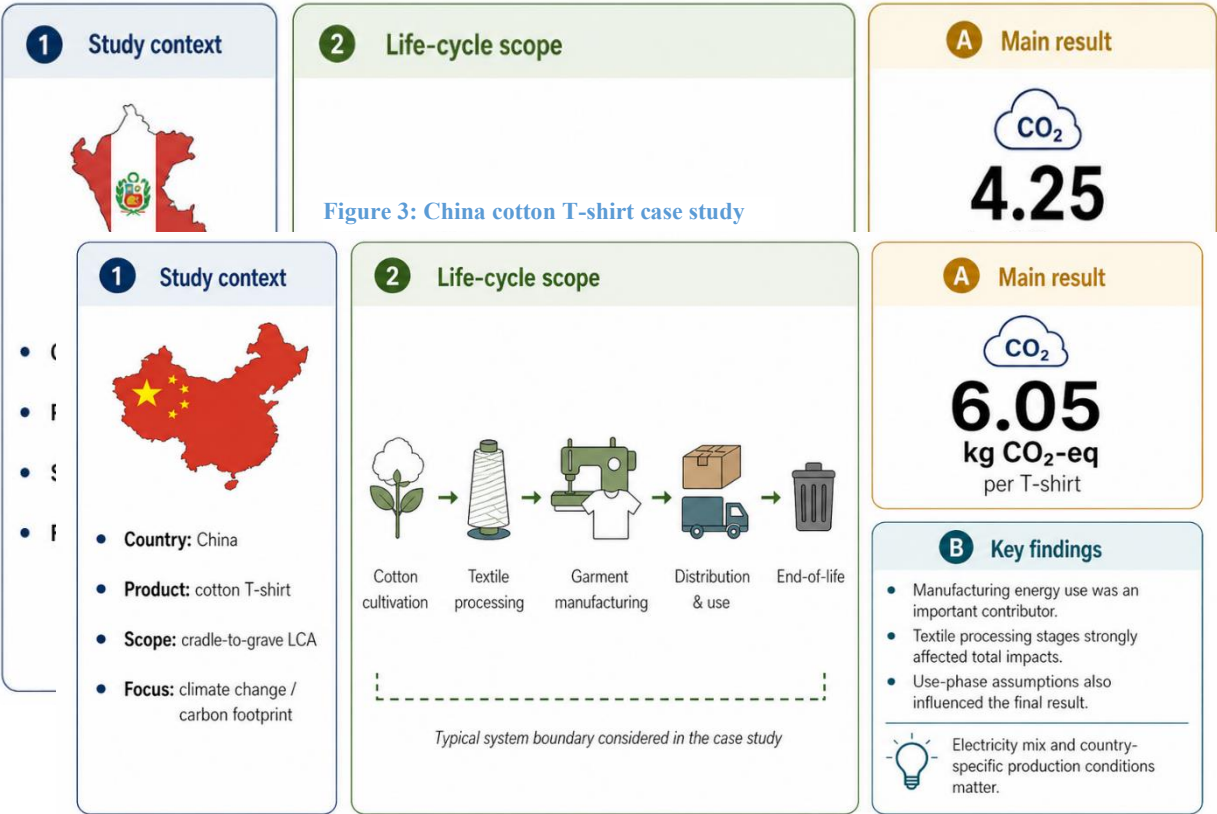
The carbon-intensive evidence collected at the sector level indicates that the recent estimates suggest that Tier 2 textile processing accounts for around 55% of apparel-sector emissions, while raw material production contributes about 22% [1] Hence, both the fibre production and manufacturing stages play a major role in understanding the climate footprint.

The cotton apparel is relevant because T-shirts are among the most common and frequently studied/used

textile products in product carbon footprint research. Their relatively simple structure makes them a useful model for tracing emissions across the textile value chain and comparing the influence of different geographical conditions, energy systems, and consumer-use assumptions [3], [5], [8]. In addition, cotton-based clothing has received substantial attention in recent LCA scholarship because it combines agricultural production with industrial wet processing and consumer-use impacts, making it highly suitable for cradle-to-grave assessment [3], [5]

A growing body of literature has assessed the environmental performance of cotton garments in different national contexts. Chen et al. conducted a systematic review of cotton textile studies and showed that cotton-related LCA commonly examine cultivation, ginning, spinning, knitting or weaving, dyeing, finishing, and garment construction, while also highlighting the importance of allocation choices, recycling assumptions, and data comparability across studies [3]. More recent work by Feichtinger et al. demonstrated that cotton T-shirt impacts are also strongly influenced by supply-chain design, automation, transport configuration, and overproduction, with conventional supply chains producing substantially higher climate impacts than more demand-oriented automated alternatives [8].

Figure 2 : Peru cotton T-shirt case study



These findings indicate that product carbon footprints are sensitive to their own technical needs. Both case studies are useful here to use: The first is the Peru case study by Montoya Flores and Salhofer, who reported a cradle-to-grave carbon footprint of 4.25 kg CO₂-eq for a cotton T-shirt and identified the use phase as an important contributor, while also showing the relevance of country-specific consumer behaviour and production assumptions [6]. Figure 2 is a good example to showcase this case study. The second is a China-based case study by Zhang et al., who reported a higher cradle-to-grave carbon footprint of 6.05 kg CO₂-eq per cotton T-shirt, reflecting differences in production energy use, system boundaries, and modelling assumptions [9].

Therefore, it is safe to say that carbon footprint results can vary considerably across geographical contexts. In the final manuscript, this comparison may be visualised in Figure 3 as concise case-study infographics summarising country context, system scope, total carbon footprint, and key hotspot stages.

Moreover, published studies further indicates the same findings: Baydar et al. reported an even higher cradle-to-grave impact of approximately 8.44 kg CO₂-eq for cotton textile products in Turkey, while recent research from South Asia similarly identifies wet processing, electricity consumption, and assumptions related to the use phase as key drivers of total environmental impact [7], [9].

Overall, recent developments in textile Life Cycle Assessment literature have shifted beyond impact quantification toward the lifecycle stages. [8], [9], [10].

As Pakistan is among the major global producers and consumers of cotton but, due to the scale and economic significance of its cotton and textile sector, the research is limited to cotton garments. [11]. Given this strong economic dependence on cotton and textiles, there is a clear need for product-level carbon.

Accordingly, this study aims to evaluate the cradle-to-grave carbon footprint of a 100% cotton T-shirt in Pakistan, using Life Cycle Assessment methodology. It also seeks to identify the key life-cycle hotspots and to situate the Pakistan case within the broader international literature on cotton apparel impacts. By integrating a global life-cycle perspective with Pakistan-specific modelling conditions, this research provides a context-relevant case study for the environmental assessment of cotton garments and offers a baseline for future sustainability research in the country's textile sector.

2. Methodology

This study quantifies the carbon footprint of a single cotton T-shirt produced and used in Pakistan, covering its complete life cycle from raw material extraction to end-of-life disposal. It examines how greenhouse gas emissions are distributed across the various life cycle stages and identifies the processes that contribute most significantly. The assessment focuses on climate-related impacts associated with cotton cultivation, textile processing, garment manufacturing, transportation, consumer use, and final disposal.

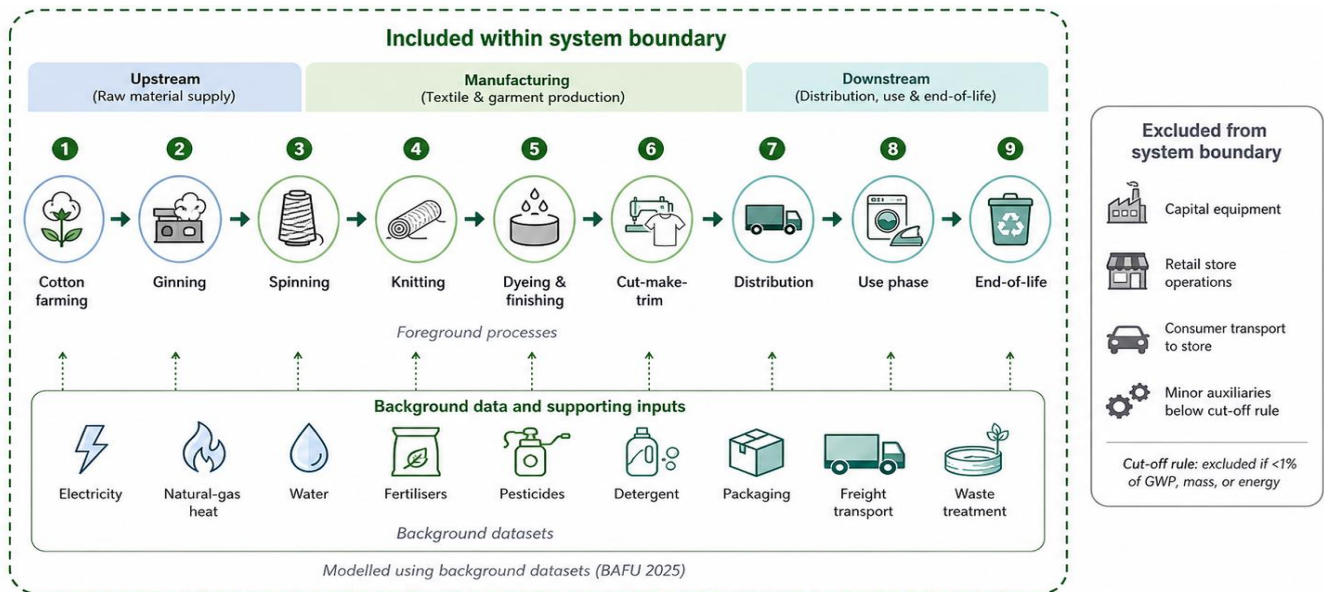
The methodological framework is based on ISO 14067:2018, which provides guidelines for the quantification and reporting of product carbon footprints, and is consistent with the Life Cycle Assessment principles outlined in ISO 14040 and ISO 14044 [12]. The modelling was conducted using open LCA 2.6.1, an open-source Life Cycle Assessment software platform [13]. Climate change impacts were assessed using the IPCC 2021 GWP100 characterization method, based on the Sixth Assessment Report (AR6) [14]. The study is limited to climate change impact (kg CO₂-eq), in line with the defined scope of a product carbon footprint and the selected impact assessment method. The functional unit of this study is defined as:

One 100% cotton T-shirt of 200 g, providing 50 wash cycles of clothing service under Pakistan's use conditions

All material and energy diagrams are quantified and normalised with respect to this specific unit, so that the final result represents the carbon footprint of a single garment. The specification of mass (200 g), service performance (50 wash cycles), and geographical context (Pakistan) is required under ISO 14067 to ensure the functional unit provides a consistent and complete basis for comparison.

The system boundary is cradle-to-grave and includes: (A) upstream: cotton farming and ginning; (B) core manufacturing: spinning, knitting, dyeing and finishing, and cut-make-trim; (C) downstream: distribution, use phase (washing, ironing), and end-of-life disposal. Capital equipment, retail store operations, and consumer transport to store are excluded under the applied cut-off rule (<1% of GWP, mass, or energy) as shown in figure 4

Figure 4: System boundary of the present cotton T-shirt

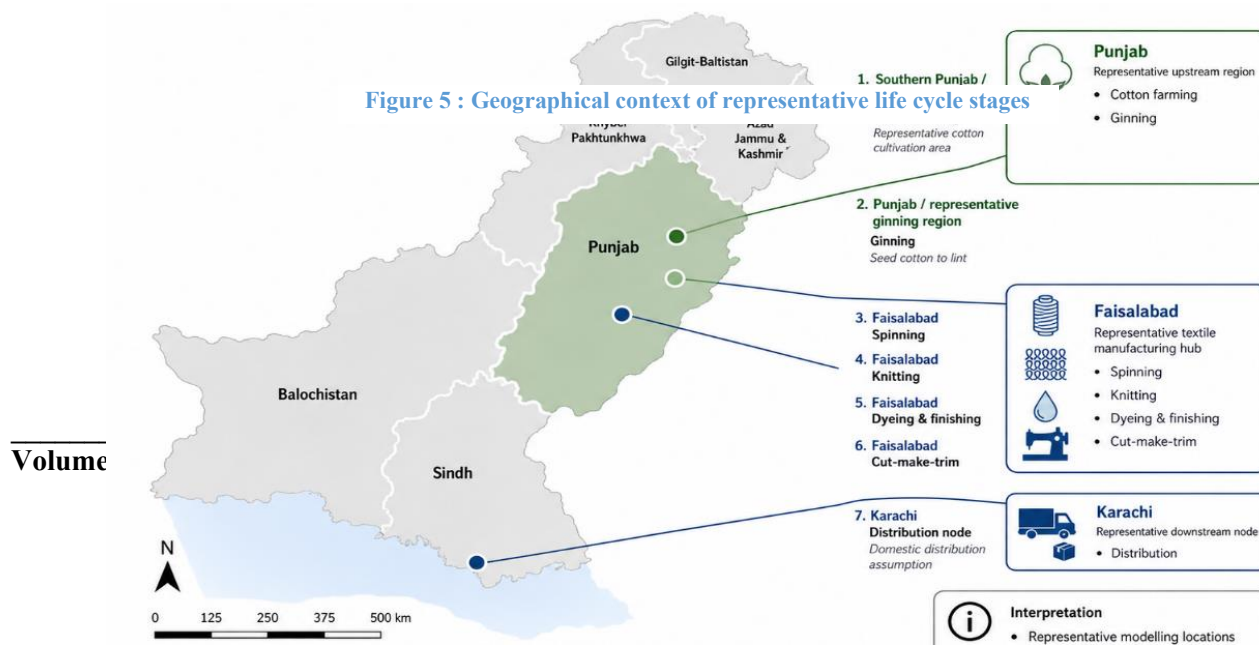


2.1 Life Cycle Inventory:

The life cycle inventory was developed within openLCA 2.6.1 by combining manually constructed foreground processes with supporting background datasets from the BAFU 2025 LCI database (ecoinvent-based). This foreground-background structure is consistent with carbon-footprint modelling under ISO 14067[12]. Background datasets were used for urea, diammonium phosphate, potassium sulphate, pesticide inputs, electricity, natural-gas-based heat, LDPE packaging, cardboard, freight transport, tap water, detergent, and municipal solid-waste treatment. All foreground processes were parameterised to maintain consistency between mass-based intermediate flows and the item-based functional unit. The geographical context adopted for the representative life-cycle stages, including upstream production, textile manufacturing, and domestic distribution within Pakistan, is shown in Figure 5.

1. Cotton farming represents the starting point of the foreground system, modelled as seed-cotton production in Punjab, Pakistan[15]. The inventory was expressed per kilogram of seed cotton and included urea (nitrogen fertiliser), diammonium phosphate (phosphorus fertiliser), potassium sulphate (potassium fertiliser), pesticides, diesel for field machinery, and electricity for irrigation pumps. A direct soil emission of N_2O was modelled using the IPCC Tier 1 emission factor ($EF = 0.01 \text{ kg } N_2O\text{-N per kg N applied}$), consistent with standard LCA practice for agricultural systems. Cotton farming inputs were scaled to the Pakistan-relevant yield assumption using the official cotton policy analysis report[15]
2. The ginning stage separates seed cotton into cotton lint and cottonseed. In the present study, the ginning inventory was expressed per kilogram of cotton lint output. Based on the Pakistan Agriculture Policy Institute report, 120 kg of seed cotton yields 40 kg of lint and 80 kg of cottonseed, corresponding to a lint mass fraction of 0.333 [15]. This value was applied consistently in both the foreground model and the allocation calculation. Electricity consumption was set at 0.07 kWh per kilogram of lint, based on the Better Ginning Practices Manual.[16] Mass allocation was applied at this stage: 33.3% of ginning impacts assigned to lint; 66.7% to cottonseed. Economic allocation was considered as a sensitivity scenario.

3. The spinning stage converts cotton lint into cotton yarn (ring-spun, Ne 30s count) and was assigned to Faisalabad as the representative textile-manufacturing location [17] The inventory was expressed per kilogram of yarn output. Cotton lint was modelled at 1.15 kg per kilogram of yarn (representing 13% fibre waste), and electricity at 3.5 kWh per kilogram of yarn. Fibre waste of 0.15 kg per kilogram was modelled as a waste flow with no economic value and therefore no allocation. Lubricants were excluded under the applied cut-off rule (<1% GWP) [18]
4. The knitting stage converts cotton yarn into grey single-jersey knit fabric (180 gsm) and was also assigned to Faisalabad, consistent with Pakistan's knitwear production geography [19] The inventory was expressed per kilogram of grey fabric output. Yarn input was modelled at 1.05 kg per kilogram of fabric (5% knitting waste), and electricity at 0.5 kWh per kilogram. Knitting waste of 0.05 kg per kilogram was treated as a waste flow. No sizing agent or water is required for knitting, which distinguishes it from weaving and reduces its environmental profile relative to wet processes [6]
5. Dyeing and finishing converts grey fabric into finished fabric and is one of the most resource-intensive stages in the foreground system.[20] The inventory was expressed per kilogram of finished fabric output. Grey fabric input was modelled at 1.02 kg per kilogram of finished fabric. Process inputs included reactive dye (0.04 kg), electricity (1.0 kWh), thermal energy for steam (10 MJ, from a natural gas boiler at 85% efficiency), and process water (169 kg). Wastewater output (152.1 L) was modelled as a waste flow linked to a generic wastewater treatment background process. This stage has been widely identified as a major environmental hotspot in cotton textile LCAs due to its combined chemical, water, heat, and electricity demands [21]
6. The CMT stage converts finished fabric into the final T-shirt and was modelled per functional unit (one garment). Finished fabric input was approximately 0.266 kg per T-shirt (accounting for 8% fabric offcut waste), and electricity was 0.15 kWh per garment. Fabric offcuts of approximately 0.021 kg per T-shirt were modelled as waste flows. Sewing thread and labels were excluded under the cut-off rule (<1% GWP) [22] This stage is the conversion point from mass-based intermediate flows to the item-based functional unit.
7. Distribution was modelled from the garment factory to a domestic retail point within Pakistan, with Karachi as the representative distribution node [23]Inputs included LDPE polybag packaging (0.005 kg per T-shirt), cardboard box packaging (0.033 kg per T-shirt), and truck freight transport (0.16 t·km per T-shirt, representing two domestic transport legs totalling 800 km). No sea freight was included, as domestic sale is assumed. Retail store operations and consumer transport to store were excluded under the cut-off rule.
8. The use phase was modelled per functional unit using scenario-based assumptions for garment care over 50 wash cycles, consistent with the defined functional unit. Pakistan household context was applied: top-load washing machine (60 L water per cycle, 0.5 kWh electricity per cycle), cold/warm wash, line drying (0 kWh tumble dryer), and ironing (0.1 kWh per cycle). Total use-phase inputs



were: 3.0 m³ water, 1.25 kg detergent, and 30 kWh electricity per T-shirt over its lifetime. Tumble drying was excluded as line drying is representative of Pakistan household behaviour; this assumption was flagged as a key sensitivity variable.[6] Published cotton T-shirt studies consistently identify garment care as one of the most influential stages in cradle-to-grave assessments [7], [24], [25]

9. The end-of-life stage was modelled as the disposal of one used cotton T-shirt (0.200 kg) through municipal solid waste collection and landfill treatment, using a generic background dataset from BAFU 2025. This simplified disposal scenario was adopted due to the limited availability of Pakistan-specific textile waste-management data. Open burning was noted as an alternative scenario for sensitivity analysis. Biogenic carbon in cotton fibre was treated as climate-neutral over the 100-year GWP100 time horizon, consistent with IPCC 2021 methodology[6]

2.2 Analysis

The foreground model was built around a sequential mass-conversion chain from seed cotton to the final garment. Key inventory parameters are summarised below in Table 1. All values are literature-derived estimates (labelled as modelled assumptions) in the absence of primary facility data:

Table 1 :Key inventory parameters used in the foreground model

Stage	Key Parameter	Value
Ginning	Lint fraction of seed cotton	0.333
Ginning	Electricity per kg lint	0.07 kWh
Spinning	Lint input per kg yarn	1.15 kg
Spinning	Electricity per kg yarn	3.5 kWh
Knitting	Yarn input per kg fabric	1.05 kg
Knitting	Electricity per kg fabric	
Dyeing & finishing	Thermal energy per kg fabric	10 MJ
Dyeing & Finishing	Electricity per kg fabric	1.0 kWh
CMT	Fabric per T-shirt (incl. waste)	0.266 kg
CMT	Electricity per T-shirt	0.15 kWh
Distribution	Freight transport	0.16 t·km
Use phase	Wash cycles	50
Use phase	Total electricity	30 kWh
Use phase	Total water	3.0 m ³
End-of-life	Mass to landfill	0.200 kg

2.3 Limitations:

The present inventory has several limitations. First, not all stages were based on primary local process data;

parameters were derived from published literature, background datasets, and modelled assumptions. Second, downstream stages were represented in a simplified manner, introducing additional uncertainty. Third, several supporting processes were linked through generic background datasets rather than verified Pakistan-specific inventories. These limitations are consistent with published cotton T-shirt studies where missing data are addressed through literature-based assumptions.[6], [7], [24] Overall, this study should be interpreted as a Pakistan-context modelled carbon-footprint case study rather than a fully site-specific industrial inventory.

3. Results and Discussion:

Using the IPCC 2021 GWP100 approach, the total cradle-to-grave carbon footprint of a single cotton T-shirt was calculated to be 5.19 kg CO₂-eq per functional unit. This result represents the combined contribution of upstream cotton production, core textile-manufacturing stages, and downstream processes including distribution, use phase, and end-of-life disposal.

The contribution analysis showed an uneven distribution of impacts across life cycle stages. As presented in Table 2 and in Figure , the use phase was by far the largest contributor at followed by spinning at 0.483 kg CO₂-eq (9.30%) and dyeing and finishing at 0.296 kg CO₂-eq (5.70%). The remaining stages; cotton farming (1.99%), CMT (1.44%), knitting (1.21%), distribution (0.86%), and ginning (0.07%) contributed comparatively smaller shares. End-of-life contributed a negligible amount under the landfill scenario adopted.

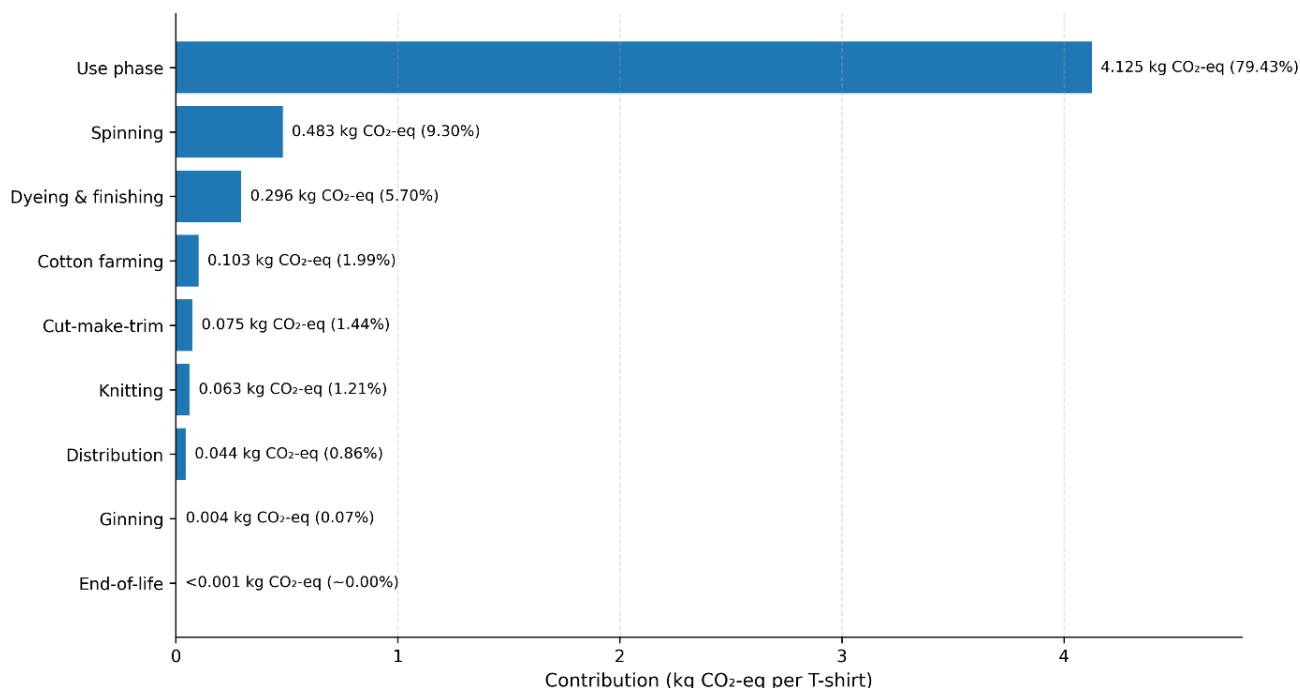
Table 2 : Carbon footprint results per life cycle stage for one cotton T-shirt (200 g, 50 wash cycles).

Life Cycle Stage	Contribution (kg CO ₂ -eq)	Share (%)	Notes
Cotton farming (A1+A2)	0.103	1.99	incl. ginning
Ginning	0.004	0.07	mass alloc. 33.3%
Spinning	0.483	9.30	electricity-intensive
Knitting	0.063	1.21	
Dyeing & Finishing	0.296	5.70	steam + electricity
Cut-Make-Trim	0.075	1.44	
Distribution	0.044	0.86	domestic only
Use phase	4.125	79.43	50 cycles, PK grid
End-of-life	<0.001	~0.00	landfill, biogenic neutral
TOTAL	5.19	100.00	IPCC 2021 GWP100

The dominance of the use phase is consistent with published cotton T-shirt studies, which frequently identify garment care as one of the most influential stages in cradle-to-grave assessments. Flores and Salhofer found that the use phase contributed 36% of total GWP, mainly due to energy demand for garment drying.[6] The higher share observed in the present study (79.43%) compared to Flores and Salhofer (36%) is primarily attributable to the higher electricity demand assumed per wash cycle under Pakistan top-load machine conditions, the higher number of wash cycles modelled (50 vs. 32), and the fact that the reference

study included tumble drying which shifted more impact to manufacturing stages in relative terms. The relatively higher contributions of spinning and dyeing in the present model are also consistent with the broader literature identifying these as key manufacturing hotspots[4], [21]

Figure 6: Carbon footprint results per life cycle stage for one cotton T-shirt (200 g, 50 wash cycles).



When compared with published cradle-to-grave cotton T-shirt studies, the present result falls within a plausible range shown in Table 3. Flores and Salhofer reported 4.25 kg CO₂-eq[6] Zhang et al. reported 6.05 kg CO₂-eq [24] and Baydar et al. reported approximately 8.44 kg CO₂-eq.[7]The result obtained here is consistent with the broader cotton T-shirt LCA literature and represents a reasonable Pakistan-context estimate.

Table 3 : Comparison of cradle-to-grave carbon footprint results with selected cotton T-shirt studies.

Study	Country/Context	Scope	Carbon Footprint (kg CO ₂ -eq/T-shirt)
Present study	Pakistan (modelled)	Cradle-to-grave	5.19
Flores & Salhofer	Peru	Cradle-to-grave	4.25
Zhang et al.	China	Cradle-to-grave	6.05
Baydar et al.	Turkey	Cradle-to-grave	8.44

The present result (5.19 kg CO₂-eq) falls within the range of published cradle-to-grave cotton T-shirt assessments. Differences between studies reflect variations in system boundaries, electricity mix,

agricultural assumptions, wet-processing intensity, and use-phase modelling. Review studies on cotton textile products emphasise that environmental results vary substantially due to geographical context and methodological choices[4], [21]

The results should be interpreted in light of several limitations. First, the inventory was not based entirely on primary local data; several stages were modelled using literature-derived values and generic background datasets. Second, the use phase and end-of-life were represented in simplified form, introducing additional uncertainty, particularly because use-phase results are sensitive to wash frequency, machine type, drying behaviour, and local electricity grid emissions. Third, supporting processes such as electricity, chemicals, transport, packaging, and waste treatment were linked through non-site-specific background datasets. These limitations are consistent with the broader cotton LCA literature [6], [7], [24]. Accordingly, the present study should be understood as a transparent Pakistan-context case study designed to estimate the carbon footprint of one cotton T-shirt under a defined set of assumptions, rather than as a universally representative or site-verified industrial result.

4. Conclusion:

This study assessed the cradle-to-grave carbon footprint of one 100% cotton T-shirt in a Pakistan-context system using life cycle assessment. The functional unit was defined as one 200 g cotton T-shirt providing 50 wash cycles of clothing service. The analysis was conducted in openLCA 2.6.1 using the BAFU 2025 database and the IPCC 2021 GWP100 method, with the system boundary covering cotton farming, ginning, spinning, knitting, dyeing and finishing, cut-make-trim, distribution, use phase, and end-of-life disposal. Based on the modelled inventory and defined assumptions, the total carbon footprint was estimated at 5.19 kg CO₂-eq per functional unit. The results fall between the range of 4.25 and 8.44 kg CO₂-eq per T-shirt.

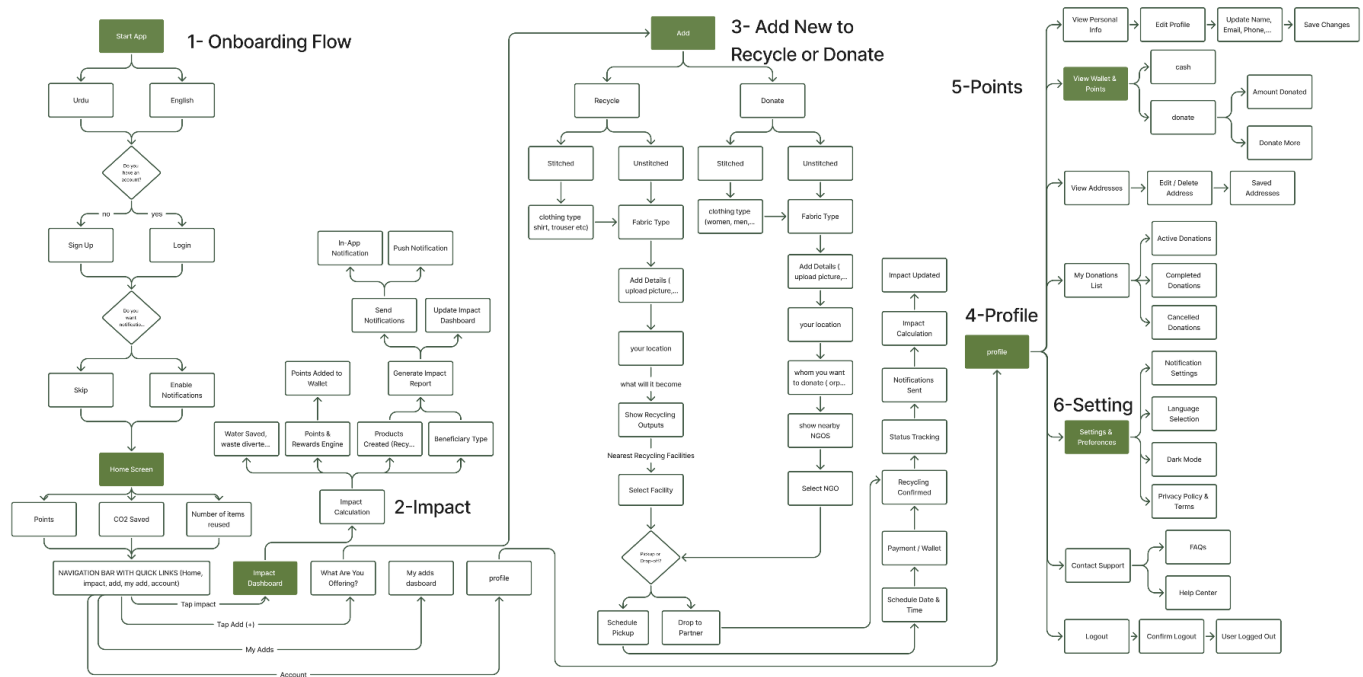
The contribution analysis showed that the use phase was the dominant life-cycle stage, accounting for 79.43% of the total carbon footprint. This result was mainly driven by electricity demand associated with washing and ironing over the assumed 50 wash cycles under Pakistan household conditions. Among the production-related stages, spinning contributed 9.30%, while dyeing and finishing contributed 5.70%. These stages were identified as the most important manufacturing hotspots due to their reliance on electricity, heat, water, and process-related inputs. Other stages, including cotton farming, knitting, cut-make-trim, distribution, ginning, and end-of-life, made comparatively smaller contributions under the assumptions adopted in this model.

So, the carbon footprint is shaped by the consumer and the manufacturing energy intensity. The consumer garment-care practices had an influence on the overall result, while textile manufacturing stages remained secondary. Therefore, assessing the full life cycle of apparel products is more important than focusing on raw material production/factory operations. In a country like Pakistan, where the textile sector has major economic and industrial importance, the results suggest that cleaner electricity, improved energy efficiency in spinning and wet-processing operations, optimised steam and boiler systems, and better process management could reduce production-stage emissions. At the consumer level, lower-temperature washing, reduced ironing, efficient washing machines, line drying, and longer garment use could help reduce the carbon footprint per garment.

In addition to identifying carbon hotspots, this study also supports the need for practical circular-economy solutions for post-consumer textile management. Based on the study findings, a digital service-design concept is proposed to encourage clothing donation, reuse, and recycling. The proposed platform would allow users to donate reusable garments to NGOs or direct unsuitable garments to textile recycling industries. To encourage participation, users may receive reward points based on the estimated avoided CO₂-eq associated with donation or recycling pathways. Selected mock-up screens of the proposed digital solution are presented in Figure . Such a solution could improve access to textile recovery channels, increase user awareness of the environmental value of garment reuse and recycling, and support behavioural change

through feedback and incentive mechanisms. However, these potential avoided emissions should be treated as indicative estimates unless further scenario modelling is conducted.

Figure 7: User flow of the proposed digital solution for clothing donation and recycling.



Overall, this study provides a Pakistan-context modelled case study for the carbon footprint of a cotton T-shirt and contributes to the limited product-level LCA literature available for Pakistan’s textile sector. It also demonstrates how LCA results can inform practical sustainability interventions by identifying priority areas for reduction and linking them to service-design opportunities. Nevertheless, the results should be interpreted as modelled estimates rather than verified site-specific measurements, because the inventory relied on literature-derived parameters, scenario assumptions, and generic background datasets rather than primary data from individual farms, textile mills, households, or waste-management facilities.

Future research could strengthen this analysis by incorporating primary facility-level data from Pakistani textile mills, collecting farm-level data for cotton cultivation, and refining consumer-use assumptions through household surveys. Further work could also develop Pakistan-specific end-of-life scenarios, including landfill, open burning, reuse, donation, and textile recycling pathways. In addition, scenario-based modelling could be used to estimate the avoided emissions associated with the proposed digital donation and recycling solution. Expanding the assessment beyond climate change to include water use, eutrophication, acidification, ecotoxicity, human toxicity, and resource depletion would also provide a more comprehensive understanding of the environmental performance of cotton apparel in Pakistan.

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