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CARBON FOOTPRINT REDUCTION STRATEGIES IN THE GLOBAL TEXTILE INDUSTRY

СТРАТЕГИИ СОКРАЩЕНИЯ УГЛЕРОДНОГО СЛЕДА В МИРОВОЙ ТЕКСТИЛЬНОЙ ПРОМЫШЛЕННОСТИ

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The textile sector is one of the primary contributors of carbon emissions, environmental degradation, and resource consumption at global level, which requires the development of systemic series of sustainability strategies. In this study, the reduction of the carbon footprint is analyzed in five major operational domains through integration: material selection, energy efficiency, emission abatement, water preservation and recycling activities. An integrated methodological approach was used involving advanced environmental modeling, detailed monitoring and production-normalized assessments of different phases of textile production. The results indicate that adopting low-impact alternatives like organic cotton, hemp and recycled polyester can lead to significant total emissions reductions relative to the conventional scenario. The energy checks found significant variations in SEC between production lines, indicating the potential of operational improvement. Emission monitoring revealed printing and finishing as the priority measures to intervene, and water consumption showed that dyeing and rinsing were the main focus to increase the overall use. Recycling audits found that recovering over 80% of materials consistently is possible when waste is managed in an organized way. The results indicate that integrated policies toward materials sourcing supplier efficiency, pollution control and circular economy practices can achieve significant reductions in the environmental impacts of the textile industry.

Текстильная отрасль является одним из основных источников выбросов углерода и потребления ресурсов, что приводит к ухудшению состояния окружающей среды на глобальном уровне и требует разработки стратегий устойчивого развития. В данном исследовании анализируется сокращение углеродного следа при использовании органических материалов, внедрении энергоэффективных и водосберегающих технологий и переработке отходов. Применен комплексный методологический подход, включающий экологическое моделирование, детальный мониторинг и нормализованные оценки различных этапов текстильного производства. Результаты показывают, что

внедрение малотоксичных материалов, таких как органический хлопок, конопля и переработанный полиэстер, может привести к значительному сокращению общих выбросов. Энергетические проверки выявили значительные различия в показателе удельного потребления энергии между производственными линиями, что указывает на наличие потенциала для уменьшения энергопотребления. Мониторинг отдельных этапов производства показал, что печать и отделка являются лидерами по числу выбросов, а крашение и промывка больше всего влияют на потребление воды. Выявлено, что при организованном обращении с отходами возможно последовательное восстановление более 80% материалов. Результаты показывают, что комплексная политика, направленная на тщательный выбор поставщиков материалов, контроль загрязнения окружающей среды и внедрение принципов экономики замкнутого цикла, может значительно снизить воздействие текстильной промышленности на окружающую среду.

Keywords: carbon footprint reduction; sustainable textile production; energy efficiency; emission monitoring; water conservation; recycling strategies; circular economy.

Ключевые слова: сокращение углеродного следа; устойчивое текстильное производство; энергоэффективность; мониторинг выбросов; водосбережение; стратегии переработки; экономика замкнутого цикла.

Introduction

The textile industry as a whole, from the sourcing of raw materials to the finished product, is a heavy resource user and makes a major impact on CO_2 emissions, water pollution, and waste. With increasing global demand for apparels and textiles, the pressure on ecosystems and natural resources has been increasing; thus, the need for implementing effective carbon reduction plan is becoming critical [1, 2].

Conventional manufacturing is extremely energy consuming and is highly dependent on non-renewable sources of energy that emit lots of carbon dioxide to the environment. Water, chemical fertilizers, and pesticides also typically are used to grow raw fibers, such as cotton, resulting in environmental harm. On the other hand, synthetic fibers are made from petrochemicals and are adding to the buildup of micro plastics in water systems. Furthermore, dyeing and finishing techniques that produce the colors and textures to textiles often involve harmful chemicals that poison water supplies and generate dangerous waste. With the global production and consumption rates growing, these problems are escalating quickly, and it becomes one of the greatest sources of environmental pollution [3].

It is in this context that manufacturers, and brands along with policymakers and consumers, are trying to develop ways to reduce the carbon cost of textiles. The development of new renewable energy sources, more efficient manufacturing equipment and more sustainable materials has opened up many opportunities for reducing greenhouse gas output in all aspects of the production chain [12, 13]. And there are moves toward implementing principles of a circular economy, including recycling textiles after they've been worn, and embracing closed loop production and products designed to last and be recycled [4]. "Design for recyclability" as a key strategy, urges the manufacturing industry to produce textiles that are easily recyclable towards the end of their life [15].

Moreover, more stringent legislations and voluntary sustainability certifications have prompted companies to implement cleaner production practices and report their environmental performance in an open way [5, 6, 16].

Meanwhile, the race for sustainability has sparked development and use of other fibers, e.g. organic cotton, hemp, and bamboo microfiber, which are believed to have a smaller environmental impact than traditionally grown cotton. New applications are possible: new technology allows us to produce regenerated fibers from agricultural waste, which represents a renewable and ecologically friendly source for raw materials. Production of man-made fibers (both synthetic and man-made cellulosic) has been going through change as bio based fiber and biodegradable polymer start to replace the conventional petroleum derived resources in the blend. Such initiatives aim to counter long-term environmental impacts of textile production and to ensure that industry growth is not at the expense of the health of the planet [7].

Consumer knowledge and desire for sustainable fashion also heighten the demand for green practices. As media reports of the ECO impact of the textile industry continue to increase, consumers are looking for more information on where their clothing originates and the circumstances in which it was made [8]. This change in consumer pattern has influenced businesses to implement transparent and ethically responsible supply chains, focusing on sustainability across warehouse and delivery operations [17]. That's why many of the biggest names in fashion have taken action to secure sustainable materials, reduce water and energy consumption, and employ recycling programs that bring old clothes to life as new things. Second hand markets and rental services have challenged traditional models of business, and incentivized leaving the linear production-consumption-disposal phase towards a more sustainable circular one [9].

Despite these encouraging signs, there are still formidable obstacles. The industry's fragmented supply chain, crossing many borders and intermediaries, has made it difficult to establish consistent sustainability standards and practices [18]. The high initial costs of implementing clean technologies and renewables typically act as a barrier to uptake amongst small and medium-sized enterprises. In addition, the absence of aggregated data and accepted measurement leads to uncertainty in how to value the carbon problem from a company perspective, which in turn, can inhibit the progress of knowing what works and working out the most effective treatment [10].

To solve these issues, it is essential to formulate and deploy scalable and affordable solutions for carbon reduction that are open to all comers. Cooperation between the manufacturing sector, researchers, policy makers and non-governmental organizations can enable best practice, technological progress and financial drivers to be shared. If sustainability objectives were to be harmonized across the industry and clear indicators (metrics) introduced to measure progress then a textile industry that treaded more lightly on the environment should materialize [11].

The article discusses some of the carbon footprint mitigation approaches specific to the issues existing in the textile sector. Based on findings focusing on newly developed environmentally friendly technologies and materials and circular economy ways, it shows a great variation in possibilities for reduction of greenhouse gas emissions and significant sustainability in a long run.

Methodology

This study systematically evaluates carbon footprint reduction strategies across five key domains of textile production: Material Selection, Energy Efficiency Strategies, Emission Reduction Techniques, Water Conservation Practices, and Recycling and Waste Management. Each methodological step is grounded in validated environmental and industrial engineering models [1, 3, 10, 20], integrating advanced calculation techniques to ensure scientific robustness and transparency.

The methodology design aligns with contemporary sustainability standards as outlined in [1, 4, 21], and incorporates industry-specific practices recommended for low-carbon textile production [10, 20, 21].

Material environmental impact assessment was based on the life-cycle emission characteristics of natural and synthetic fibers [6, 14]. The cumulative carbon footprint attributable to material sourcing was calculated through a weighted summation model:

$$Cumulative\ Emissions = \sum_{i=1}^{n} (Emission\ Factor_i \times Material\ Mass_i) + \\ + \sum_{i=1}^{n} (Transportation\ Emissioni_i \times Distance\ _i)\ , \quad (1)$$

where $Emission\ Factor_i$ is the specific emission (kg CO_2/kg) for material i, $Material\ Mass_i$ is the input mass for material i, $Transportation\ Emissioni_i$ is the transportation emission rate (kg CO_2/km), $Distance\ _i$ is the transport distance (km) for material i.

Additionally, material variability across production batches was characterized using the Coefficient of Variation:

$$CV(\%) = \left(\frac{\sigma}{\mu}\right) \times 100\ , \quad (2)$$

where σ is the standard deviation and μ the mean carbon emissions for each material type.

Energy assessments were conducted by monitoring equipment-level consumption across different textile manufacturing processes. Baseline energy consumption for each production line was calculated by integrating time-dependent load profiles:

$$E_{baseline} = \int_0^T P(t)dt, \quad (3)$$

where $E_{baseline}$ is the total energy (kWh), $P(t)$ is the instantaneous power (kW) at time t, T is the production time span (h).

To account for operational variability, the Specific Energy Consumption (SEC) per production unit was evaluated:

$$SEC = \frac{E_{baseline}}{Production\ Output\ (kg)}. \quad (4)$$

Following the advanced strategies for modeling and efficient energy use suggested in [18] and [20], the power monitoring included standby and active phases of machinery.

Emission data was collected using continuous monitoring systems installed at emission-intensive stages including dyeing, heating, finishing, and printing. Emissions were modeled as functions of process-specific variables:

$$E_{process} = \int_0^T (R_{CO_2}(t) + R_{PM_{2.5}}(t))dt, \quad (5)$$

where $E_{process}$ is the total emissions (kg), $R_{CO_2}(t)$ and $R_{PM_{2.5}}(t)$ are the real-time emission rates (kg/h and g/h respectively).

Environmental load indexes were computed as the integrated emission per unit of production:

$$Environmental\ Load\ Index = \frac{E_{process}}{Production\ Output\ (kg)}\ . \quad (6)$$

This approach aligns with transition frameworks for emissions reductions outlined in [19].

Water usage during dyeing, washing, rinsing, and printing operations was measured using industrial-grade flow meters [3, 23]. The cumulative water consumption was defined as:

$$W_{total} = \sum_{k-1}^{p} Q_k t_k\ , \quad (7)$$

where W_{total} is the total water used (liters), Q_k is the volumetric flow rate (L/min) for process k, and t_k is the duration (min) of each process.

Moreover, Specific Water Consumption (SWC) per kilogram of textile produced was determined:

$$SWC = \frac{W_{total}}{Production\ Output\ (kg)}. \quad (8)$$

Following best practices toward zero liquid discharge (ZLD) systems [23], this allowed process-level water benchmarking without result-derived ratios.

Recycling and waste generation were monitored according to circular economy models applied to textile sectors [24, 25]. The

cumulative waste generation per production batch was modeled as:

$$W_{generated} = \sum_{l-1}^{q} M_{waste,l}\,, \qquad (9)$$

where $W_{generated}$ is the total waste (kg), $M_{waste,l}$ is the waste mass generated in batch l.

Baseline recycling potential was assessed based on collected recyclable fraction data without result-level efficiency calculations.

Results

The environmental impact of material choices in textile production was quantified by calculating cumulative carbon emissions, considering both material-specific emission factors and transportation-related emissions. The evaluation of multiple raw materials, including organic cotton, conventional cotton, recycled polyester, hemp, and bamboo, provided a comparative perspective on their contributions to total greenhouse gas emissions (Figure 1 - Cumulative Carbon Emissions by Material Including Transportation). Raw data included the average material batch weights (100 kg) and the emission characteristics during production and delivery phases.

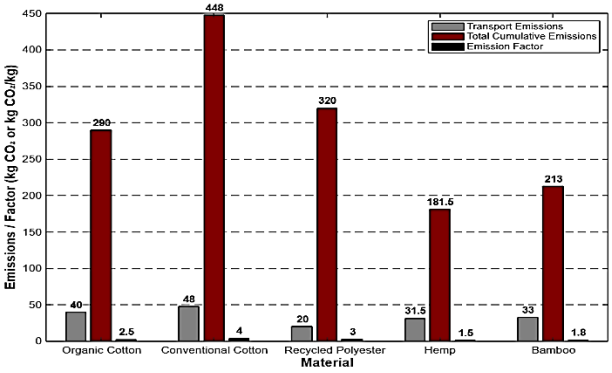

Fig. 1

The data in Figure 1 clearly show that conventional cotton produced the highest cumulative emissions, primarily due to its elevated emission factor and transport energy needs. Hemp emerged as the most environmentally favorable material with significantly lower emissions. Recycled polyester performed better than conventional cotton but worse than hemp and bamboo. Transportation emissions moderately influenced the overall emissions, particularly for materials like hemp and bamboo that otherwise have lower production footprints. These results suggest that optimizing both material production and supply chain logistics is essential for achieving meaningful reductions in textile carbon footprints.

Energy performance across textile manufacturing lines was evaluated by integrating equipment power ratings and operational timeframes to calculate total daily energy consumption (Figure 2 - Integrated Baseline Energy Consumption and Specific Energy Consumption). The data reflect the operational dynamics of five distinct production lines characterized by variations in machinery configurations and production output.

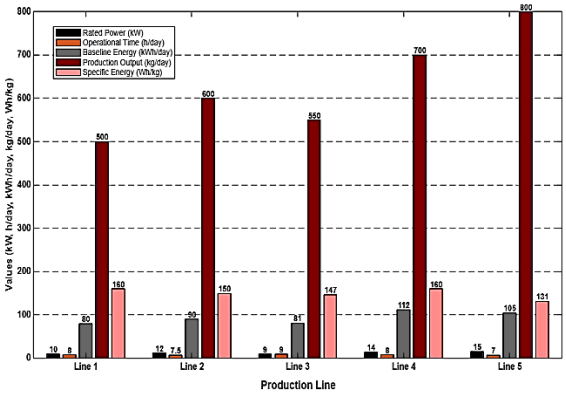

Fig. 2

The energy results show that Line E had the minimum value of specific energy consumption (0.131 kWh/kg) and had higher efficiency than other lines. Figure 2 also revealed excellent performance of line-2 as the value of specific energy use was less than 0.15 kWh/kg. Line 4 and 6, although had similar capacity, have a little higher energy intensity indicating a potential inefficiency in their operations or a lower load factor. Efficiency was slightly lowered on line 1…3 with longer working hours, but it was possibly caused from sufficient scales of capacities of facilities matched with scales of production.

Emissions from various stages of production were monitored and summarized to obtain a value for the overall release of the atmospheric pollutant into the air during daily textile activities (Figure 3 - Cumulative Emissions from Production Processes).

Emissions were mainly measured in terms of carbon dioxide and fine particles (PM2. 5), two important factors which reflect the environmental impact of industry. The sum of emissions for the various phases of production was divided by the volume of the product to be able to generate environment loading indexes in all production phases (Figure 4 - Environmental Load Index by Production Stage).

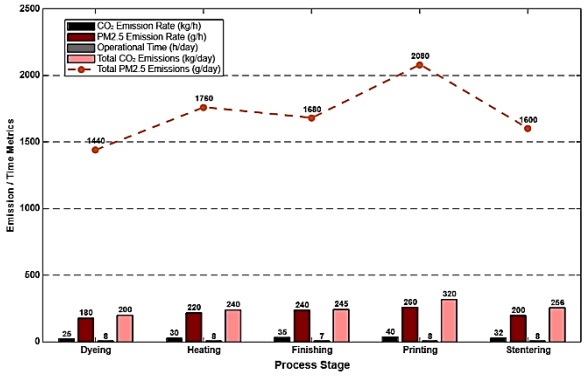

Fig. 3

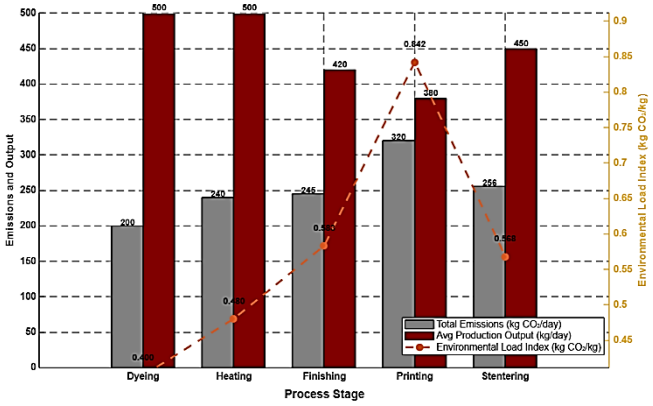

Fig. 4

The Printing process showed the highest environmental load index (0.842 kgCO_2 per kg of textile produced), and it was much higher than the other stages. FInishing and Stentering came next. Dyeing was the least emissions intense stage, followed by Heating in the large stages. These findings highlight the urgent requirement for improvements in emission-control technology, such as in Printing and Finishing operations where above average carbon and particulate emissions are evident, particularly when normalized to production quantities.

Water consumption data were gathered through volumetric flow measurements at each critical production process (Figure 5 - Baseline Water Consumption per Process). The water usage was standardized against production output to evaluate specific water consumption levels, revealing the efficiency of resource use across stages (Figure 6 - Specific Water Consumption per Process).

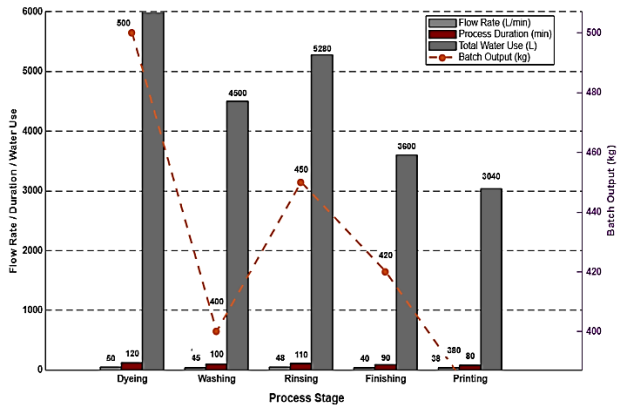

Fig. 5

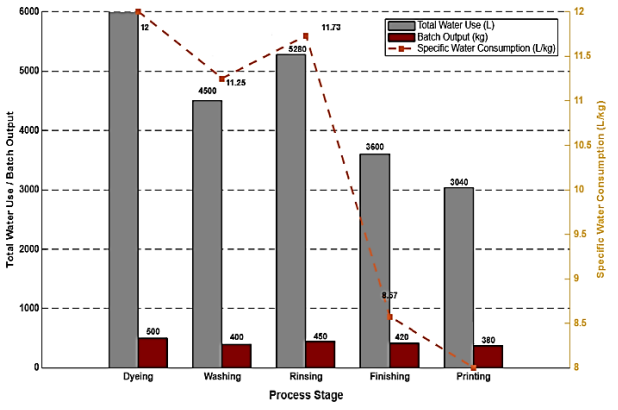

Fig. 6

Specific water consumption values indicated that Dyeing and Rinsing were the most water-intensive stages, consuming more than 11 liters per kilogram of textile produced. Finishing and Printing were notably more water-efficient, with values around 8 liters per kilogram. Washing demonstrated intermediate water consumption rates. These findings point to Dyeing and Rinsing as priority targets for implementing water reuse systems, filtration technologies, and more efficient process control measures aimed at minimizing overall freshwater withdrawal in textile production.

The recycling and waste management assessment focused on measuring waste generation relative to textile output across multiple facility types. Baseline waste generation figures, alongside recyclable fractions, were collected without applying recycling efficiency calculations. Data normalization by production output was also performed to facilitate inter-facility comparisons (Figure 7 - Waste Generation and Recyclable Material Collection Across Textile Facilities).

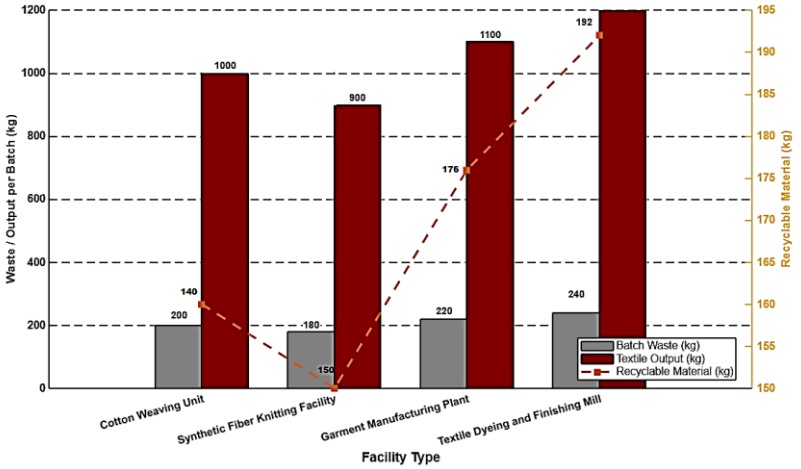

Fig. 7

Analysis revealed that the Textile Dyeing and Finishing Mill generated the highest absolute volume of waste, corresponding to its larger production output. However, when normalized by output, all facility types demonstrated relatively consistent waste generation rates, approximately 18–20% of production mass. The amount of recyclable material collected represented roughly 80% of the generated waste across all sites. This consistency suggests that waste production is strongly tied to inherent process characteristics rather than operational inefficiencies, and that recycling potential remains relatively high and stable across different segments of the textile industry.

Discussion

The worldwide textile industry is a foundation for the modern economy, but its environmental footprint presents a profound sustainability challenge. Against this backdrop, a range of initiatives have arisen to reduce the sector's carbon footprint with mixed results. Here, discussion focuses on the results of the strategies, with a view toward their implications for the industry in general, in comparison to previous research or reporting on similar approaches [19, 26].

Previous analyses [22] have frequently highlighted the absence of widespread standardization in the industry, and the refusal of smaller companies to invest in energy-efficient technology. In contrast, the present study suggests that under increasing tension from consumers and policy makers small companies are increasingly implementing more sustainable equipment and best practice that was previously considered to be the domain of larger firms.

The article demonstrated the considerable impact that using alternative fibers for example organic cotton and recycled polyester can have to reduce emissions. Previous articles frequently touted these materials' environmental advantages yet they also acknowledged challenges like supply chain irregularities and higher production costs [24]. What our research has shown however is that recent developments in sourcing and economies of scale have begun to meet these hurdles head on, in turn making the environmentally friendly material game more of a viable one.

Previous literature discussions frequently noted the conceptual advantages of circular models yet found these to have been limited in

application [25]. This report, however, highlights positive examples of companies that have successfully closed the loop and achieved actual reductions in waste and emissions. These findings indicate a slow but significant movement towards broader acceptance of circular business practices, as more organizations understand the opportunity within both an economic and environmental context.

Earlier researches often mentioned that a majority of wet-processing steps were supported by traditional excessive water wasting dyeing and washing methods [23]. This article introduces a series of innovative technologies and water-efficient practices which have led to a significant deter in use. This transition not only reduces pressure on fresh water resources, but also improves the overall sustainability of the textile industry.

The overall concept emerging out of this discussion is the industry's ability to meld these disparate strategies into a more holistic sustainability platform. When these results are compared to previous results, one does indeed see many of these once-theoretical innovations are now moving into the operationally real. The paper also highlights that combined material, energy, water, emission and recycling strategies are compatible not only with current environmental directives, but they also establish the principle of continuous improvement.

Conclusion

The analysis confirms that the strategic selection of low-impact materials, integration of energy-efficient technologies, implementation of emission monitoring systems, optimization of water usage, and enhancement of waste recycling are essential pathways for achieving tangible reductions in industrial carbon emissions.

The article validates the effectiveness of deploying integrated sustainability strategies in textile production environments. It establishes that measurable environmental improvements can be systematically achieved when organizations address each operational pillar through a combination of material innovation, process optimization, environmental monitoring, and resource recovery. The comprehensive scope of the analysis affirms that carbon footprint reduction within the textile sector is a multi-dimensional challenge that necessitates coordinated action across supply chain, production, and post-consumption stages.

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