

Article

Value Extraction from End-of-Life Textile Products in Pakistan

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Abstract: Overconsumption and unplanned disposal of garments result in millions of tons of textile products going to landfills. Understanding the environmental benefits and impact of various recycling options is crucial for integrating recycling into the apparel waste stream. This study aims to assess the environmental impacts of products made from post-consumer textile waste fibers, highlighting the importance of closed-loop textile supply chains in developing countries. Using Open LCA software, the cradle-to-gate approach for life cycle assessment is used to calculate the environmental impacts of post-consumer textile waste, virgin cotton, virgin polyester fibers, and their blends in two different scenarios. The life cycle inventory data for functional units (1000 kg apparel) has been collected from the industrial units and the Ecoinvent v3.0 database. The results of 16 environmental impact categories are computed, showing that textile products made from virgin cotton fiber have 60% more global warming potential than those made from post-consumer textile waste fibers. Hence, the environmental impact of textile products can be controlled by recycling them. Consumption of post-consumer textile waste fiber is the key to reducing the new material needs in the textile supply chain. The closed-loop apparel supply chain can help developing countries generate maximum financial value with minimal environmental damage. In developing countries, value extraction from post-consumer textile waste recycling is essential to meet international consumer demands for cleaner production.



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Keywords: life cycle assessment; environmental impacts; end-of-life textile products; post-consumer textile waste; textile supply chain

1. Introduction

The global population is estimated to be 9.6 billion by 2050, while global resources are becoming increasingly scarce, and the climate is changing dramatically [1]. In this situation, the reuse of textile fibers is highly important for a sustainable future. The clothing industry is valued at USD 1.3 trillion and employs more than 300 million people worldwide [2]. It is the second most polluting industry in the world [3]. Sustainability in the textile, apparel, and fashion industry has attracted international attention [4]. Textile products at the end of their lifetime (post-consumer textile) are mostly landfilled or used as less-valued products, such as dusting cloths. The use of PCTW (post-consumer textile waste) can help bring around 87% of textile waste back into the textile chain, which normally ends up every year in landfills, from which 90% of the waste can be upcycled or reused [5].

The textile industry is highly resource-intensive, and reusing already-used materials can help to reduce demand for new raw materials, which could eventually lead to reduce

the environmental impacts of this industry [6]. Textile production is based on multiple manufacturing and wet-processing stages. These production stages consume a substantial amount of water, dyes, chemicals, and energy [4], and each step in the textile life cycle has potential environmental problems [7]. Due to fast fashion, the growth of the textile industry has led to a consequent increase of textile waste [8]. Statistics collected by the Council for Textile Recycling indicate that less than 25% of total post-consumer textile waste is recycled annually [9]. The growth of the textile and apparel industries is possible with social, environmental, and economic sustainability [10,11].

The extensive natural resource consumption by the global textile and apparel industry is adversely impacting the environment. Furthermore, textile industries significantly impact water footprints, by using 215 trillion liters of water per year [12], in terms of cultivation and textile processing. Cotton is the most dominant natural fiber in the textile and apparel industry. The production/cultivation of 1 kg of cotton (equivalent to a pair of jeans) can take more than 20,000 L of water. Being a key consumer of fertilizer, cotton has a huge role in global climate change [13]. An extremely large volume of water is needed for cotton cultivation, which is 2.6% of the global water [14].

The million tons of textiles in landfills every year impact environmental pollution. These textiles are reported as being 13 million tons of solid waste, from which only 15% was recovered in 2010 [15]. Although textile waste contains organic substances, landfill textile waste requires space and takes a relatively long time to decompose (6 months–20 years) [16]. Synthetic fibers, especially polyester, are biodegradable-resistant fibers. There was no evidence of microbial degradation found after 4 weeks of landfill [17].

There are some basic challenges in using recycled materials, such as the increased cost of new technology, the uniform ratio of the fiber mix, production difficulties, and an uncertain supply chain [18,19]. These challenges make it difficult to accurately assess the environmental footprint of a textile chain. Many strategies and policies have been formulated to promote workable textile waste management for impactful environmental conservation and economic efficiency [9,19,20], which helps in measuring and controlling the environmental impacts of the textile production process.

The textile sector of Pakistan plays an effective part in the economic progress of the country. According to All Pakistan Textile Mills Association (APTMA), this sector contributes 8.5% to the GDP (Gross Domestic Product) and more than 63% in total exports of Pakistan [21]. Growing awareness of the environmental footprint of textile industries is increasing pressure on manufacturers and brands to impose sustainable practices in the designing, production, and commercialization stages of the product lifecycle [22–24]. The aim of this study is to measure the difference between the environmental impacts of textiles made from virgin materials and those of PCTW fibers, so that the benefits of economic growth and environmental impact reduction can be achieved. In this respect, very few studies are found to be relevant working with simple textiles made of PCTW.

Hence, to measure the environmental burden of the textile production process, the life cycle assessment (LCA) method is used. LCA is a technique to assess environmental impacts related to all the stages of a product's life. This method has a fixed structure and is practiced according to international standards (ISO-14040, 2006) [25–28]. LCA is the most commonly used method to ascertain the environmental impact of textiles and to control wastage in apparel production [29]. There are many LCA studies focused on calculating the environmental impact of textile products such as yarns spun from recycled cotton fibers and virgin cotton fibers [30], T-shirts [31,32], cotton woven shirts [14], cotton knit shirts, polyester knit shirts, woolen undershirt [33], wool sweaters [34], and face masks for daily usage [35]. LCA analysis is also considered an important tool to manage waste in the fashion and textile industries, contributing to the circular economy [36].

The study of LCA analysis of PCTW is tricky because the processes of textile production are complex, and the scope of available literature in this domain is not defined. So, data for textile production processes were taken from literature, LCA software was used, and professionals working in the field were consulted. The end-of-life is really an important aspect while measuring environmental impact because the quality of PCTW is directly related to its handling at its life span. An LCA study of cross culture utilization of textiles provides information about important parameters to achieve a better environmental impact from consumer handling of their garments, and washing and ironing cycles in different demographical locations [37]. In this prospect, an LCA study of the application of water repellent chemicals over the fabric surface is also considered helpful in reducing the environmental impact of garments because it helps to reduce the need for washing and gives long life to garments [38,39]. The nature of the fiber used to make textile products really matters in their environmental impact. The LCA studies of different fibers such as polyester, nylon, acrylic, cotton, and spandex have shown various environmental impacts related to fiber nature, and within these studies, textile products made from cotton fiber have shown greater environmental impacts [40]. The LCA studies on PCTW have much more to deliver, one important case is bio-recycling methods, but its calculation is a challenge; moreover, controlling the quality of the product is really difficult [41]. The stages of life cycle assessment are illustrated in Figure 1, which denotes clear steps of measuring environmental impacts by following LCA methodology.

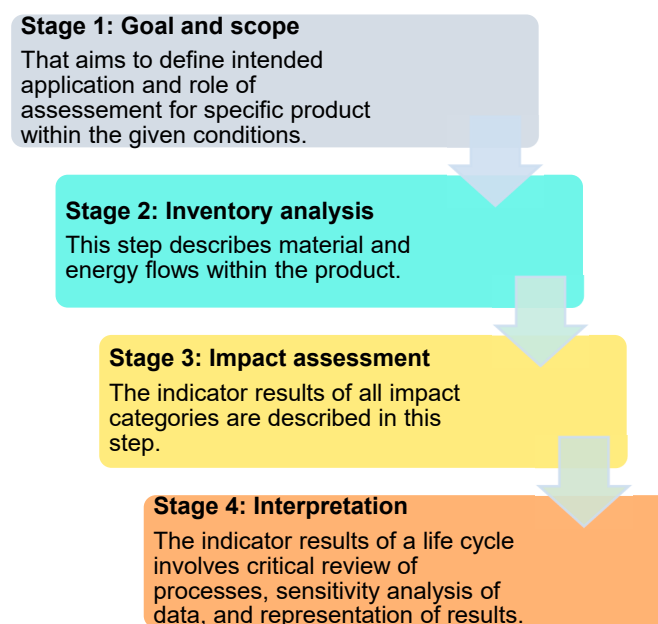


Figure 1. Stages of the life cycle assessment [42].

While several studies have assessed the environmental impacts of virgin or recycled textile fibers separately, there remains a significant gap in comprehensive comparative analyses that evaluate virgin fibers, recycled fibers, and their blended combinations within a single framework. This study addresses that gap by conducting a detailed scenario-based life cycle assessment (LCA) using the ReCiPe method in OpenLCA, comparing garments made from 100% virgin cotton, 100% polyester, 100% post-consumer textile waste (PCTW), and various fiber blends. Such a comparative approach has not been previously reported in the literature and provides critical insights into the trade-offs between material choices. This innovation not only refines the methodological scope of textile LCAs but also provides stakeholders, particularly manufacturers, policymakers, and sustainability

strategists, with practical, evidence-based guidance for reducing environmental burdens through material selection.

The environmental performance of virgin and recycled yarns, which can be woven into varieties of textile products, has not been well studied so far. In this study, the LCA method is applied to apparels made from blends of post-consumer waste fibers, cotton, and polyester. The LCA results are compared to the same textile products made from virgin cotton. This method helped to understand changes required in the production processes to reduce environmental impact.

2. Results and Discussion

2.1. LCIA Results

Most of the textile products have similar supply chains comprising fiber production, yarn production, fabric production, wet processing, and garment manufacturing. The primary resources used in the production stages are electricity, heat, water, chemicals, auxiliaries, and dyes. These main factors or parameters have different environmental impacts based on product type because resource consumption (e.g., raw materials, energy, and water) is directly related to the burden a particular product generates on its environment.

2.1.1. Raw Material Extraction

Environmental impact categories associated with cotton cultivation under conventional and organic agriculture differ slightly. The global warming potential (GWP) impact for conventional cotton is slightly higher (0.62–5.5 kg CO₂ eq) than that reported for organic cotton (0.98–2.40 kg CO₂ eq), most likely due to the differences in the use of human labor, tractors, and other farm machinery in every cotton crop. However, they can be considered similar taking into account the high variability within the same kind of cultivation [43]. LCI data for conventional cotton were obtained from various studies, as presented in Table 1. Scarce LCA data have been obtained from the literature regarding ginning operations, mainly due to the common inclusion of the ginning effects within the general framework of cotton cultivation. Thus, environmental impacts caused by the ginning process appear minimal when they are compared to those obtained for cotton cultivation. Moreover, the operations of ginning and fiber transportation to apparel production units are considered in the environmental impact calculations for the cultivation of virgin cotton. The most prominent environmental impact caused by cotton cultivation is its potential for climate change or global warming (31240 kg CO₂ eq), which is higher than that of PCTW fiber, polyester, and the two designed scenarios. During fiber recycling, the collection, cutting, and shredding are integral steps in the extraction of raw materials. The global warming potential of PCTW fiber at the raw fiber stage is 3817 kg CO₂ eq, whereas for cotton, the value at the raw fiber stage is 14,459 kg CO₂ eq. The climate change potential of polyester fiber at this stage is 806 kg CO₂ eq. In this stage, transportation of raw materials is also included, but the major contributor to environmental impact is resource consumption.

2.1.2. Spinning and Weaving

In the spinning process, yarns are made by spinning fibers and, if required, mixing different fibers together. This stage has the most significant energy consumption compared with other phases [30]. The number of resources required for the production of yarn, according to the given functional unit, was selected to produce 10 Ne yarn count through open-end spinning. In order to consider the fact that the thinner the yarn, the higher the contribution to environmental pollution per kilogram [30]. The coarser yarn count is selected to facilitate a fair comparison of the given scenarios for 1000 kg of apparel production. The environmental impacts associated with spinning processes are almost

similar in all five situations. The main reason for this is the yarn count. The PCTW fibers happened to be weaker than virgin fibers. The global warming potential of spinning is (399 kg CO₂ eq), and the overall environmental impact of the spinning stage is the same for all the situations.

Table 1. The LCIA results of the virgin cotton, virgin polyester, PCTW fiber, and two scenarios for 1000 kg apparel production.

Impact Category	Unit	Virgin Cotton	PCTW	Virgin Polyester	Scenario 1	Scenario 2
Fine particulate matter formation	kg PM2.5 eq	2196	31	35	43	30
Fossil resource scarcity	kg oil eq	2572	2948	2869	2802	2833
Freshwater ecotoxicity	kg 1,4-DCB	519	607	580	577	583
Freshwater eutrophication	kg P eq	8	22	21	21	21
Global warming potential	kg CO ₂ eq	31,240	19,220	18,729	21,881	18,467
Human carcinogenic toxicity	kg 1,4-DCB	1058	1169	1139	1120	1123
Human non-carcinogenic toxicity	kg 1,4-DCB	15,596	16,892	16,439	16,269	16,227
Ionizing radiation	kBq Co-60 eq	8577	9295	9043	8951	8928
Land use	m ² a crop eq	39	44	43	42	42
Marine ecotoxicity	kg 1,4-DCB	736	839	815	799	806
Marine eutrophication	kg N eq	2	2	1	1	1
Mineral resource scarcity	kg Cu eq	30	14	14	18	14
Ozone formation, Human health	kg NOx eq	53	30	29	35	29
Terrestrial ecosystems	kg NOx eq	53	30	30	36	29
Terrestrial acidification	kg SO ₂ eq	7217	94	108	145	90
Terrestrial ecotoxicity	kg 1,4-DCB	75,803	13,292	82,444	14,630	12,772
Water consumption	m ³	313,019	353,202	343,698	336,905	339,259

The construction parameters of fabric weaving are kept constant for all five situations, such as the ends-to-picks ratio and weave design. As a result, the environmental impact of weaving is also somewhat similar. The 1000 kg woven fabric of selected construction has a (6902 kg CO₂ eq) units global warming potential.

2.1.3. Wet Processing

Textile wet processing involves many steps according to requirement, such as pre-treatment, dyeing, finishing, and drying. The standard input parameters for wet processes were used to model this study. The production of conventional cotton fabric went through pretreatment, bleaching, cotton dying, wet processes, finishing, and drying process, which creates a climate change potential of 1444 kg CO₂ eq. The fabric made of synthetic polyester fiber of the same functional unit has different wet processing steps and material used as compared to natural cotton, but overall, the climate change potential of 1000 kg of polyester fabric is 2581 kg CO₂ eq. The fabric developed from PCTW fibers carries the color of raw fabrics. In this study, the inherited color of PCTW fibers was not bleached for developing a fabric, avoiding chemically intensive wet processes. However, fabric finishing and drying processes were considered for a proper finish. Furthermore, scenario 1 and scenario 2 blends of PCTW fibers also have reduced wet processing steps, and the PCTW fabric has the least environmental impact potential at this step, and overall climate change potential is 66 kg CO₂ eq, which is considered high.

The LCIA results of five situations in all selected categories are presented in Table 1. The potential impacts generated from the transportation phase and the mixing phase were noted to be insignificant. The spinning stage is the dominant contributor towards most impact categories, except for water depletion. Contributions to the categories are primarily attributable to the fiber acquisition stage, which is the cotton cultivation for the virgin cotton, and the fiber recycling for the recycled PCTW.

The life cycle inventory results were analyzed and interpreted in this section based on the impact category climate change or global warming potential (kg CO₂ equivalent, CO₂

-e). Supply of raw fiber to produce finished apparel depends on fiber type and the mass loss during production processes.

Global warming potential is the most important impact category to study the environmental impact of certain products and the supply chain. The difference and comparison of the global warming potential of the five given situations are presented in Figure 2. The climate change potential of virgin cotton fiber is higher than all other fibers because the conventional cultivation methods use a large number of pesticides that cause the emission of gases from fields. The dying process is the next harmful step in cotton apparel manufacturing. It requires several chemicals in the wet processing and dying process, which are harmful to the environment. PCTW fibers are next to cotton in generating global warming because the fiber collection process requires huge amounts of electricity in sorting, cutting, and shredding processes. However, the consumption of waste garments reduces the consumption of virgin cotton very much. This reduces the environmental impact to a significant extent as well as lessens the burden of used textiles that are otherwise dumped on land and cause environmental pollution by emission of dangerous gases. The climate change potential of virgin polyester fiber is slightly less than that of PCTW fiber and significantly less than cotton fiber, but the use of virgin polyester fiber carries a lot of other issues, such as freshwater toxicity and marine ecotoxicity. In the other two specific scenarios, the climate change impact of polyester and PCTW fiber is far less than that of cotton fiber. For scenario 1, the functional unit carries the environmental burden of virgin cotton fiber by 25% and that of PCTW fibers by 75%. However, scenario 2 generates less global warming potential than all other fibers.

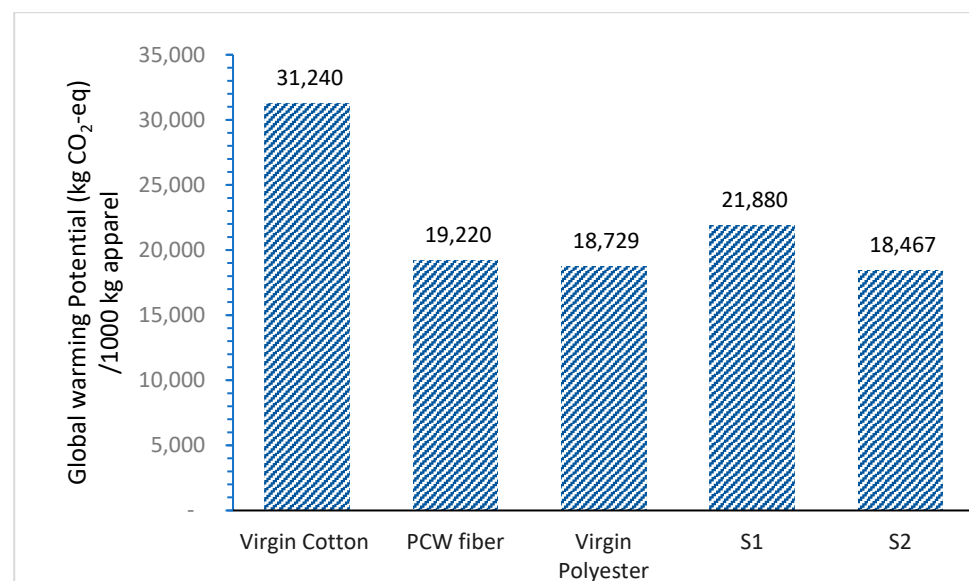


Figure 2. Global warming potential per 1000 kg apparel.

3. Materials and Methods

3.1. Apparel Production Process

The textile production chain is a complex network of different production processes that starts from the extraction of fibers, which is followed by yarn spinning, weaving, dying, finishing, stitching, etc. To reduce environmental impact, the apparel production by using PCTW fibers involves different fiber extraction processes, which are divided into different phases. Steps for apparel production for virgin cotton, polyester fiber, and PCTW fibers are given in Figure 3.

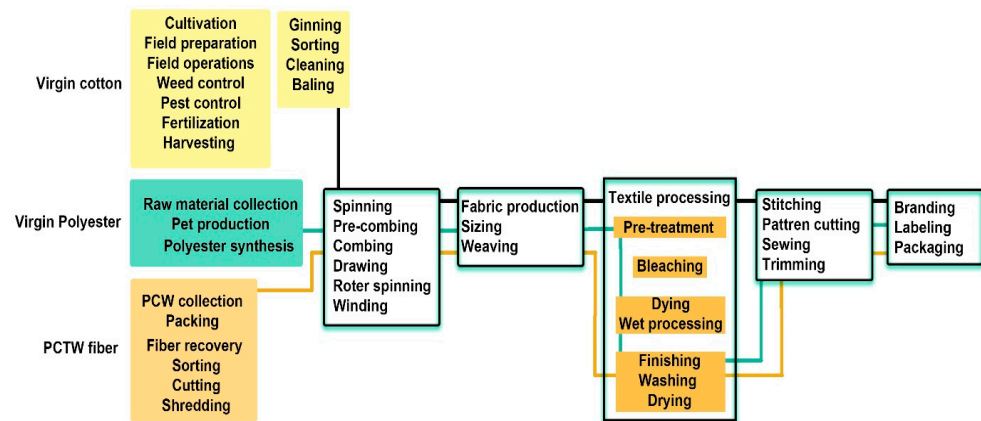


Figure 3. Steps involved in the production of textile clothes using conventional cotton fiber, polyester fiber, and PCTW fiber.

3.2. Life Cycle Assessment Methodology

The LCA methodology systematically helped to find the potential environmental impact of textiles made from virgin fibers and PCTW fibers using a set of processes that evaluate relevant inputs and outputs produced during product life. According to the standard, 14040:2006 [25], the LCA process consists of four steps as provided in Figure 1. Step (1) defines the purpose of LCA, its functional units, and system boundaries. In step (2), process flow charts are developed, which are followed by data collection of system processes such as energy, water, and material inputs and emissions to the environment. Step (3) calculates the environmental impact of the product under consideration by using the data collected in step (2). Finally, in step (4), LCA results are interpreted, and significant environmental impacts are identified (International Organization for Standardization). These steps are categorically applied to the product under consideration as defined in Figure 3.

3.2.1. Goal and Scope of Study

The goal of the study is to calculate the environmental impacts of the garments made from virgin fibers (cotton, polyester) and the garments made from PCTW fibers. The aim of this LCA study is to control the environmental impact of developed garments and identify investment opportunities to produce garments from PCTW in a developing country. The findings of this study will give information about how much the environmental impact of the apparel industry can be controlled by recycling end-of-life garments. The product system of this study is the apparel production system.

3.2.2. Functional Units

The functions of the apparel production system are carried out in selective steps of collection of fibers, production of yarn, production of fabrics, production of garments, retailing, and consumer use. The functional unit (FU) of the product delivers calculated data of all the related inputs and outputs in the LCA analysis [30]. Defining a functional unit is also an attempt to provide a quantitative definition of the system under consideration and to compare alternative systems [44]. The basic purpose of a functional unit is to provide a reference system to which the inputs and outputs are related. In this study, the (FU) is defined as “production of 1000 kg of apparel”. This gives the count of all the process flows in two systems and facilitates comparison between processes that create apparel from virgin raw materials, and processes that create apparel from a mixture of recycled materials.

3.2.3. The System Boundary

This LCA study is based on a “cradle-to-gate” approach for product life to calculate the environmental impacts. Therefore, system boundaries are defined by considering all the production processes for apparel production. LCA is done by defining product systems that describe the key elements of physical systems and unit processes to be included in the system, as given in Figure 4.

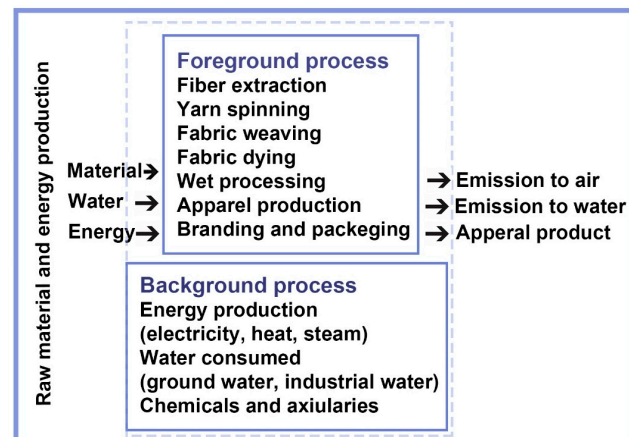


Figure 4. Key elements within foreground and background processes.

The system boundaries help to note the inputs and outputs within the system. The system boundaries of this LCA study, while considering the main production processes of apparel, are given in Table 2.

Table 2. System boundaries of this study (included and excluded).

Include in system boundaries	- Production and transference of raw fibers - Making of yarn - Construction of fabric - Wet procedures of fabrics (e.g., scouring, bleaching, dyeing, etc.) - Manufacture of garments - Transportation of resources
Excluded from system boundaries	- Packing of garments - Transport of chemicals and pigments - Garment accessories (e.g., buttons, zippers, etc.) - Solid waste transportation and recycling to other processes - Product care label and other labels - Manufacturing and maintenance of production machines (e.g., weaving looms, knitting machines, washing machines, etc.) - Maintenance of building and other office equipment - Use of clothing (e.g., washing, drying, ironing) - Clothing end of life (e.g., disposal option; reuse, recycling, landfill)

In this study, two systems of apparel production are used. The first system is used to produce apparel from virgin fibers, while the second system is used to produce apparel by using recycled post-consumer waste fibers. Two scenarios were taken in this study, as shown in Figure 5.

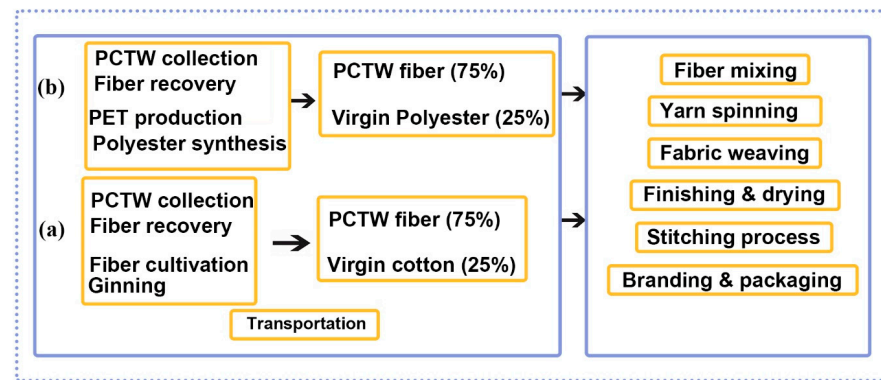


Figure 5. (a) Scenario 2: Regular polyester and post-consumer waste fibers and (b) Scenario 1: (conventional cotton and post-consumer waste fibers).

3.2.4. Allocations

An important choice in conducting LCA is allocating the environmental burden of multi-functional processes within the functions. For products made from recycled feedstock, it is important to solve such allocation problems. The key query is whether the incoming recycled (pre- or post-consumer) textile material should be considered responsible for any environmental burden of its earlier life cycle (mainly, the initial raw material extraction) or whether it should be taken free of environmental burden from its prior processes. The first point to consider is that the recycled material is a co-product of the earlier product system, and that, for example, the monetary profit of the prior product system is. Therefore, the demand for the recycled material is affected by the consequent recycling of the material. The second point is that the recycled material is a waste that has negligible economic influence on the previous production system and should, thus, be free of environmental impact. Here, “cut-off allocation” is applied, which allows for the deduction of the raw material burden of the recycled material, which reduces the chance of ambiguity in deciding its share. The second option is adopted for this study as it is the most common allocation method for the recycled material [45], in which no production or environment burden of recycled material is calculated. Only the resource consumption and emissions during post-consumer fiber collection and recovery are calculated and used in LCA analysis. This is a common practice in this type of study, so the raw material processes are skipped in case of post-consumer waste fibers. It is considered that no by-product is produced, and no mass allocation is needed. For example, post-consumer waste fibers already exist in the loop.

3.2.5. Life Cycle Inventory, Analysis, Data Collection, and Assumptions

The life inventory data of the textile chain is required to build the life cycle model. There are some studies available that provide textile general processing data regarding energy, water, and resources. Life cycle inventory data are divided into two categories: foreground data and background data. Foreground data (e.g., spinning, wet processing, etc.) have been collected from the secondary data source in field observations and other published references, while the background data (e.g., energy production, chemical, and auxiliaries’ production) was collected from the Ecoinvent v3.0 database. Chemicals and auxiliaries’ production have been modelled using the Ecoinvent v3.0 datasets. Some assumptions are made when specific dyes and chemicals are not in the Ecoinvent v3.0 datasets. Alternative or similar types of chemicals (e.g., organic or inorganic) are considered in this case. Estimated output emissions from the processes were calculated in the estimation of discharge, as given in the literature. Inventory data collected and compiled from the literature are given in Table 3.

Table 3. Inventory data for the entire process for 1000 kg of apparel production.

Processes	Sub Processes	Categories	Units	Values
Cotton Fiber	Cultivation and harvesting	Electricity	kWh	3.89
		Fertilizers	kg	0.184–0.204
		Pesticides	kg	0.0043–0.00506
		Water	kg	4823–5947
		H ₂ SO ₄	kg	0.00092–0.00166
		Tillage	Ha	0.00046–0.00050
		CO ₂	kg	3.05–3.42
		NO _x	kg	0.00282–0.00315
		NH ₃	kg	0.0179–0.0200
		NO ₃	kg	0.202–0.223
		PO ₄	kg	0.018–0.030
			[46]	
Yarn spinning		Electricity	MJ	4.2
				[47]
Fabric weaving	Warping and sizing	Electricity	kWh	10.63
	Weaving		kWh	9.39
				[40]
Pretreatment		Polyvinyl alcohol	kg	0.025
		Water	kg	0.075
		Washing agents	kg	0.005
		Water	kg	10
		Electricity	kWh	0.16
				[48]
Bleaching		Electricity	MJ	3.04
		Steam	MJ	26.74
		Water	kg	177
		Hydrogen peroxide	kg	0.02955
		NaOH	kg	0.02955
		Salt	kg	0.8274
		Softener	kg	0.02364
		Silicon	kg	0.01182
		Acetic acid	kg	0.04728
		Chemicals	kg	0.06855
		Wastewater	kg	175.8
		COD	kg	0.2303
				[43]
Dyeing		Electricity	MJ	3.86
		Coal	MJ	69.12
		Steam	MJ	3.16
		Water	kg	186
		Dyes	kg	0.050
		Auxiliaries	kg	1.346
		Water vapor	kg	77.78
		NO _x	kg	0.095
		CO ₂	kg	7.843
		Fly ash	kg	0.044
		SO ₂	kg	0.0078
		Wastewater	kg	84.3
		Phosphorus	kg	0.0000588
		Hydrocarbons	kg	0.0000588
		Solids (dissolved)	kg	0.0045752
		Nitrogen	kg	0.0058824
		COD	kg	0.0065359
				[43]

Table 3. Cont.

Processes	Sub Processes	Categories	Units	Values
Wet processing		Electricity	kWh	3.79
		Liquefied petroleum gas	MJ	69.9
		Light fuel oil	MJ	0.38
Finishing				[40]
		Electricity	kWh	0.6
		Natural gas	MJ	28.8
		Water	L	27.0
		Acid detergent	kg	0.005
Drying				[40]
		Electricity	kWh	0.04
		Natural gas	kWh	0.27
Garment stitching				[48]
		Electricity	kWh	23.42
Packaging PCTW fiber	Cutting Shredding Sorting			[49]
		Electricity	kWh	0.8
		Electricity	kWh	10.25
		Electricity	kWh	0.9
		Electricity	kWh	0.000125
Polyester dyeing				[50]
		Electricity	MJ	12.06
		Suspended particle	kg	0.0603
		Hydrocarbon	kg	0.0402
		Water	L	73.7
		CO ₂	kg	5.963
		NO _x	mg/m ³	0.0067
		SO ₂	mg/m ³	0.0201
		CO	mg/m ³	0.0268
				[51]

The life cycle inventory (LCI) data used in this study were obtained from previously published peer-reviewed literature and well-established LCA databases. Sources were selected based on their methodological rigor, data transparency, and relevance to textile production processes. All data points are appropriately cited in the manuscript. Where multiple sources were available for a given input or process, preference was given to the most recent and geographically relevant data (e.g., studies conducted in South Asia or using production systems similar to those in Pakistan). For each dataset, the reliability was assessed based on the clarity of system boundaries, data collection methods, and reported assumptions. Cross-verification with other literature sources was performed where feasible to ensure consistency. No primary data collection was conducted; however, reliance on verified secondary sources ensures that the findings are robust and representative of current industry practices.

The common data sources for electricity, heat, transport, waste management, and water supply were used in the modelling for the production stage. The main processes are used to model raw material production, transportation, and electricity in the production stages. All the production processes use electricity. The electricity dataset for Pakistan has been deduced by using the main apparel production organization. Inventory data regarding the production of chemicals, equipment, materials, electricity, wastewater treatment, and the production of transport modules were taken from the Ecoinvent v3.0 database [48].

3.2.6. Impact Assessment Method and LCA Software

The life cycle inventory (LCI) analysis phase involves collecting and calculating data pertaining to its life span [52]. Then, the life cycle impact assessment converts LCI results to indicator results for different impact categories. The Life cycle impact assessment (LCIA) helps the interpretation of LCA studies by translating these emissions and resource extractions into a limited number of environmental impact scores called as characterization factors (CF) which indicate the environmental impact per unit of consumption (e.g., per kg of resource used or emission released) [53]. In this study, the Open LCA software developed by Green Delta was used to assess the environmental impacts [54,55]. An assessment method that allows for finding environmental burden by doing systematic calculations, and the ReCiPe method is designed to transform the long list of life cycle inventory results into a limited number of indicator scores, which have an impact on the mid-point and damage on the end-point category level. The scores of these indicators express the relative severity on an environmental impact category [30,56–59]. The core objective of the ReCiPe method is to develop a comprehensive approach that combines the Eco-Indicator 99 and CML life cycle impact assessment methods. In the ReCiPe, the mid-point indicates characterization factors at the midpoint level, commonly at a stage after which the environmental mechanism is similar for all the environmental flows assigned to that specific impact category [60]. The hierarchist (H) consensus model that relates to the time frame (100 years) and credibility of impact systems [53].

A “cut-off” allocation method was employed in this study. This means that we did not allocate the impacts to individual stages in cases where data were unavailable or where assumptions had to be made about shared resources or co-products. This method was chosen based on its common application in LCA when product systems involve multiple stages with overlapping processes, such as textile production and recycling. We assume that impacts from non-relevant processes were excluded to avoid overcomplicating the study and to focus on the key life cycle stages that most significantly contribute to the overall environmental impact.

The ReCiPe midpoint (H) method in the OpenLCA software was used for life cycle impact assessment (LCIA) of two scenarios. In total, 16 impact categories LCI results were analyzed, including climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), ozone depletion (OD), water depletion (WD), mineral resource depletion (MRD), fossil depletion (FD), freshwater ecotoxicity (FET), marine ecotoxicity (MET), terrestrial ecotoxicity (TET), human toxicity (HT), ionizing radiation (IR), particulate matter formation (PMF), and photochemical oxidant formation (POF). The ReCiPe method follows a sequence of operations for five life cycle impact calculations, which are characterization, damage assessment, standardization, weightage, and sum-up score. Characterization factor for all substances that contribute to an impact category is amplified according to the relative contribution of the corresponding substance. For example, for the climate change category, the carbon footprint (CF) of carbon dioxide (CO₂) is 1, whereas the CF of methane (CH₄) in the respective impact category is 25 kg. This can be narrated as 1 kg, CH₄ is contributing to the same amount of climate change as 25 kg CO₂. At last, all the impacts are calculated in a sum-up score, adding the impact contributions of relevant substances. Moreover, it is crucial to know that each impact contribution at the mid-point level can impact other assessment categories at the same time [61]. The formula that is used for mid-point characterization is provided in Equation (1) as follows.

$$I_m = \sum_i Q_{mi} m_i \quad (1)$$

In this equation, i is the amount of intervention (e.g., the mass of CH₄ released to the air), Q_{mi} is the CF that connects intervention i with its midpoint impact category m , and I_m is the indicator result of midpoint impact category m [60]. The Global Warming Potential (GWP) is the most commonly used CF for the climate change category. The GWP shows the amount of additional radiative forcing increased over time by emission of 1 kg of greenhouse gases (GHG) relative to the additional radiative forcing increased over an equal time span as caused by the release of 1 kg of CO₂, Which yields a time-horizon-specific GWP with the unit kg CO₂ eq/kg GHG [53].

4. Conclusions

The solutions of all recent challenges of today's textile supply chain such as increased environmental impacts, massive production of textile products and not suitable end-of-life planning and treatments can be addressed by using renewable, safe and biodegradable textile materials. The demands of the future textile industry are different; intensive use of resources will not be possible. Longevity and quality are the key elements for future garments. The proper care at the usage and optimal disposal of the used clothing could be fuel points of the textile supply chain by providing quality inputs for another life of its raw material. Textile recycling has high potential to decrease the environmental impact of textile industry by reuse of resources and potential decrease in natural resources consumption. In this study, the environmental impact of 1000 kg of apparel made of PCTW, cotton, and polyester fibers was calculated and analyzed to find the quantified value of the environmental impact of discarded fibers. The results indicated that the use of PCTW fiber not only reduces its environmental burden due to land filling but also reduces the need for virgin fibers and the use of fresh resources. Bringing the discarded textiles in a closed-loop production can help to support developing countries like Pakistan in textiles exports. The findings suggest that policymakers should support textile recycling initiatives, while industries can adopt recycled fibers to improve sustainability and gain a competitive edge in global markets. Investment in recycling infrastructure and consumer education will be crucial for resource conservation and waste reduction. Future studies could build on this work by including sensitivity and uncertainty analyses to further refine the results and inform policy decisions. Moreover, the research can be revised by integrating environmental impacts at end-of-life and consumer behavior within system boundaries.

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