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Sustainable Innovations in Cotton Spinning: From Raw Fiber to Eco-friendly yarn

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ABSTRACT

The cotton spinning industry is a cornerstone of the global textile sector, supplying yarns that form the basis of apparel, home textiles and industrial fabrics. However, conventional cotton spinning is associated with significant environmental challenges, including excessive water and energy consumption, heavy reliance on agrochemicals and high levels of waste generation. In response to increasing environmental concerns, regulatory pressures and growing consumer demand for sustainable products, the cotton spinning industry is undergoing a fundamental transformation. This review paper provides a comprehensive analysis of sustainable innovations in cotton spinning, covering the entire production chain from raw fibers cultivation to eco-friendly yarn manufacturing. Emphasis is placed on sustainable cotton farming, advanced spinning technologies, environmentally responsible processing techniques, waste reduction strategies and the development of sustainable yarn products. The paper highlights how technological innovation and responsible management practices can reduce environmental impact while maintaining productivity, yarn quality and economic viability.

Keywords: *Sustainable, Innovations, Cotton Spinning, Raw Fibe, Eco-friendly yarn*

Introduction

Cotton is one of the most widely used natural fibers in the world due to its comfort, breathability and versatility. The spinning process, which converts raw cotton fibers into yarn, is a critical stage in textile manufacturing. Despite its importance, traditional cotton spinning practices have long been criticized for their environmental footprint. Intensive cotton cultivation consumes large volumes of water and agrochemicals, while spinning mills require substantial electrical energy and generate waste in the form of short fibers, dust and emissions (Kılıc *et al*., 2020).

Cotton cultivation is vital for mankind but it has severe environmental impacts. Runoff from cotton fields contains harmful pesticides and fertilizers those pollute water systems like rivers, lakes, marine beaches and also underground aquifers (Ütebay *et al*., 2019). Other than cotton cultivation, the textile industry is a large source of pollution and a waste generating sector in the world (Stanescu, 2021). Textile waste is produced in every phase of the textile manufacturing process, viz. spinning, weaving, knitting, dyeing, finishing, garment manufacturing and even at the consumer end (Jamshaid *et al*., 2021). In addition, with rapid growth and evolution in fashion trends along with the fast throwaway culture of the new generation, textile production and waste generation rates have increased substantially over the last decades (Sun *et al*., 2021; Rahman*et al*., 2022). Globally, around 87% of total discarded textiles, of which around 90% are reusable and recyclable, ended up through landfill or incineration creating a serious environmental threat (Moazzem *et al*., 2021).

Table .1: Properties of knit fabrics produced from rotor and ring yarn

Properties	Rotor yarn	Ring yarn
Moisture vapor transmission rate (g/m^2/24 h)	6.31–8.81	7.25–9.46
Water vapor permeability (kg/m^2 s Pa)	0.142	0.131
Thermal insulation (Km^2/W)	4.54	4.88
Low-stress compression resilience (%)	7.71	4.47

Based on the reported differences in yarn structure and spinning mechanisms discussed in the literature, noticeable variations in knitted fabric properties can be expected between rotor and ring spun yarns. Table 1(Gedilu *et al*., 2022; Jhanji, Yetal., 2021) summarizes the key comfort and mechanical properties of knitted fabrics produced from these two spinning systems. Fabrics made from ring spun yarns generally exhibit higher moisture vapor transmission and better thermal insulation, which can be attributed to improved fiber migration, lower twist levels and more compact yarn structure. In contrast, rotor spun yarn fabrics show comparatively higher compression resilience, owing to their bulkier structure and the presence of wrapper fibers. These observations are consistent with previous studies reporting that rotor yarns, particularly those containing recycled fibers, tend to be stiffer and less moisture absorbent, whereas ring spun yarns provide softer and more breathable fabrics suitable for apparel applications.

In recent decades, sustainability has emerged as a central theme in textile production. Governments, environmental organizations and consumers are increasingly demanding cleaner production methods and transparent supply chains. As a result, cotton spinning mills are adopting innovative technologies and sustainable practices to reduce resource consumption,

minimize waste and lower greenhouse gas emissions. This review paper explores these developments and evaluates their role in shaping a more sustainable future for the cotton spinning industry. Blend yarns from pre and post consumer recycled cotton and virgin cotton were manufactured in ring spinning line following the steps given in Figure 1:

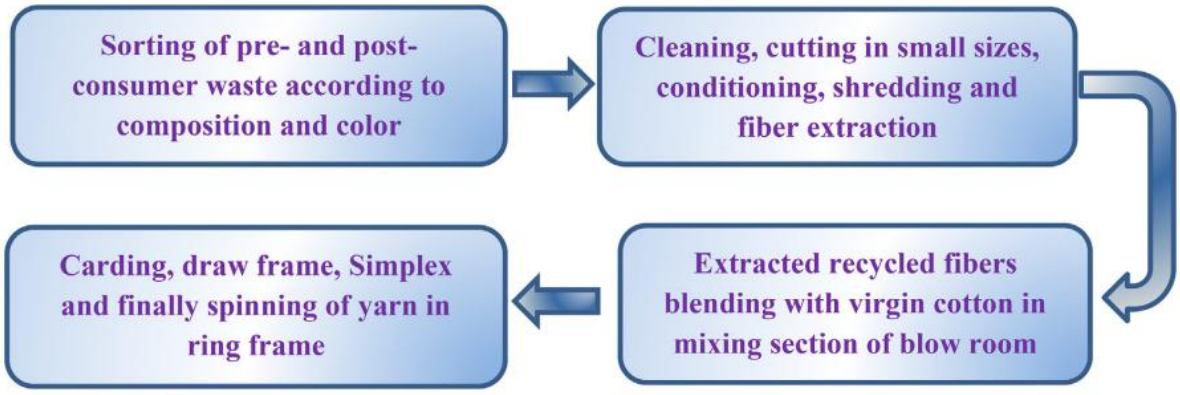

Figure.1. Flow chart of manufacturing ring spun yarns from blends of virgin cotton and recycled cotton fibers extracted from pre and postconsumer textile wastes. (Ernst, 2014)

Apparel manufacturers nowadays want sustainable and eco friendly yarns containing recycled fibers to produce knit top garments like T shirts and polo shirts. In this case, improved wear ability such as a smooth and soft feel with high moisture absorbency of yarns is desirable. Such yarns can be produced in ring spinning system with lower twists with careful controlling of balloon tension due to the existence of recycled short fibers. Utilizing recycled cotton fibers obtained from pre- and postconsumer yarn and fabric wastes, the current attempt was undertaken to manufacture medium count yarn in ring spinning frame with a lower twist suitable to produce knit top garments useful for all users irrespective of age and gender (Shaikh and Bhattacharya, 2016).

Environmental Challenges in Conventional Cotton Spinning

Before discussing innovations, it is important to understand the key environmental issues associated with traditional cotton spinning:

1. High water consumption during cotton cultivation and fiber processing
2. Excessive use of pesticides and fertilizers, leading to soil degradation and water pollution
3. High energy demand in spinning machinery, especially in ring spinning systems
4. Solid waste generation, including droppings, fly and hard waste
5. Air pollution and dust emissions, affecting worker health and environmental quality

These challenges have driven the need for sustainable alternatives across the entire cotton spinning value chain (Sandin and Peters, 2018).

Sustainable Raw Fiber Production

Organic Cotton Farming

Organic cotton production is one of the most significant innovations in sustainable fiber sourcing. It avoids synthetic pesticides, chemical fertilizers and genetically modified seeds. Instead, it relies on natural pest control, crop rotation and organic manure. Organic farming improves soil structure, enhances biodiversity and reduces water pollution. Although organic cotton yields are often lower than conventional cotton, the environmental benefits and growing market demand make it an important sustainable option (Wanassi *et al*., 2018).

Better Cotton Initiative (BCI)

The Better Cotton Initiative represents a practical and scalable approach to sustainability. It encourages farmers to adopt responsible practices such as efficient water management, reduced chemical usage and improved labor conditions. BCI cotton is not fully organic but significantly reduces environmental impact compared to conventional cotton. Its wide adoption makes it particularly relevant for large scale spinning industries (Lawrence, 2010).

Regenerative and Climate Smart Agriculture

Emerging approaches such as regenerative agriculture focus on restoring soil health, increasing carbon sequestration and improving ecosystem resilience. Climate smart cotton farming aims to reduce greenhouse gas emissions while adapting to climate variability. These methods are gaining attention as long term sustainable solutions (Almetwally *et al*., 2014).

Cotton Fiber Recycling

Recycling cotton waste from spinning mills, garment factories and postconsumer textiles plays a crucial role in sustainability. Mechanical recycling converts cotton waste into reusable fibers, while chemical recycling dissolves cellulose to produce regenerated fibers. Recycled cotton reduces demand for virgin cotton, conserves water and lowers energy consumption (Regar *et al.*, 2017).

Innovations in Sustainable Spinning Technologies

Compact Spinning Technology

Compact spinning is an advanced modification of ring spinning that condenses fibers before twisting. This results in stronger yarns with lower hairiness and reduced fiber loss. Compact spinning improves raw material utilization and reduces waste, making it a more sustainable alternative to conventional ring spinning (Haleem and Wang, 2015).

Energy Efficient Ring Spinning Systems

Modern ring spinning machines are equipped with high efficiency motors, optimized spindles and intelligent control systems. These upgrades significantly reduce electricity consumption and maintenance requirements. Energy monitoring and automation further enhance efficiency (Islam and Uddin, 2022).

Table .2: Efficiency and end breakage rate during ring spinning.

Variables	Virgin cotton	Pre-consumer recycled yarn				Post-consumer recycled yarn			
		10%	20%	25%	30%	10%	20%	25%	30%
Efficiency (%)	95.2	93	92.2	91.6	91	92.8	91.9	91.3	89.5
End breakage%/100 spindle per hr	3.95	4.05	4.15	4.61	4.83	4.25	4.45	5.05	5.18

The tenacity of yarns produced from blends of virgin cotton/recycled cotton decreases proportionally with the increase of recycled fiber% in yarn and the rate of decrease is higher in the case of postconsumer recycled fibers. The strength of the yarns was found to have reflected in the efficiency and end breakage rate of the ring spinning as shown in Table 2. (Oner *et al*., 2019).

Rotor (Open End) Spinning

Rotor spinning eliminates several preparatory processes and offers high production speeds. It consumes less energy per kilogram of yarn compared to traditional ring spinning and efficiently

utilizes recycled fibers, making it suitable for sustainable yarn production. (Ray *et al*., 2018; Lawrence 2010).

Air Jet and Vortex Spinning

Air jet and vortex spinning technologies use air streams to bind fibers instead of mechanical twisting. These systems offer very high productivity, reduced energy usage and minimal fiber waste. Although yarn structure differs from ring spun yarn, these technologies are ideal for specific sustainable applications. (Garside, M., 2020).

Eco friendly Processing Techniques in Cotton Spinning

Enzyme Based Fiber Processing

Enzymes are biodegradable and operate under mild conditions. They replace harsh chemicals used in de sizing, scouring and fiber cleaning. Enzyme treatments improve fiber quality, reduce processing time and minimize effluent pollution (Thilagavathi and Karthik, 2016).

Ozone Processing Technology

Ozone is a powerful oxidizing agent used for fiber treatment with minimal water consumption. Ozone processing significantly reduces chemical use and energy demand, making it an environmentally friendly alternative to conventional wet treatments (Wanassi *et al*., 2018).

Ultrasound Assisted Processing

Ultrasound technology enhances chemical penetration and reaction efficiency through cavitation. This reduces processing time, water usage and chemical concentration while improving fiber uniformity and yarn quality (Chattopadhyay and Sinha, 2007).

Waste Management and Circular Economy in Spinning Mills

Sustainable cotton spinning increasingly follows circular economy principles. Waste fibers generated during carding, drawing and spinning are reused in lower count yarns or blended products. Dust and fly control systems improve air quality and worker health. Efficient waste segregation and recycling reduce landfill disposal and operational costs. (Memon *et al*., 2022)

Sustainable Yarn Products and Market Trends

7.1 Recycled Cotton Yarns

Recycled cotton yarns are widely used in denim, knitwear and home textiles. They significantly reduce environmental impact and align with circular fashion trends. (Awgichew *et al*., 2021).

Organic Cotton Yarns

Organic cotton yarns are preferred for baby wear, medical textiles and premium apparel due to their chemical free nature and skin friendly properties. (Regar *et al*., 2017).

Biodegradable and Bio based Yarns

Biodegradable yarns made from natural fibers decompose at the end of their life cycle, reducing long term environmental pollution. These yarns support sustainable and ethical fashion movements. The correlations and significance of paired samples such as the amount of recycled fiber% of pre and postconsumer recycled blend yarns with various yarn parameters. A positive correlation was found between recycled fiber% and yarn unevenness i.e., with the increase of pre consumer recycled fiber%, yarn unevenness increased, as seen in Figure 2 (Ray *et al*., 2018).

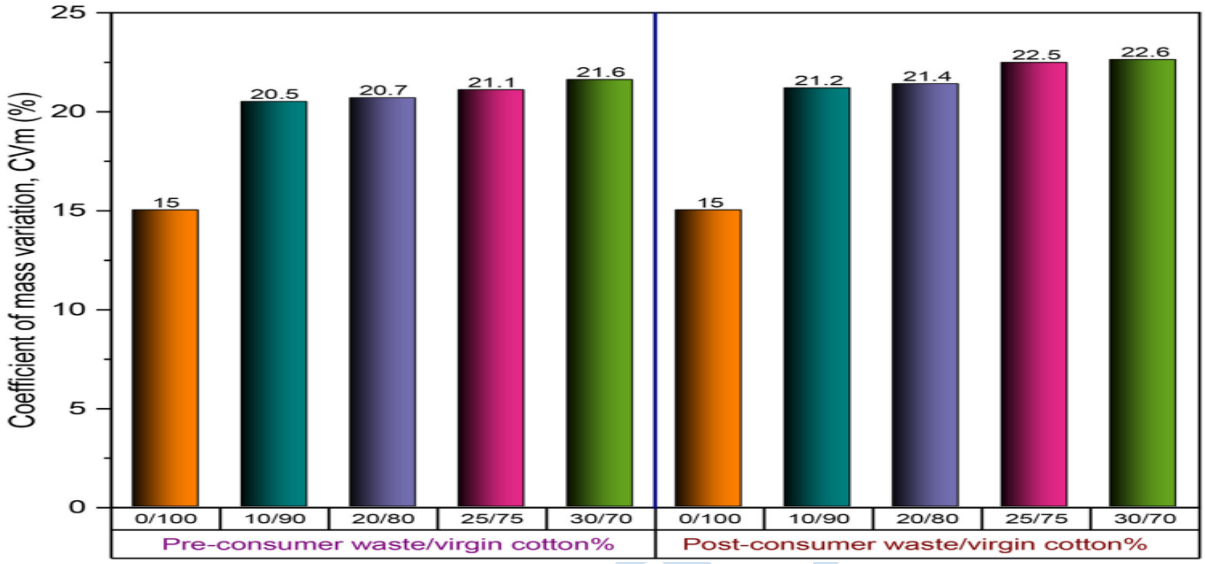

Figure.2. Coefficient of mass variation (CVm%) of 30 Ne ring yarn produced from pre and postconsumer recycled cotton and virgin cotton with different blend ratios.

Economic and Social Impacts of Sustainable Cotton Spinning

Sustainability in cotton spinning is not limited to environmental benefits. It also improves worker safety, creates better livelihoods for farmers, enhances brand reputation and opens access to international eco certified markets. Although initial investment costs may be high, long-term savings and market advantages justify sustainable adoption. Sustainable spinning also increases the market value of yarn by enabling premium pricing and access to eco certified international markets (Parsi *et al*., 2016).

Challenges in Implementing Sustainable Innovations

Despite progress, several challenges remain:

1. High initial investment in advanced machinery
2. Limited availability of organic and recycled fibers
3. Technical limitations in recycling fiber quality
4. Lack of awareness and skilled workforce in some regions

Addressing these challenges requires policy support, industry collaboration and continuous research.

Future Research Directions

Future research should focus on:

1. Improving fiber recycling technologies
2. Developing low energy spinning systems
3. Life cycle assessment (LCA) of cotton yarn production
4. Integration of digitalization and Industry 4.0 for sustainability

Conclusion

Sustainable innovations in cotton spinning are transforming the textile industry by addressing environmental, economic and social challenges. From responsible raw fiber production to advanced spinning technologies and eco friendly processing methods, the industry is steadily moving toward sustainability. Continued investment in research, technology and sustainable practices will be essential to ensure the long-term viability of cotton spinning in a resource

constrained world. Concerning the strength of yarns, lower yarn strength resulting from the addition of recycled fiber may slightly shorten the lifespan of the produced garments. A slightly shorter lifespan of garments can be mitigated by the benefit of sustainable raw material utilization in producing fancy yarn. Consumers these days are aware of the negative impacts of purchasing items that are not produced sustainably or ethically.

Final Statement

"Sustainable cotton spinning represents a holistic approach that integrates environmental responsibility, technological innovation and economic efficiency to produce eco friendly yarns for a sustainable textile future".

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