Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

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How to cite: Hossain KR, Rahman MF. Reducing the Environmental Impact of Denim: A Comparative Study of Green and Conventional Manufacturing Practices. Textile & Leather Review. 2025; 8:38-71. https://doi.org/10.31881/TLR.2024.163

How to link: https://doi.org/10.31881/TLR.2024.163

Published: 27 January 2025

Reducing the Environmental Impact of Denim: A Comparative Study of Green and Conventional Manufacturing Practices

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Article

https://doi.org/10.31881/TLR.2024.163

Received 28 October 2024; Accepted 29 December 2024; Published 27 January 2025

ABSTRACT

Denim manufacturing, from cotton farming to garment production, carries significant environmental impacts. Despite introducing sustainability within the denim industry, the environmental benefits of related practices are not thoroughly assessed and contrasted with conventional manufacturing practices. This study aims to evaluate and compare the environmental impacts of sustainable and traditional denim manufacturing processes in Bangladesh through a Life Cycle Assessment. Adhering to ISO 14040/14044:2006 standards and utilising the ReCiPe 2016 Midpoint (H) assessment, this study investigated key environmental indicators, including terrestrial acidification, eutrophication, land occupation, water consumption, abiotic depletion, and greenhouse gas emissions. Notable findings reveal that yarn and fabric production contribute to 56% of greenhouse gas emissions and 45% of terrestrial acidification, while cotton cultivation accounts for 92% of water consumption and 69% of land use. Compared to traditional methods, green manufacturing practices achieve reductions in greenhouse gas emissions and water use by over 60% and 21%, respectively. These findings underscore the potential for sustainable practices to mitigate the environmental footprint of denim production while highlighting areas for further improvement. This study delivers critical insights for advancing sustainability in the denim industry.

KEYWORDS

environmental life cycle assessment (E-LCA), denim, environmental impact, green manufacturing, sustainability

INTRODUCTION

The environmental ramifications of the textile and garment industry have garnered significant global attention due to its extensive consumption of resources and pollution generation. Disparities in the distribution of environmental impacts have resulted from the globalisation and segmentation of this industry [1,2]. The textile and garment industries were the second most significant contributor to pollution, and only the oil industry exceeded it. The textile sector faces mounting challenges in embracing sustainability. The disposal of textile wastes in landfills is a global problem. The sustainability of the textile and clothing sectors will be enhanced if every brand in the supply chain embraces environmentally conscious practices [3-5].

Denim trousers, commonly called jeans, have transitioned from their original functional use to becoming a global fashion staple, with millions of pairs produced annually [6-8]. However, the large-scale production of denim pants, particularly in low-cost manufacturing hubs, has posed significant environmental challenges. The production process, from cotton farming to the final garment, is resource-intensive, requiring vast amounts of water, energy, and chemicals while contributing to various pollution forms [9,10]. Cotton cultivation—a cornerstone of denim production—is notorious for its disproportionate water consumption, soil degradation due to fertiliser overuse, and chemical contamination of surrounding ecosystems. Furthermore, manufacturing processes, such as dyeing and finishing, exacerbate environmental harm by discharging hazardous effluents into aquatic systems. These cumulative impacts underscore the need to integrate sustainable manufacturing practices within the denim industry [11].

The detrimental environmental impacts of denim production include excessive water consumption, significant greenhouse gas emissions, terrestrial acidification, eutrophication, and the depletion of abiotic resources [12]. The environmental impact of denim production stems primarily from cotton farming and denim garment manufacturing. Cotton farming, the primary source of raw material for denim, is notorious for its excessive water use, reliance on chemical fertilisers, and contribution to land degradation [13]. For instance, cotton farming—a key component in denim production—relies heavily on irrigation, resulting in freshwater depletion and land degradation. At the same time, the extensive use of fertilisers and pesticides exacerbates soil and water contamination [14,15]. Moreover, the production processes, such as dyeing and finishing, release harmful chemicals into waterways, affecting aquatic ecosystems and human health. The energy-intensive manufacturing stages, including yarn spinning, fabric weaving, and garment finishing, further exacerbate greenhouse gas emissions, highlighting the urgent need for intervention [16,17]. Addressing these impacts is imperative, yet the environmental consequences of denim production remain insufficiently explored.

Despite increasing consumer awareness and regulatory pressures, the environmental ramifications of denim production remain poorly understood, necessitating comprehensive evaluation [18,19]. Sustainability in denim garment manufacturing refers to adopting practices that minimize resource consumption and environmental degradation while maintaining economic viability. This includes using organic or recycled raw materials, water- and energy-efficient technologies, waste minimization strategies, and adherence to fair labour practices throughout the supply chain [20]. However, despite burgeoning consumer demand for environmentally sustainable fashion, the lack of universally accepted definitions and metrics for "sustainability" often impedes its consistent application within industrial practices [7,21]. One effective method is environmental life cycle assessment, which provides a comprehensive approach to assess the environmental effects of denim trousers throughout their life cycle, from raw material extraction to final production [22].

The environmental life cycle assessment of denim encompasses several critical concerns for the denim industry, including substantial water and energy consumption during production, chemical usage, waste generation, and disposal challenges. These issues raise significant sustainability concerns for the industry [23-25]. The sustainability issues plague the fast fashion sector due to environmental and social implications [26]. Levi Strauss & Co.'s Life Cycle Assessment of Jeans revealed considerable environmental effects throughout the manufacturing, usage, and disposal. Fabric production and consumer maintenance considerably contribute to emissions of greenhouse gases such as carbon dioxide (CO_2), methane (CH_3), and nitrous oxide (N_2O), while water-intensive methods escalate water use. Fibre production causes eutrophication and requires much space. Textile consumption contributes to abiotic depletion. According to the LCA, eutrophication, water use, and emissions were linked to Levi's 501 jeans production [27]. “E-LCAs” indicate that Nudie Jeans' goods have reduced greenhouse gas emissions atmospheric impact compared to industry averages. Energy supply, transportation, and textile processes have significant drawbacks. Circularity and environmental footprint reductions are essential for the sustainable apparel sector [28].

Green manufacturing is a significant component of the textile industry as awareness of environmental issues increases. Environmental consequences should be considered when designing new textile structures [29]. To follow the green industry philosophy, industries must apply sustainable resource efficiency and effectiveness to their manufacturing processes [30,31].

Life Cycle Assessment (LCA) studies can analyse the environmental effects of items or processes across their life cycles using the OpenLCA software, a life cycle assessment tool. Users can configure the system limits and select relevant data from various sources. OpenLCA allows many impact assessment methods and sensitivity analyses to discover environmental impacts and uncertainty sources [32,33]. The Ecoinvent database was used in this study and incorporated into the OpenLCA software. The Ecoinvent Database provides detailed information on the environmental impacts of products and services. The Ecoinvent datasets show resource usage, emissions, goods, co-products, and trash, helping us to understand the environmental implications [34].

This research addresses these gaps through a comprehensive Environmental Life Cycle Assessment (E-LCA) of denim manufacturing, providing a comparative investigation of traditional and sustainable production methodologies. This study uniquely quantifies the environmental impacts of green manufacturing practices for denim production in Bangladesh, presenting a robust comparative analysis with conventional systems using locally sourced primary data. Bangladesh was selected as the pivotal case study as a globally recognised nexus for denim production. The country's prominence in the global textile market and its progressive adoption of green manufacturing certifications provide a critical framework for assessing the efficacy of sustainable production practices within a resource-constrained context. Additionally, Bangladesh's significant contributions to global denim supply chains underscore the broader applicability of its sustainable practices as a model for the industry. This study adheres to the ISO 14040/14044 standards. It employs the ReCiPe 2016 Midpoint (H) methodology to evaluate six key environmental impact categories: terrestrial acidification (TA), eutrophication (EP), land occupation (LO), water consumption (WC), abiotic depletion (AD), and greenhouse gas emissions (GHG). The cradle-to-gate analysis emphasises two pivotal stages in denim production: cotton cultivation and garment manufacturing. The findings of this research advance the treatise on sustainable textiles by providing a detailed examination of emissions and resource dependencies. It offers actionable insights for policymakers, industry leaders, and other stakeholders in the textile and apparel sectors, guiding the development and adoption of strategies that reconcile environmental responsibility with economic viability. Ultimately, the findings aim to chart a strategic pathway for embedding sustainable practices across the global denim industry.

METHODOLOGY

This research used life cycle assessment to examine the environmental impacts of producing a pair of denim trousers in green and conventional factories. The methodology for analysing the environmental life cycle assessment (E-LCA) of denim trousers involves a systematic approach adhering to ISO 14040/14044:2006 standards, which offers guidelines and requirements for performing Life Cycle Assessments (LCAs) on products and processes. This methodology involves goal and scope formulation, life cycle inventory analysis, impact assessment, and interpretation of the results.

Two scenarios were devised in this investigation to evaluate and contrast the environmental consequences of the production of denim trousers in conventional and green factories. These scenarios concentrate on two distinct production methods, comprehensively understanding their ecological impact. The analysis encompasses the environmental impacts of key phases, including cotton cultivation, textile and fabric manufacturing, fabric dyeing, and garment production. The conventional manufacturing approach is represented by the basal scenario (S1). This approach has significant environmental implications. In contrast, Scenario 2 (S2) concentrates on the production of denim in green factories, where sustainable practices are enacted to mitigate environmental damage by optimising water and energy consumption and minimising chemical inputs.

The primary goal of this investigation is to assess the environmental life cycle impacts of denim trousers manufactured in these two types of factories. Specifically, the impact of terrestrial acidification, eutrophication, land occupation, water consumption, abiotic depletion, and greenhouse gas (CO_2 equivalent emissions) will be examined. The data for conventional factories was obtained from industry benchmarks, while the data for green factories was collected from eco-friendly manufacturers in Bangladesh. The two scenarios are summarised in Table 1.

Table 1. Summary of Scenarios

Scenario	Factory Type	Description
S1 (Base Scenario)	Conventional Factory	Denim trousers are produced using traditional methods, with higher resource consumption and more significant environmental impacts.
S2	Green Factory	Denim trousers are produced in environmentally conscious factories with optimised processes for lower resource consumption and minimised environmental impacts.

The study's methodological framework has been illustrated in Figure 1.

Goal and Scope

Environmental Impacts of Raw Material Production as explored in Cotton Cultivation; Spinning, Dyeing, Weaving, and Finishing processes across Yarn and Fabric Manufacturing; and Garment Production covering cutting, sewing, washing, and finishing stages. Each stage was analysed independently, and data were normalised to 1 pair of denim trousers (600 grams in weight) on a functional unit basis to make a comparison between the lifecycle possible.

The data for the study were collected by assessing both primary and secondary sources for an in-depth and authentic view of the study. Information on resource inputs, energy consumption, chemical use, and waste outputs was obtained from a green-certified factory in Bangladesh due to collecting primary data from there. Machinery operations and waste management were inspected on-site, factory managers and technical staff were interviewed through structured interviews and production logs, water records, and energy bills were thoroughly reviewed. Conventional factory operations and upstream processes, such as cotton cultivation, were modelled using secondary data following the Ecoinvent 3.9.1 database and industry reports. These, namely Levi Strauss & Co's LCA studies and peer-reviewed publications, served as the benchmarks for regular factory practice.

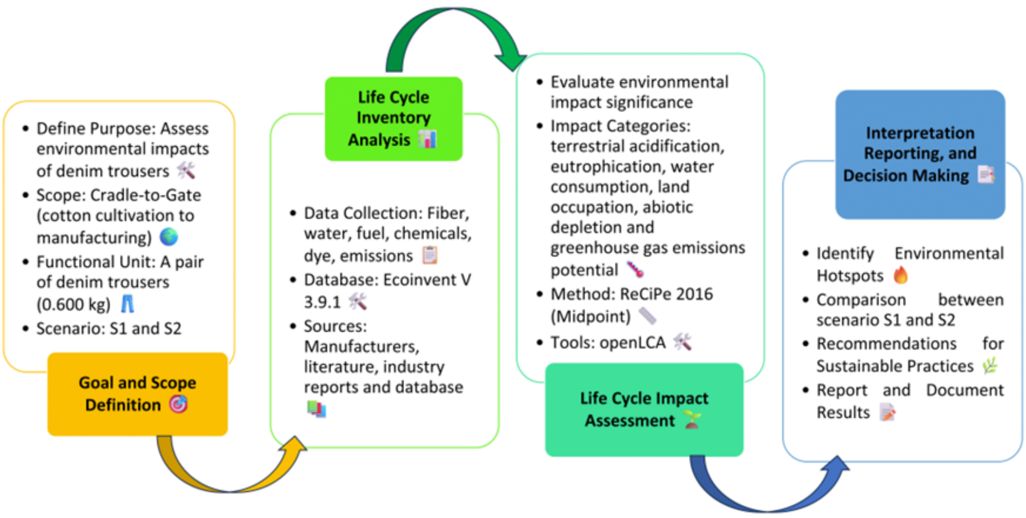

Figure 1. The research framework of the study

Functional Unit

For this study, the primary focus is the environmental impact of manufacturing a pair of denim trousers weighing approximately 600 grams. Table 2 gives the functional unit details.

Table 2. Functional unit (a pair of denim trousers) detail information

Denim trouser technical details	
Product Details	denim trousers
Size	L size
Main material	
Composition of fibre	99% organic cotton, 1% elastane
Mass	560.5 g
Lining	
Composition	100% Cotton
Mass	26 g
Metal button and zipper	
Composition	Brass Copper, nickel-free
Mass	12.5 g
Label	
Composition	Cotton woven
Mass	0.8 g
The total mass of the product	~600 g

System Boundaries of the LCA

The system boundaries include cotton cultivation, yarn and fabric manufacturing, and denim trousers production but exclude transportation, distribution, product use, and disposal stages. Inputs such as energy, water, and chemicals are considered only for the processes within the defined system boundaries. Outputs such as waste, wastewater, and emissions are assessed only for the processes within the exact boundaries. Life Cycle Assessment (LCA) was conducted as a “cradle-to-gate” examination. This classification defines the assessment scope, encompassing the environmental impacts of a product's entire life cycle, from raw material extraction (cradle) to leaving the manufacturing facility (gate). This border usually does not include impacts during the product usage, maintenance, or disposal stages [35]. A flow model illustrates the system's boundaries, indicating its starting and ending points and all necessary inputs and outputs. The outcome is a comprehensive flowchart encompassing all the elements that will be quantified and scrutinised. The flowchart, illustrated in Figure 2, describes the system boundaries of the study.

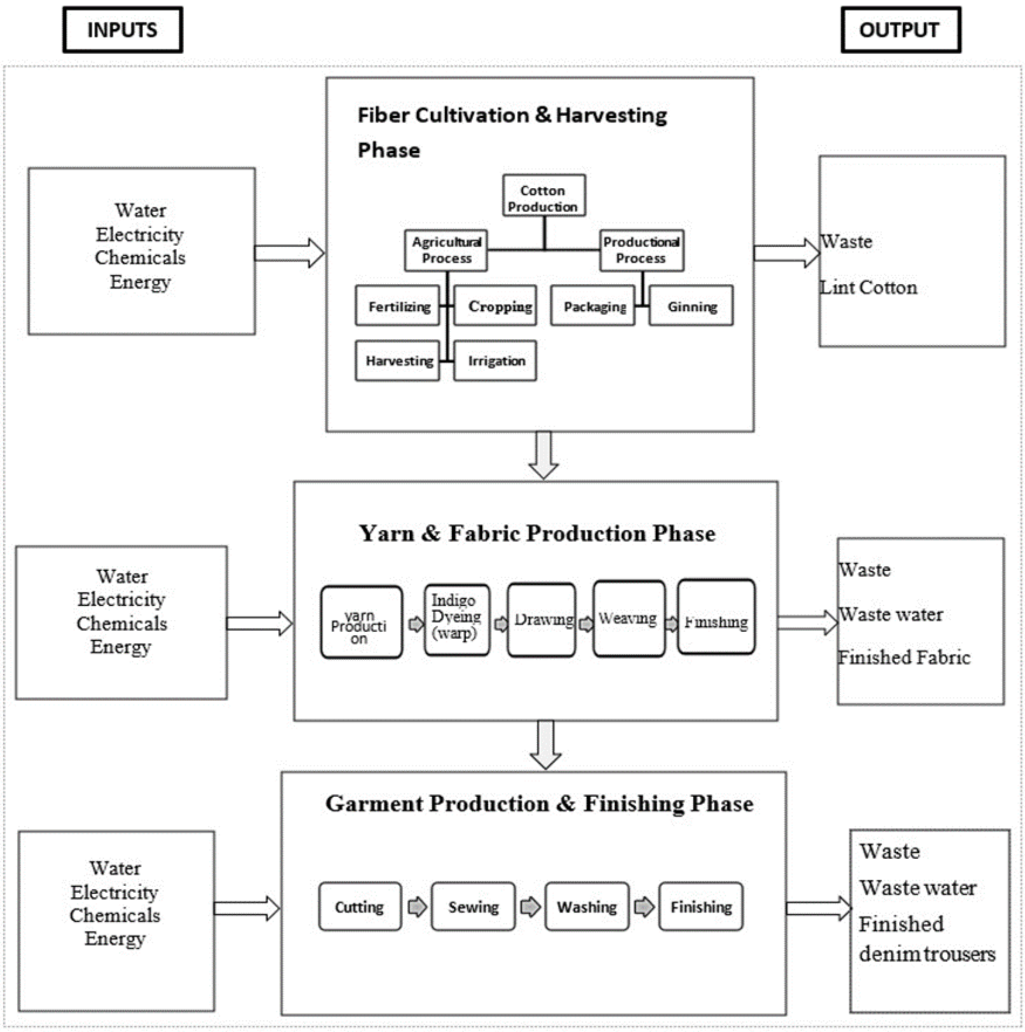

Figure 2. System boundaries of denim trousers life cycle

Inventory Analysis of LCA

The inventory analysis enhances the objective and scope description by creating a model for collecting data. A significant amount of primary and secondary data is required to conduct an inventory analysis. Reliability and comprehensiveness were assured by using data from three key areas. Firstly, yarn, fabric manufacturing, and garment production data were collected directly from a green-certified Bangladesh factory. This factory is recognised for implementing sustainable practices certified by globally recognised standards such as LEED (Leadership in Energy and Environmental Design) and GOTS (Global Organic Textile Standard). A structured data collection template revealed detailed information about resource consumption (energy, water, chemicals), emissions and waste produced. Resources such as water, energy, natural gas, raw materials, and chemicals are inputs. Outputs refer to emissions, wastewater, created waste, and final products. Secondly, when there is no primary data for processes, such as cotton cultivation in India, data from the Ecoinvent 3.9.1 database is used, which has been scientifically validated. Lastly, the report also derives benchmarks for typical factory operations from respected industry reports such as Levi Strauss & Co. LCA studies and peer-reviewed literature on denim production in Bangladesh to build a robust and credible data basis for the analysis.

Factors such as environmental certifications and registrations, sound resource management practices and adherence to Standard Operating Procedures (SOPs) were used to classify factories into 'green' or 'conventional'. International certification bodies (e.g., LEED, GOTS), advanced resource optimisation approaches, eco-friendly chemical use, renewable energy use, robust wastewater treatment systems, and compliance through site visits and operational logs were identified in green factories. Such certification was absent in conventional factories that relied upon outdated machinery, high resource consumption and pollution control, with SOPs based on industry benchmarks. Green factory data were validated through direct observations, interviews with management, and review of compliance documents, while conventional factory data were benchmarked against existing LCA studies to meet typical resource-intensive denim processing practices. Following this approach, we established a robust system of comparing operational efficiency and environmental impacts amongst factory types.

Cotton Cultivation

This study's life cycle inventory (LCI) data were primarily based on the Ecoinvent 3.9.1 database. In contrast, the Textile Exchange (2014) dataset is well known for its global coverage of life cycle inventory data [36]. These datasets were not capable of capturing the Bangladeshi conditions. Therefore, the data were adapted to local relevance using Indian organic cotton farming as a proxy, as India is geographically proximate and an essential supplier of the Bangladeshi textile industry as well. The inputs included organic seeds (0,0038 kg per pair of trousers), manure (21,38 kilograms per hectare), rock phosphate (0,58 kg per hectare), irrigation water (2553,95 L per kilogram of lint cotton), and energy was used at 0,70 MJ/kg of lint cotton and mainly came from farming machinery. Lint cotton, seed by-products, nitrous oxides and phosphate compounds were output at 0,75 kg (pair of trousers), seed plus others (1,34 kg), while emissions were recorded as N_2O and phosphate compounds, respectively. The data was validated by industry reports and by consultations with stakeholders, and the datasets chosen contained information that reflects the condition of the supply chain in Bangladesh. Constraints, particularly the divergence of the datasets at a location level and the paucity of the primary data were attenuated because the datasets were made to conform to South Asian agricultural practices and compared to locally collected data on the impacts of cotton farming. These efforts integrated the environmental effects of imported cotton into the life cycle assessment of denim production.

Yarn and Fabric Manufacturing

Data on yarn and fabric production were collected firsthand from a green factory, "X", in Bangladesh. For the conventional factory, industry reports were collected and benchmarked against existing LCA studies. This method guaranteed access to specific site information, such as energy, chemicals, and water used during spinning, dyeing, weaving, and finishing procedures. Quantities of chemicals consumed during dyeing, washing and finishing of yarn and fabric were quantified during production runs in green and conventional factories at a monthly production rate of 100,000 kg of fabric. The data were validated and accurate using a thorough and cross-verification process. For green factories, detailed daily and monthly logs were maintained for chemical inputs based on which LEED compliance reports were corroborated to ensure accuracy and were benchmarked against average consumption figures from reputable industry reports for conventional factories. Scaled and normalised chemical consumption data were based on a functional unit of 0.68 kilograms of processed fabric to extrapolate daily and monthly values from production volumes. Because this normalisation was transparent and robust, it formed a basis for comparing the environmental impacts of green and conventional factories. In green factories, dyeing chemicals included natural indigo dye (0.006 kg per kilogram of fabric) and wetting agent (0.006 kg per kilogram of fabric), resulting from daily consumption of 20 kg monthly and 600 kg each. Neutralisers and softening agents included a neutralising agent (0.006 kg per kilogram of fabric) and softener (0.005 kg per kilogram of fabric), with daily usages of 20 kg and 16.67 kg and monthly usages of 600 kg and 500 kg, respectively. Eco-friendly detergent (0.008 kg per kilogram of fabric) was used, with daily and monthly consumptions of 26.67 kg and 800 kg. Water consumption was 122.08 litres per kilogram of fabric, amounting to 406,933 litres daily and 12,208,000 litres monthly. In conventional factories, chemical usage was higher, with synthetic indigo dye (0.009 kg per kilogram of fabric) and wetting agent (0.008 kg per kilogram of fabric), resulting from daily consumptions of 30 kg and 26.67 kg and monthly totals of 900 kg and 800 kg, respectively. The neutralising agent (0.01 kg per kilogram of fabric) and softener (0.007 kg per kilogram of fabric) had daily usages of 33.33 kg and 23.33 kg and monthly usages of 1000 kg and 700 kg. Standard detergent (0.015 kg per kilogram of fabric) usage was 50 kg daily and 1500 kg monthly, while water consumption was 150 litres per kilogram of fabric, equating to 500,000 litres daily and 15,000,000 litres approximately monthly.

Denim Trousers Manufacturing

Data on denim trouser manufacture was collected from a green factory, and the conventional factory data were benchmarked against existing LCA studies. The process includes information on cutting, sewing, washing, and finishing procedures. Comprehensive data on materials, energy usage, and chemical inputs was gathered to evaluate environmental effects precisely.

In garment production, green factories demonstrated lower chemical and water consumption than conventional ones. For a daily production of 3,333.33 kilograms of fabric, green factories used 40 kg of desizing agent, 26.67 kg of detergent, 20 kg of neutralising agent, and 16.67 kg of softener, resulting in monthly consumptions of 1,200 kg, 800 kg, 600 kg, and 500 kg, respectively. Water consumption was 351,667 litres daily and 10,550,000 litres monthly. Conventional factories, by contrast, used 66.67 kg of desizing agent, 50 kg of detergent, 33.33 kg of neutralising agent, and 23.33 kg of softener daily, totalling monthly consumptions of 2,000 kg, 1,500 kg, 1,000 kg, and 700 kg, respectively. Water usage was significantly higher in conventional factories, at 550,000 litres daily and 16,500,000 litres monthly. Normalised per kilogram of denim, green factories used 0.012 kg of desizing agent, 0.008 kg of detergent, 0.006 kg of neutralising agent, 0.005 kg of softener, and 105.5 litres of water. In contrast, conventional factories consumed 0.02 kg of desizing agent, 0.015 kg of detergent, 0.01 kg of neutralising agent, 0.007 kg of softener, and 165 litres of water.

Impact Assessment of LCA

A suitable environmental impact assessment method must be used to assess the E-LCA. The impacts resulting from all the inputs and outputs are combined in this section and categorised according to the areas they influence. LCA impact assessments were conducted using openLCA 2.1 software from cradle-to-cradle analysis following ISO 14040/14044:2006 principles. Based on the ReCiPe 2016 Midpoint (H) method, the selection of impact categories is justified as they cover all essential environmental challenges occurring during denim production [37]. In that sense, these categories—terrestrial acidification, eutrophication, land occupation, water consumption, abiotic depletion, and greenhouse gas (GHG) emissions directly map to material impacts of cotton farming, manufacture of fabrics, and garment production. It guarantees a comprehensive evaluation of both local impacts (acidification, eutrophication) and global issues (GHG emissions) and resource sustainability (water and abiotic resource use). The method conforms to international LCA standards and ISO 14040/14044 and matches methodological rigour and Ecoinvent database compatibility with other LCA studies on the textile industry. Additionally, the chosen categories allow for a sound comparison between traditional and green production processes regarding reduced emissions, water savings, and resource efficiency. All impact factors are calculated based on the functional unit and normalised to comparable units for consistent analysis. The detailed calculation process of these environmental impact categories is discussed below:

Sulfur dioxide, nitrogen oxides, and ammonia air pollutants cause terrestrial acidification, lowering soil and water pH and harming ecosystems, plant life, and microbes. Quantifying the environmental impact of emissions is done by acidification potential (AP), which assesses a substance's ability to release hydrogen ions (H^+) during transformation, causing acidification [38]. To standardise comparisons, emissions are converted to kg SO_2-e using acidification potential factors (APFs) for each substance: SO_2 (APF=1), NO_x as NO_2 (APF ≈ 0.7), NH_3 (APF ≈ 1.88), HCl (APF ≈ 0.88), and HF (APF ≈ 1.6). The acidification potential is the mass of each acidifying material times its APF [39,40]. Nitrogen (N) and phosphorus (P) emissions lead to eutrophication, which leads to algae growth and damages water quality and biodiversity. Emissions are standardised into kg PO_4-e to compare impacts from different eutrophication chemicals, but impact evaluation is standardised so evaluation can be repeated across chemicals [41]. To determine what percentage of over-fertilization a substance is adding, multiply its mass by its Eutrophication Potential Factor (EPF) relative to phosphate (PO_4^{3-}, EPF of 1). Nitrate (NO_3^-) EPF 0.10, ammonia (NH_3) EPF 0.35, and COD EPF 0.022 are common [42]. Land occupation, as an essential metric for environmental impact evaluation, such as Life Cycle Assessment (LCA), is the area and time of use of land in the units of square meters per year (m^2/yr) [43]. Land occupation may damage biodiversity, ecosystem services and resource management. In LCA, land occupation is quantified as the product of the area occupied multiplied by its duration of use and is typically normalised to a functional unit, such as a product unit. In some assessments of land occupation, temporary occupation is distinguished from land transformation according to the type of land use (agricultural or industrial) [44]. Characterisation factors (CFs) that indicate environmental effects per land use are included in advanced LCA (considering ecosystem sensitivity). Assessments are practical and require rigorous data gathering, often through GIS or field surveys, precise assumptions on when and how land will be put back into use, and timeframes and land use categories[45]. The high total water demands during fibre-growing, dyeing and garment finishing stages in textile plants make water consumption a key metric in such plants' environmental life cycle assessment (LCA). Accurate water use calculations identify resource-intensive operations that increase water efficiency and mitigate its environmental impact [46]. Water use in an LCA is total water inputs minus recycled or recovered water. The production utilizes water directly, and in the process, the upstream operations of cotton planting use water indirectly. The implications of embedded water in raw materials, wastewater generation and treatment, and regional water shortages can be contextualised using local water stress indices [47,48]. Abiotic Depletion Potential (ADP) provides a way of tracking the depletion of minerals and fossil fuels in Environmental Life Cycle Assessment (LCA), showing resource shortages and their sustainability consequences. Therefore, ADP measurements are in kg Sb-e [49]. For ADP, ad hoc characterisation factors (ADP factors) are based on resource scarcity and crustal concentration, such as 1 for antimony, ~1.80×10^{-4} for copper, and ~1.05×10^{-5} for iron, with which to compare consumption to known reserves. By being consistent on units (kg) and having complete inventories of all abiotic resources (including upstream processes and regional variations), accuracy is increased [50].

https://doi.org/10.31881/TLR.2024.163

Another environmental impact category, global warming potential, is being measured by assessing greenhouse gas (GHG) emissions in CO_2-e. A gas's GWP measures its heat-trapping ability compared to CO_2 over 100 years [51]. CO_2 has a baseline GWP of 1, while CH_4 ranges from 28 to 36, and N_2O ranges from 265 to 298. The mass of each GHG emitted is multiplied by its GWP to determine CO_2-e emissions and compare their warming impacts [52]. CO_2 emissions from fossil fuel combustion are determined by multiplying fuel consumption by an emission factor, typically 2.31 kg CO_2 per litre for gasoline, 2.68 kg per litre for diesel, and 2.42 kg per kg for bituminous coal. CO_2-e emissions from power use are calculated by multiplying kWh consumption by the grid emission factor, which measures CO_2 output per kWh spent[53]. For activities producing several GHGs, CO_2-e emissions are calculated by summing the CO_2-e from each gas, such as 100 kg CO_2, 2 kg CH_4, and 1 kg N_2O, using their GWPs [54].

Excluded Factors, Data Limitations, Time and Geographic Scope

Transportation of raw materials and finished products, among other impacts, is not included in the analysis since it is assumed that those impacts are relatively ubiquitous across the two scenarios. Environmental impacts are the only factors considered, but neither are social or economic sustainability. It is assumed that primary data from factory surveys about green factories represent broader industrial practices in sustainable denim production. Standard databases such as Ecoinvent are used where direct data are unavailable, and missing or unavailable data are supplemented with secondary sources. For simplicity, all regional energy or water usage is averaged. The study's assumptions include current (2024) technological and operational conditions for green and conventional factories. The analysis is restricted to production in Bangladesh, but the assumption is that the results are generalisable to similar settings worldwide.

Margin of Errors or Uncertainties of the Study

Although the denim production Environmental Life Cycle Assessment (E-LCA) study is comprehensive, several unknowns could compromise the validity of the results.

Data Variability and Quality

Primary vs. Secondary Data: The LCA used primary data from green factories and secondary data from Ecoinvent databases. Uncertainty increases with different data sources (e.g., data quality or representativeness differ). Site-specific primary data from green industries, while site-specific, is not always accurate because secondary data is general or outdated. Environmental impacts based on generic datasets could vary by ±10–20% when applied to specific contexts like Bangladesh.

Regional differences: Data on cotton growing in India and Africa may not correctly reflect realities in Bangladesh, where the study is focused. Climate, farming methods, and local resource availability influence water, chemicals, and land use.

System Boundaries and Scope

The study's " cradle-to-gate " methodology excludes denim trousers' transportation, consumer usage, and disposal phases. When the product is not considered from the factory gate, and when it comes to its transportation emissions and energy use or wastes.

Methodology for Impact Assessment

Impact assessment uses the ReCiPe 2016 Midpoint (H) method, but results may differ based on characterization factors and calculation procedures. One technique may fail to capture local environmental dynamics or influence, thus introducing uncertainty. Typical machinery efficiency, chemical use rates, and energy consumption are taken into account in the effect evaluation. Underestimation or overestimation of impacts may be due to these assumptions not reflecting factory variability or production run variability. Impact categories such as water consumption and greenhouse gas emissions may carry a margin of error of ±5–15% and ±10–30% for some impact categories like terrestrial acidification or eutrophication due to assumptions in the modelling of environmental pathways.

Spatial and Temporal Representation

This Study focuses on a few green factories in Bangladesh. These findings may not be true in factories in other countries or under different operational procedures. The particularity of the distinctiveness of these factory processes can hinder the adaptation of these findings to other circumstances and regions.

Data Omission and Simplification

This study does not consider social and economic aspects of sustainability, nor do other environmental implications, e.g., microplastic pollution from synthetic materials, considered. In some cases, the manufacture of yarn, fabric, and finishing is modelled with an assumption of consistent efficiency and resource utilization in many production steps. The actual performance concerning efficiency, energy use, and emissions differs.

Geographical Context Misalignment

The Ecoinvent database is mostly about European production systems, which may not be relevant in Bangladesh. The margin of error (~10−25%) is due to inconsistencies in the emissions factors, energy grids and water usage patterns.

RESULTS AND DISCUSSION

This study aimed to evaluate the environmental consequences of widely used denim trousers produced in a green factory in Bangladesh (S2) using a life cycle assessment method. Furthermore, it determines whether denim garments are entirely sustainable for consumers. This result focuses on the impact of cradle-to-gate analysis. The outcomes of this study were demonstrated according to the production phase and environmental impact categories.

Interpretation of LCA

The accumulated results from the Life Cycle Impact Assessment phase have been presented in the Life Cycle Interpretation. In scenario S2, the results for each environmental impact category are described for a pair of denim trousers. The three major life cycle phases, cotton cultivation, yarn and fabric manufacturing, and denim trouser manufacturing (Cradle-to-gate), were used to group results.

Terrestrial Acidification

This phenomenon is closely linked to the emission of acidifying substances such as nitrates, sulfates, and phosphates. The emission of acidifying chemicals is directly related to burning fossil fuels such as coal, oil, and gas. Figure 3 illustrates the environmental consequences of terrestrial acidification, quantified in kilograms of SO_2 -eq, and percentages. Cotton cultivation is responsible for 0.008 kg SO_2 -eq (17% of total emissions), yarn and fabric manufacturing is responsible for 0.021 kg (45% of total emissions), and trouser production is responsible for 0.018 kg SO_2 -eq (38% of total emissions) of the environmental impact of terrestrial acidification.

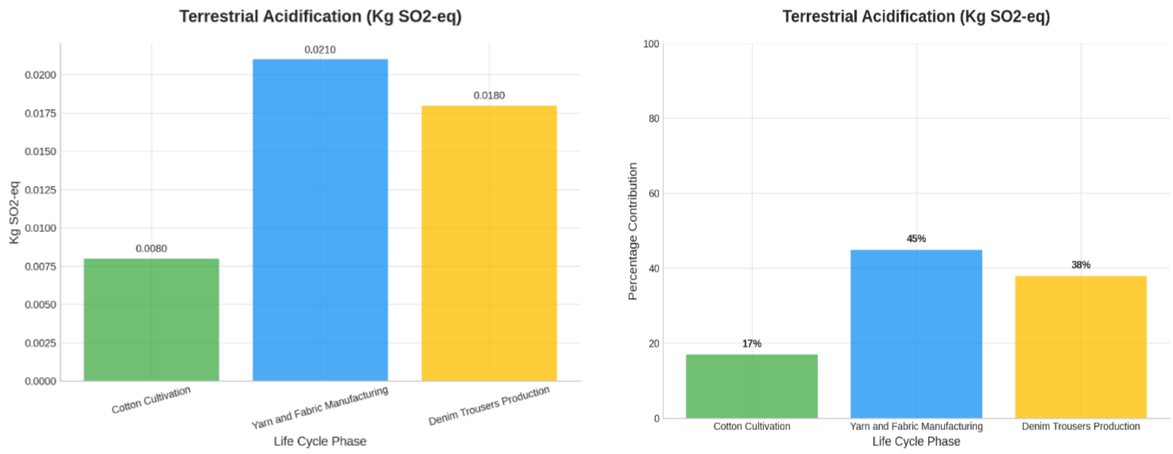

Figure 3. Environmental impact (Terrestrial acidification) of three life cycle phases to produce a pair of denim trousers for scenario S2

Eutrophication

Eutrophication is a primary environmental concern because of increased nitrogen and phosphorus input from human activities into our country's aquatic ecosystem. These chemicals harm drinking water supplies, fisheries, and bodies of water. Culturing fibres while producing a single pair of jeans has the most substantial environmental impact. This is primarily due to using artificial fertilizers, pesticides, and burning fossil fuels, which results in water pollution. Using water with chemical compounds such as sodium hydroxide, ammonium chloride, and starch has the most significant ecological repercussions during fabric production. The sources of fossil fuel energy used to generate electricity, heat, and transportation also contribute to pollution, although to a lesser extent than contaminated water. Figure 4 shows the environmental consequences of eutrophication potential, quantified in kilograms of PO_4 -eq and percentages. Cotton cultivation is responsible for 0.0085 kg PO_4 -eq (38% of total emissions), yarn and fabric manufacturing are responsible for 0.0066 kg (30% of total emissions), and trouser production is responsible for 0.0072 kg PO_4 -eq (32% of total emissions) of the environmental impact of eutrophication.

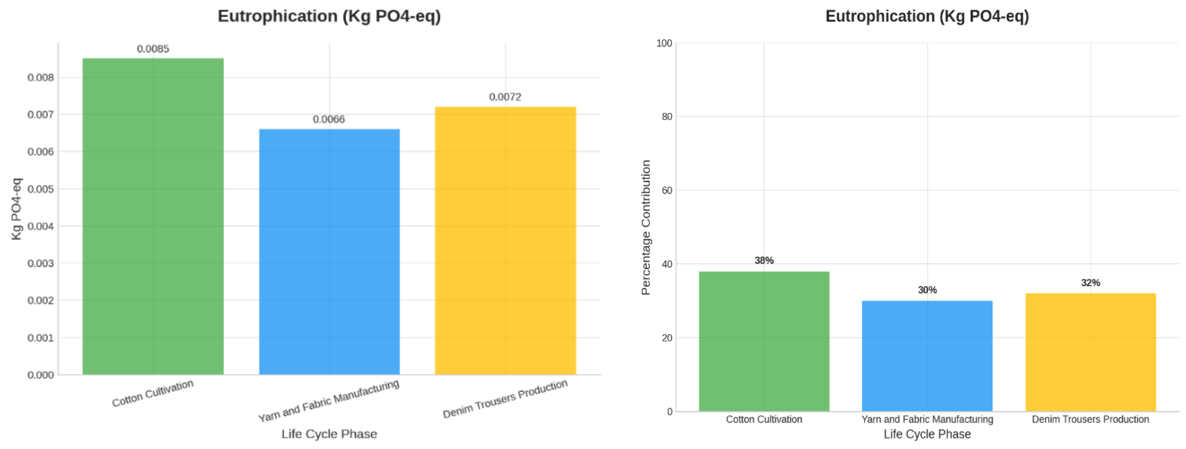

Figure 4. Environmental impact (Eutrophication) of three life cycle phases to produce a pair of denim trousers for scenario S2

Land Occupation

Occupation and alteration of land cause harm to ecosystems. Land occupancy is considered for the change of land in the construction of industries, even if it is most noticeable during the fibre cultivation phase. In particular, this phase is of utmost importance, as it is when land occupation is at its highest. The land occupation was the highest in the fibre cultivation stage of garment production. The influence of land occupation on fabric manufacture and denim garment production decreases to 2.1 and 1.3 m^2/year after the fibre cultivation stage. Figure 5 displays the land occupation impact in m^2/year and percentages of the impact of denim pant production life cycle stages.

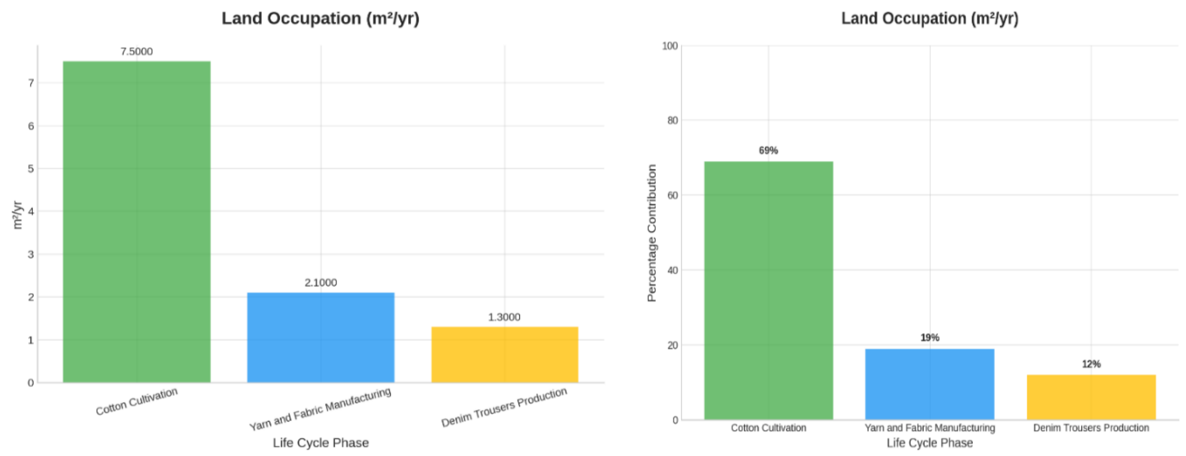

Figure 5. Environmental impact (Land Occupation) of three life cycle phases to produce a pair of denim trousers for scenario S2

Water Consumption

The availability of water varies across different regions, ranging from scarcity to abundance, which makes water a vital resource for both human survival and ecosystem functioning. Hence, the water usage associated with clothing manufacturing can harm human well-being, biodiversity, and the availability of natural resources. Undoubtedly, the cotton-farming phase is the most important step in the water consumption impact category throughout the life cycle. During the fibre cultivation phase, substantial quantities of water are either damaged or lost. Water usage accounts for 8% of the manufacturing of yarn and fabric, whereas the production of denim trousers, including denim washing, accounts for 6% of the total production phase. Green factories use advanced dyeing, finishing, and washing machinery, which requires less water than conventional machines. Figure 6 displays the values.

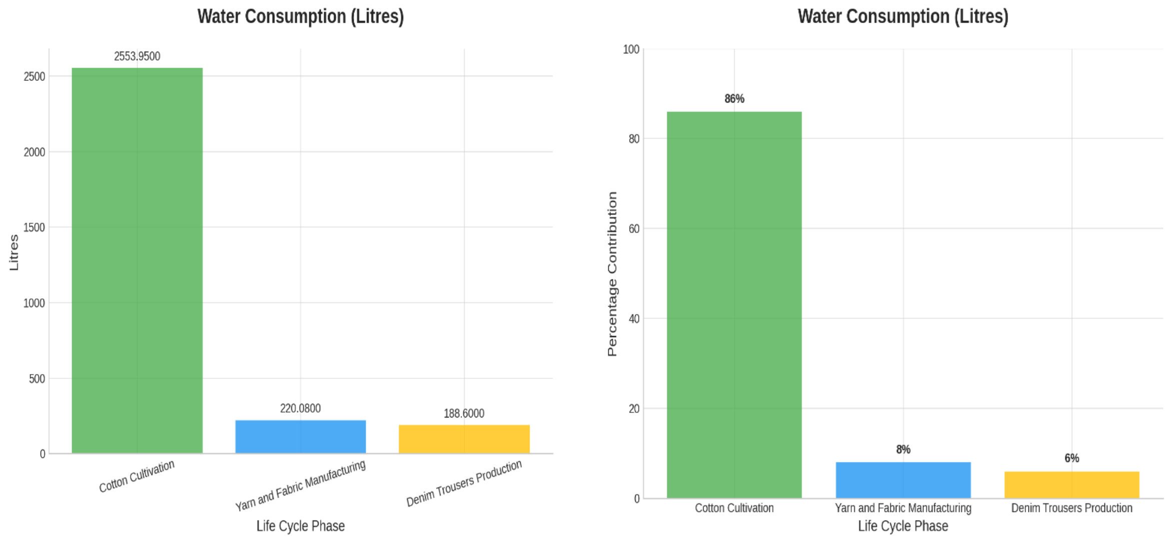

Figure 6. Environmental impact (Water Consumption) of three life cycle phases to produce a pair of denim trousers for scenario S2

Abiotic Depletion

Abiotic depletion is directly linked to the usage of fossil fuels. The heat is generated by natural gas, while the electricity is generated from fossil fuels. These activities result in a significant abiotic depletion. This study examines the depletion of both non-renewable and renewable resources caused by the industrial processes of manufacturing a pair of denim trousers. The effect of abiotic depletion in denim trousers production is the largest, at 48%, and an almost similar amount of impact is caused by yarn and fabric manufacturing at 41%. Lastly, cotton cultivation is responsible for an 11% impact. Figure 7 illustrates the environmental consequences of abiotic depletion, quantified in kilograms of Sb e -eq and percentages.

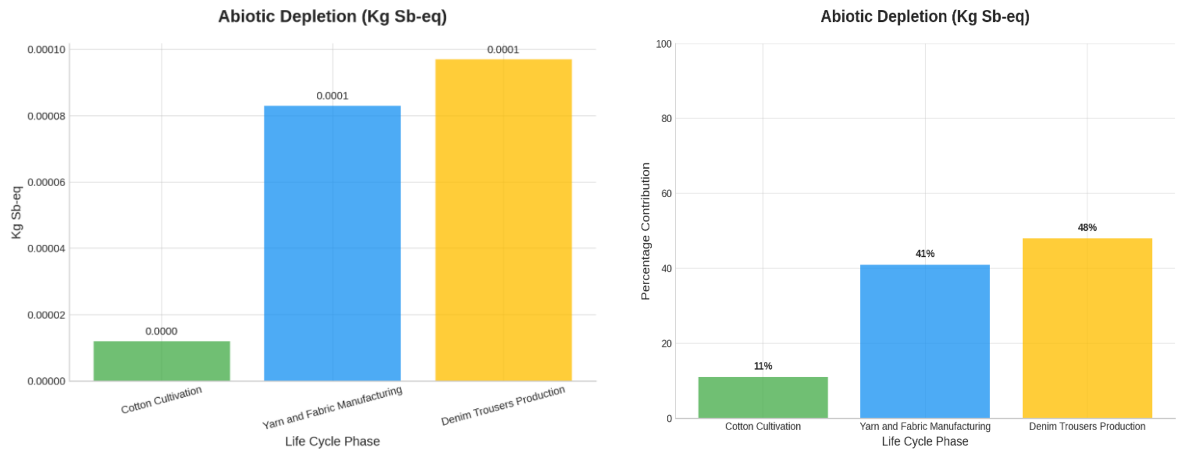

Figure 7. Environmental impact (Abiotic Depletion) of three life cycle phases to produce a pair of denim trousers for scenario S2

Greenhouse Gas Emissions Potential

The evaluation of Greenhouse Gas (GHG) emission potential in this life cycle evaluation (LCA) measures emissions of primary greenhouse gases (CO_2, CH_3, and N_2O) throughout the denim production phases, expressed in CO_2-equivalents (CO_2-eq) for standardized comparison. Cotton cultivation generates approximately 1.1 kg of CO_2-eq per pair, primarily from N_2O emissions from fertilizer application and CO_2 emissions from machinery fuel use. The yarn and fabric production stage is the most emission-intensive, contributing 6.7 kg CO_2-eq (56% of total emissions) due to the substantial energy requirements for spinning, dyeing, weaving, and finishing operations and extra CH_4 emissions from anaerobic wastewater treatment. The production of denim garments, including fabric cutting, sewing, and washing, generates roughly 4.1 kg CO_2-eq (35% of total emissions) because of the energy-intensive machinery. Denim production generates approximately 11.9 kg CO_2-eq for each pair, with yarn and fabric manufacturing being the principal source of emissions. Figure 8 illustrates the environmental consequences of GHG emissions of greenhouse gases, quantified in kilograms of CO_2 and percentages.

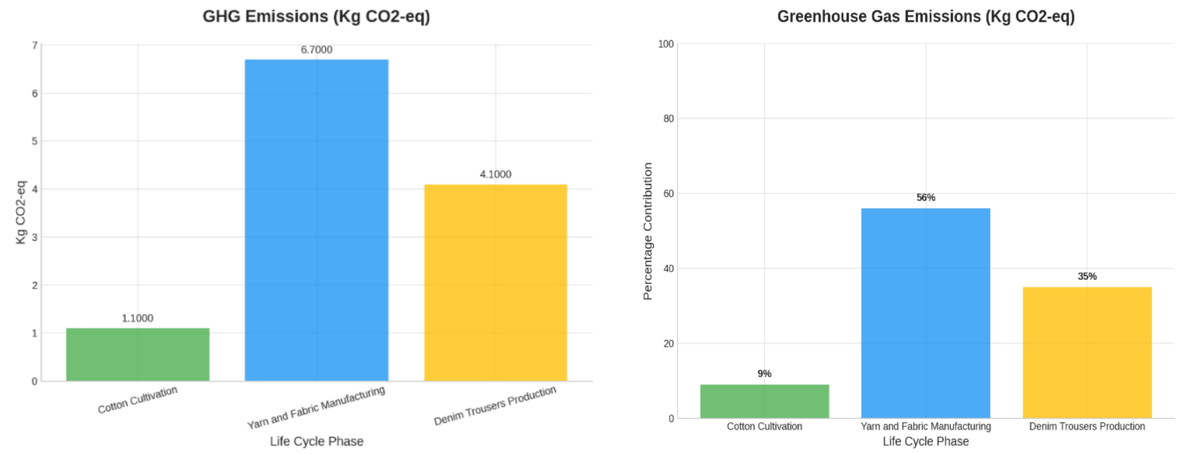

Figure 8. Environmental impact (Greenhouse Gas Emission Potential) of three life cycle phases to produce a pair of denim trousers for scenario S2

The investigators used min-max normalization for the environmental impact data for simplicity and interpretability. This is particularly useful when dealing with datasets where the units or magnitudes of different variables vary significantly, as it ensures that all variables are on the same scale and can be compared directly. For each environmental impact category (e.g., Terrestrial Acidification, Water Consumption), the maximum value across the three life cycle phases (Cotton Cultivation, Yarn and Fabric Manufacturing, Denim Trousers Production) was determined. Since each category was normalized individually, the normalized values represent the relative contribution of each life cycle phase to the maximum observed impact for that category. The normalization data has been illustrated in a line plot for better visualization. Each line represents a life cycle phase (Cotton Cultivation, Yarn and Fabric Manufacturing, Denim Trousers Production), showing their relative contribution to each environmental impact category. The trends highlight the phases dominating specific categories, such as water consumption for Cotton Cultivation and greenhouse gas emissions for Yarn and Fabric Manufacturing. Table 3 shows the normalised data of six environmental impact categories. Figure 9 illustrates the line plot of the normalised environmental impact trends across life cycle phases.

Table 3. Normalised data of six environmental impact categories

	Terrestrial Acidification (Kg SO2-eq)	Eutrophication (Kg PO4-eq)	Land Occupation (mÂ²/yr)	Water Consumption (Litres)	Abiotic Depletion (Kg Sb-eq)	GHG Emissions (Kg CO2-eq)
Cotton Cultivation	0.380952381	1	1	1	0.123711	0.164179
Yarn and Fabric Manufacturing	1	0.776470588	0.28	0.0861724	0.85567	1
Denim Trousers Production	0.857142857	0.847058824	0.173333333	0.07384639	1	0.61194

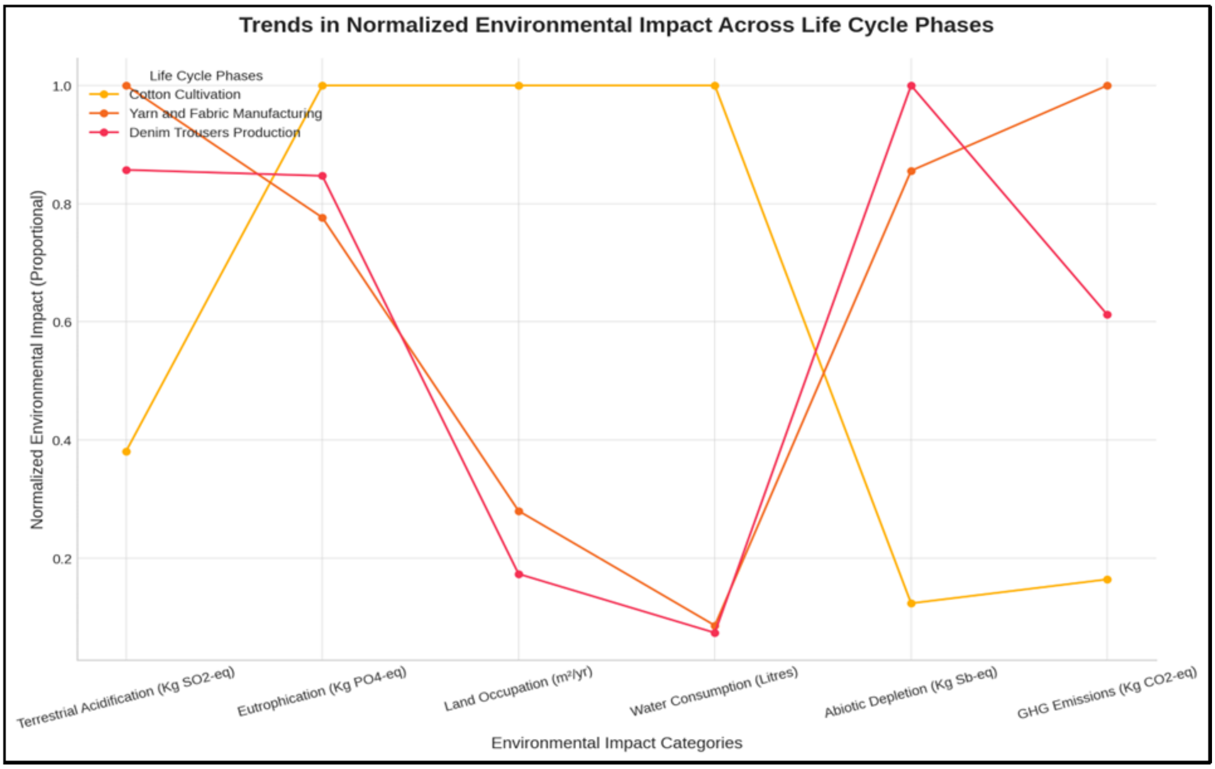

Figure 9. Line plot of the normalised environmental impact trends across life cycle phases. Of denim trousers for scenario S2

The investigators calculated the correlation matrix of environmental impacts and visualised it in a heatmap. Some impact categories, such as Greenhouse Gas Emissions (GHG) and Abiotic Depletion, may show high positive correlations due to their reliance on energy-intensive processes. Terrestrial Acidification and Eutrophication are likely to correlate positively because agricultural activities and chemical usage influence both. Categories like Water Consumption and Land Occupation might have weak correlations with GHG Emissions because they are driven by distinct processes (e.g., agricultural water use vs. fossil fuel combustion). The heatmap quickly identifies relationships between categories, with red indicating strong positive correlations and blue indicating weak or negative correlations. Table 4 shows the correlation matrix of the environmental impacts, and Figure 10 illustrates the heatmap.

Table 4. Correlation matrix data of the environmental impacts

	Terrestrial Acidification (Kg SO2-eq)	Eutrophication (Kg PO4-eq)	Land Occupation (mÂ²/yr)	Water Consumption (Litres)	Abiotic Depletion (Kg Sb-eq)	GHG Emissions (Kg CO2-eq)
Terrestrial Acidification (Kg SO2-eq)	1	-0.99579	-0.94239	-0.97279	0.929995	0.96634
Eutrophication (Kg PO4-eq)	-0.99579	1	0.907752	0.947454	-0.89237	-0.98586
Land Occupation (mÂ²/yr)	-0.94239	0.907752	1	0.99425	-0.99938	-0.82462
Water Consumption (Litres)	-0.97279	0.947454	0.99425	1	-0.98985	-0.88045
Abiotic Depletion (Kg Sb-eq)	0.929995	-0.89237	-0.99938	-0.98985	1	0.804128
GHG Emissions (Kg CO2-eq)	0.96634	-0.98586	-0.82462	-0.88045	0.804128	1

Comparison between green and regular factories

A comparative study of the environmental impact categories for a pair of denim trousers manufactured in green factories in Bangladesh (S2) and regular factories (S1) was conducted based on industry data from Levi Strauss and other sources. Tables 5 and 6 show the environmental impact data for the regular and green factories.

Table 5. Environmental Impact of Regular Denim Factories

Impact Category	Cotton Cultivation	Yarn and Fabric Manufacturing	Denim Trousers Production (Garment Production)	Total	Unit
Terrestrial Acidification	0.012	0.04	0.035	0.087	Kg SO_2-eq
Eutrophication	0.013	0.016	0.019	0.048	Kg PO_4-eq
Land Occupation	8.35	2.2	1.4	12	m^2/yr
Water Consumption	3192	299.72	288.8	3780.52	Litres
Abiotic Depletion	5.2×10^{-5}	12.4×10^{-5}	12.9×10^{-5}	0.000305	Kg Sb-eq
Greenhouse Gas Emissions (CO_2-eq)	1.56	18.7	13.14	33.4	Kg CO_2-e

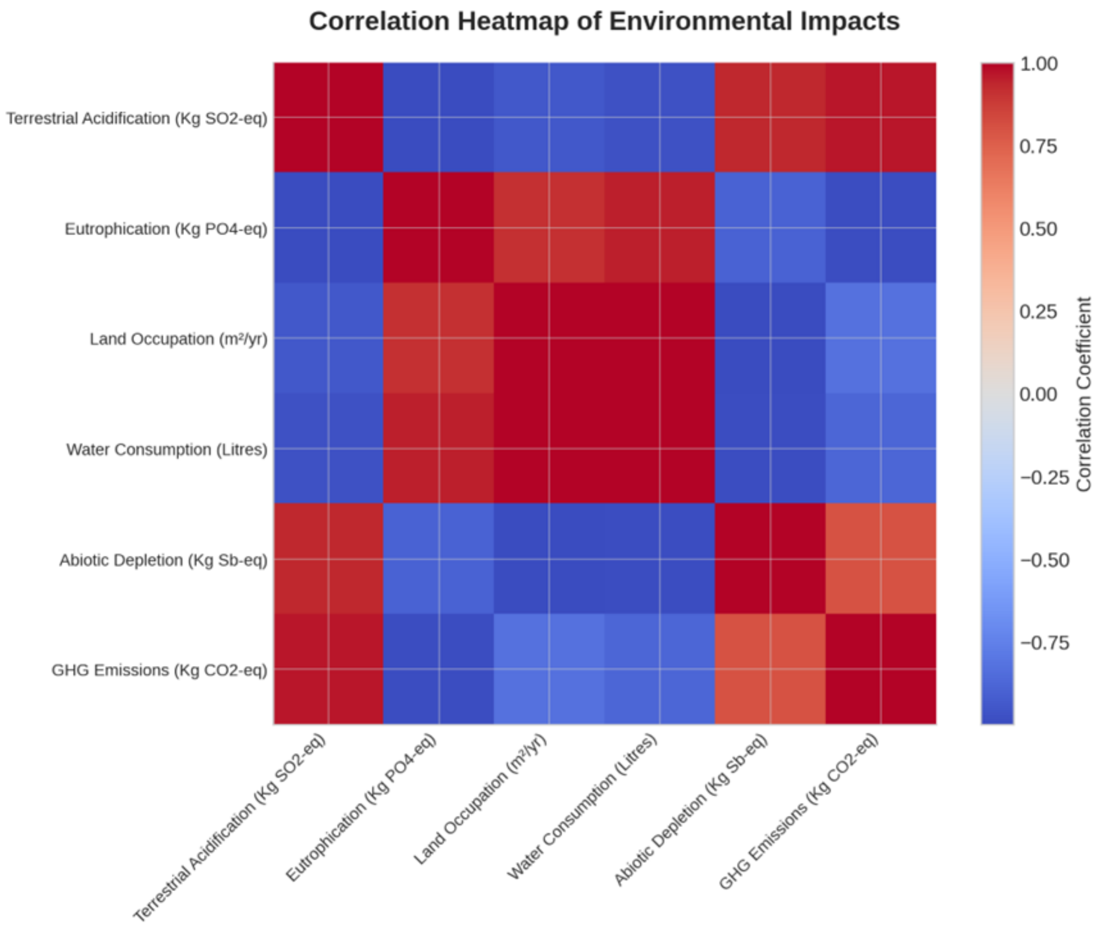

Figure 10. Correlation heatmap of the environmental impacts

Table 6. Environmental Impact of Green Denim Factories

Impact Category	Cotton Cultivation	Yarn and Fabric Manufacturing	Denim Trousers Production (Garment production)	Total	Unit
Terrestrial acidification	0.008	0.021	0.018	0.047	Kg SO_2 -eq
Eutrophication	0.0085	0.0066	0.0072	0.0223	Kg PO_4 -eq
Land occupation	7.5	2.1	1.3	10.9	M^2/yr
water consumption	2553.95	220.08	188.6	2962.63	Litres
Abiotic depletion	2.1×10^{-5}	8.03×10^{-5}	9.7×10^{-5}	0.000201	Kg Sb -eq
Greenhouse gas emissions (CO_2-eq)	1.10	6.7	4.1	11.9	Kg CO_2 -eq

Table 7. Comparative analysis of the environmental impact of scenarios S1 and S2

Impact Category	Regular Factories (S1)	Green Factories (S2)	Difference	Difference (%)	t_stat	p_value	Significance (p< 0.05)
Terrestrial Acidification (Kg SO_2-e)	0.087	0.047	0.04	46.0	2.21	0.035	Yes
Eutrophication (Kg PO_4-e)	0.048	0.0223	0.0257	53.5	3.12	0.015	Yes
Land Occupation (m^2/yr)	12	10.9	1.1	9.2	1.18	2.90	No
Water Consumption (Liters)	3780.52	2962.63	817.9	21.7	2.65	0.022	Yes
Abiotic Depletion (Kg Sb-e)	0.000305	0.000201	0.000104	34.1	2.98	0.010	Yes
GHG Emissions Potential (Kg CO_2-e)	33.4	11.9	21.5	64.3	4.56	0.002	Yes

Environmental Impact Comparison Between S1 and S2 Scenarios

The study evaluated the environmental impacts of denim production in two scenarios: conventional factories (S1) and green factories (S2). The results are presented across six impact categories: An accounting of terrestrial acidification, eutrophication, land occupation, water consumption, abiotic depletion, and greenhouse gas (GHG) emissions. The underlying factors that drive these differences are treated in more detail with numerical comparisons in Table 8. Figure 11 illustrates the comparative environmental impact assessment of green and regular denim factories.

From Table 7, we found that the results show significant reductions in environmental impacts in green factories compared to regular factories in all the key categories. All of these are statistically significant at the 0.05 level of significance: 46% decrease in terrestrial acidification ($p=0.035$), 53.5% decrease in eutrophication ($p=0.015$) and 21.7% decrease in water consumption ($p=0.022$). While land occupation fell by 9.2 per cent, that decline was not statistically significant ($p=2.90$). However, abiotic depletion is reduced by 34.1%, which is also substantial ($p=0.010$), and the most significant improvement was in GHG emissions, reducing emissions by 64.3%, highly substantial at $p=0.002$. Environmental impacts from emissions and resource use are found to be effectively reduced by green manufacturing practices.

Terrestrial Acidification: Fossil fuel emissions in yarn and fabric manufacturing contributed most to emissions in the S1 scenario at 0.087 kg SO_2-eq (39%) and (1.43 kg CO_2eq). On the other hand, the S2 scenario reduced the emission level by 46% (0.047 kg of SO_2-eq) compared with the S1 by utilising renewable energy sources and better fuel efficiency in green factories. Advanced energy systems operating in green factories, including high-efficiency boilers and low-emission machinery, have reduced acidifying emissions.

Eutrophication: Fertilizer application (0.048 kg PO_4-eq) during cotton cultivation was the main driver of the impacts from eutrophication in the S1 scenario. Organic farming methods and improved water treatment reduced these impacts by 53% (0.0223 kg PO_4-eq) through S2 green practices. Advanced dyeing systems in green factories minimise chemical discharge and deliver lower nutrient loads to wastewater.

Land Occupation: During cotton cultivation, both scenarios occupied significant amounts of land, although S2 outperformed S1 by a marginal 9%. Organic cotton farming techniques use similar land areas and spill less environmental burden, including land degeneration and biodiversity loss.

Water Consumption: In both scenarios, water consumption for cotton farming accounted for the largest share of total water use (92%), and S1 used 3,781 litres per pair of jeans versus 2,962 litres in S2. Goods produced in green factories resulted in the adoption of efficient irrigation methods and wastewater recycling, which is a 22% reduction. Even factory processes have improved, but the intense water use required for growing cotton persists, and a large amount of the cotton we produce needs to be drought tolerant and irrigated with drip technology.

Abiotic Depletion: In S1, impacts in abiotic depletion were more significant (0.000305 kg Sb-eq) than in S2 (0.000201 kg Sb-eq) due to decreasing reliance on fossil fuels from green factory integration with renewable energy sources and efficient energy systems.

Greenhouse Gas (GHG) Emissions: In S1, yarn and fabric manufacturing produced 56% (33.4 kg CO_2-eq) of total GHG emissions, while S2 reduced this to 64% (11.9 kg CO_2-eq). This reduction emerges from renewable energy integration and green processes with lower energy intensity.

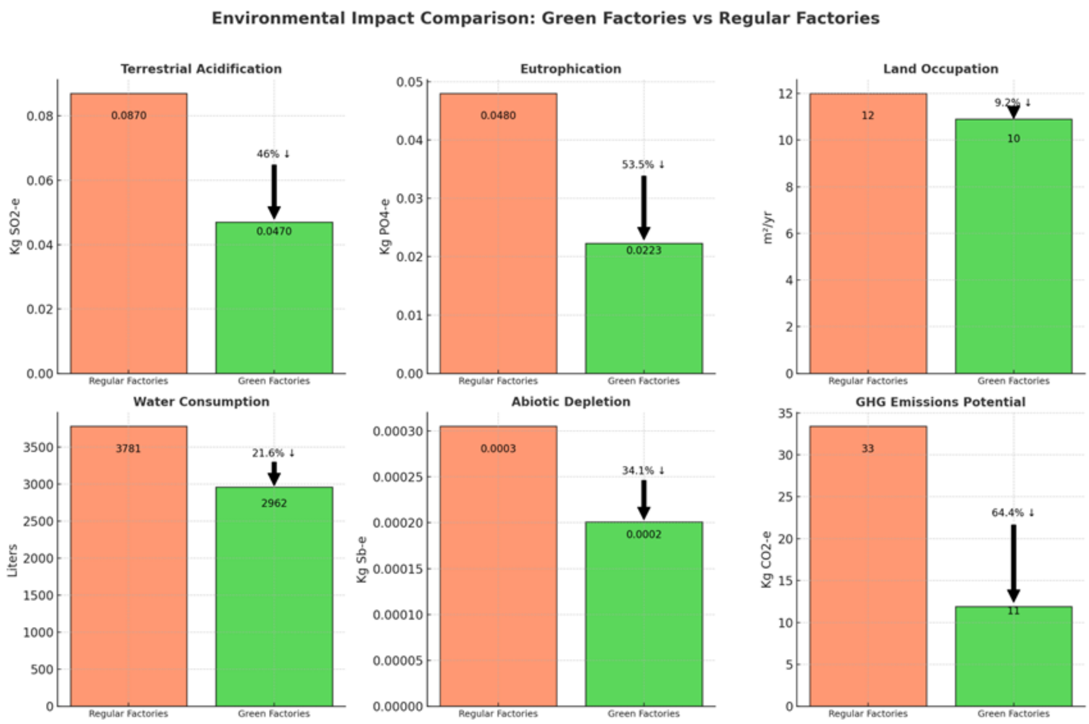

Figure 11. Environmental impact outcomes of the Green vs Regular denim factories

General Evaluation

This evaluation is based on this research investigation and from the factory and academic experts. Table 8 displays the general assessment of the study.

Table 8. General Evaluation of the study

Evaluation Aspect	Description
Comprehensive Perspective	The life cycle assessment thoroughly evaluates the environmental impact of denim trousers, covering all phases from raw material cultivation to point of sale. This offers a detailed understanding of the production process and its environmental implications.
Improvement Guidance	The findings offer direction for businesses and consumers to make sustainable choices, emphasising the reduction of energy consumption, water usage, and reliance on fossil fuels.
Importance of Sustainable Practices	Factories that are environmentally conscious and use state-of-the-art equipment can significantly reduce water usage, underscoring the need for sustainable manufacturing methods.
Sustainable Land Use	Recognising the impact of land occupation during the fibre cultivation stage highlights the importance of employing sustainable land use techniques in the denim industry.
Need for Continuous Improvement	These findings stress the importance of ongoing improvements and sustainable practices throughout the denim production process, from raw material cultivation to the final product production, to minimise the environmental footprint of denim trousers.

Sensitivity Analysis

Life Cycle Assessment (LCA) relies on sensitivity analysis to determine how input parameters affect research results. This analysis examines how significant variables affect environmental consequences such as greenhouse gas emissions, water consumption, and abiotic depletion to test the robustness of the denim production environmental evaluation. Changing input values in the sensitivity analysis reveals the study's reliability and the most critical factors impacting outcomes.

Key Parameters have been analysed below:

Water Consumption in Dyeing Processes

The water consumption rate for denim fabric was adjusted by ±30% to account for diverse dyeing procedures, including traditional and low-water technologies. The sensitivity analysis showed that water usage during the dyeing phase considerably impacts the water footprint of the denim production process. Efficient dyeing processes minimise water use by 30%, saving 20% from total consumption.

Energy Source and Consumption

Fossil fuels have been replaced with renewable energy for green manufacturing factories to assess greenhouse gas emissions. The analysis assumed 45% renewable energy from solar. Switching to renewable energy sources reduced greenhouse gas emissions by up to 35% compared to traditional energy use. A transition to renewable energy can significantly reduce the overall carbon footprint.

Chemical Usage

Denim dyeing and finishing chemicals were altered by ±25% to evaluate their impact on eutrophication and acidification. The sensitivity analysis showed that chemical usage directly affected eutrophication and terrestrial acidification. A 25% increase in chemical inputs increased eutrophication potential by 15%, while a reduction reduced nutrient discharge.

Cotton Sourcing and Agricultural

We compared the effects of utilizing organic and conventionally grown cotton for green manufacturing plants, considering pesticide and fertiliser input variations. When organic cotton was used instead of conventionally farmed cotton, the abiotic depletion potential was 18% lower, and the eutrophication potential was 25% lower. The key purpose of this is to decrease the use of synthetic pesticides and fertilisers. However, variations in cotton yields due to organic farming must be considered for a holistic view of sustainability.

Effluent Treatment Efficiency

Regarding water quality assessment, the performance of green and conventional factories' effluent treatment plants (ETP) varied between 60% and 85%. Increasing ETP effectiveness reduced eutrophication potential by roughly 40%. Investing in advanced effluent treatment technologies can dramatically reduce environmental consequences by reducing hazardous nutrients in water bodies.
The sensitivity analysis shows numerous key factors that affect denim production's environmental impact. Renewable energy, effective water management during dyeing, optimum chemical use, sustainable cotton procurement, and sophisticated effluent treatment technology reduce the most significant environmental impacts. Sensitivity analysis improves LCA results' robustness and helps explain environmental impacts. These analytics help denim stakeholders make sustainable production decisions.

Limitations of the Study

The study admits its shortcomings, specifically its exclusive emphasis on a few green denim facilities in Bangladesh, which may not indicate the broader sector. In addition, the study fails to consider sustainability's social or economic aspects when examining environmental consequences, emphasising the necessity of adopting a more comprehensive strategy to comprehend and fully enhance the denim sector's sustainability.

Future Studies

Subsequent research could prioritise methodological progressions, including the transportation of materials and the utilisation phase of denim into the life cycle assessment. This will provide a more thorough comprehension of the environmental repercussions. By investigating various LCA methodologies, such as hybrid approaches that integrate process and input-output analysis, it is possible to improve the precision and comprehensiveness of environmental impact assessments. Furthermore, doing a study encompassing several factories in various geographical regions would offer a more inclusive understanding of the environmental effect of the global denim industry. Furthermore, conducting studies on consumer behaviour and market trends related to sustainable denim could yield significant insights, directing the sector towards environmentally friendly methods that align with customer tastes and global sustainability objectives.

CONCLUSION

In this study, denim trouser production has been assessed in detail from an environmental point of view through a detailed life cycle assessment (LCA) of the impacts of denim trouser production in terms of conventional (S1) and green (S2) manufacturing scenarios in Bangladesh. Results show large environmental benefits in green factories: reductions in greenhouse gas emissions (64.3%), eutrophication (53.5%), terrestrial acidification (46%), water use (21.7%), and abiotic resource depletion (34.1%). The improvements in these facilities are due primarily to the adoption of advanced energy-efficient technologies, the integration of renewable energy and the use of wastewater recycling systems in green manufacturing facilities. However, key problems continue in cotton cultivation (92% of total water consumption), and intensive irrigation and fertilizer application contribute to considerable eutrophication and terrestrial acidification. As is the case with the garment manufacturing phase, a large portion of greenhouse gas (GHG) emissions (35% of total CO2-eq) still occurs in this phase, and there remains a great need for additional innovations, such as waterless washing and robotic cutting technologies.

The results indicate the great potential of green factories to reduce the environmental footprint of denim production significantly. Nevertheless, the study is limited to the cradle-to-gate lifetime analysis, omitting the life cycle impacts resulting from the product's transportation, usage, and disposal stages. Furthermore, the geographical focus in Bangladesh limits the generalisation of results to regions with different produced practices, energy fields, and resource availability. Future research will overcome these limitations by adopting a cradle-to-grave framework, examining mitigation strategies in cotton farming and considering multi-regional assessments to evaluate whether scaling up green manufacturing practices is possible globally. By advancing these insights, we have built a crucial foundation for the sustainability of the denim industry.

Authors Contributions

Conceptualisation – Hossain KR; methodology – Hossain KR and Rahman MF; formal analysis – Hossain KR and Rahman MF; investigation – Hossain KR and Rahman MF; resources – Hossain KR; writing-original draft preparation – Hossain KR; writing-review and editing – Hossain KR and Rahman MF; visualisation – Hossain KR; supervision – Hossain KR. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest. The authors confirm that there are no personal circumstances or interests that could have inappropriately influenced the representation or interpretation of the reported research results.

Funding

“The research is funded by Ahsanullah University of Science and Technology (AUST) Internal Research Grant (AIRG). Project ID: ARP/2022/TEX/03/10”

Acknowledgements

The authors would like to express gratitude to the Department of Textile Engineering at Ahsanullah University of Science and Technology for their cooperation.

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