ADVANCE SOCIAL SCIENCE ARCHIVE JOURNAL
Available Online: https://assajournal.com
Vol. 05 No. 01. Jan-March 2026.Page#.508-515
Print ISSN: 3006-2497 Online ISSN: 3006-2500
Platform & Workflow by: Open Journal Systems

Digitalization and Automation in Cotton Spinning: A Review of Industry 4.0 Applications

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ABSTRACT

The advancement of industry 4.0 has significantly transformed the textile sector by introducing digitalization and automation into manufacturing process. Cotton spinning being a fundamental stage of textile manufacturing is increasingly adopting industry 4.0 technologies to improve productivity, yarn quality and operational efficiency. These technologies include the Internet of Things (IoT), artificial intelligence (AI), data analytics, automation, robotics and smart monitoring systems. Their application across different spinning processes enables real-time data exchange, enhanced product control, reduced fiber damage and increased production output. This review paper examines and synthesizes existing literature on the implementation of industry 4.0 in cotton spinning, highlighting both technological advancements and their industrial impact. Despite the significant benefits, challenges such as high initial investment costs, complex system integration, data management issues, and the requirement for the skilled manpower remain major barriers to widespread adoption. Overall the review indicates that Industry 4.0 plays a crucial role in the transition of conventional spinning mills toward smart, efficient and data driven manufacturing systems.

Keywords: Industry 4.0, Cotton Spinning, Textile Industry, Automation, Optimization, Internet of Things, Robotics, Digitalization, Working Efficiency, Cloud Computing, Big Data.

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1. Introduction

The world population has very recently crossed the unbelievable fi gure of 7 billion people. The essential needs of humans include food and clothing, so the textile and clothing industry forms an integral part of the way mankind deals with such a huge population (Shishoo 2012). The term textile is a Latin word originating from the word "Texere" which means "To Weave". Textile refers to a flexible material comprising a network of natural or artificial fibers, known as yarn (Textile, 2010).

Textile industry is one of the few basic industries that have always been a necessary component of human life (Papoutsidakis, 2019). Spinning unit is a major component of the textile industry; it transforms many fibers into a long, continuous yarn by twisting them (fibers) which is later woven into apparel products in the garments manufacturing unit (Lawrence, 2015). Different types of fibers are used to produce yarn.

Cotton is the most widely used and common natural fiber used in the textile industry. To achieve high quality yarn, raw cotton undergoes multiple processing stages using specialized equipment.

Industry 4.0 (I4.0) refers to a new phase in the Industrial Revolution (Nagesh, 2022). Industry 4.0 (I4.0) transforms the business functions and growth by not only investing in new technology and tools to boost industrial efficiency. It also emphasizes an interconnectivity, automation, machine learning, and real-time data that are the parts of the Industrial Revolution. Technologies like robotics, automation, IoT, and AI have streamlined production, enabled predictive maintenance, and improved quality control (Elkateba, 2023). Industry 4.0 technologies such as cyber-physical systems and horizontal integration create smart factories that improve production flexibility and digital connectivity across the textile value (Mushtari, 2022).

2. History of industrial revolution

The industrial revolution marks the most fundamental transformation of human life in the history of the world recorded in written documents. In history, different industrial revolutions changed the production paradigm and, beyond industries, impacted the way of life (Klingenberg, 2022). The textile industry has developed over time from small-scale domestic production to highly mechanized and digitally controlled manufacturing. In the early days, textile production was mainly done at home, with spinning and weaving carried out manually within cottage industries. The First Industrial Revolution (around 1760-1840) brought major changes through mechanization. New machines for spinning and weaving, powered by water and steam, allowed production to move from homes to factories. This change greatly increased productivity and marked the shift from handmade textiles to factory-based manufacturing (Mohajan, 2019; Jonell et al., 2024).

The Second Industrial Revolution (roughly 1870-1914) further transformed textile production through the use of electricity. Electrical power improved machine efficiency, allowed factories to be arranged more flexibly, and supported continuous mass production. These changes made textile manufacturing faster and larger in scale, establishing the industry as a key part of industrial economies (Kim, 2023).

In the mid-twentieth century, the Digital Revolution, also called the Third Industrial Revolution, introduced computers, automation, and information technology to manufacturing. In textiles, technologies such as computer-aided design, programmable logic controllers, and digital monitoring systems improved precision, efficiency, and control in production. These innovations changed traditional manufacturing methods and laid the foundation for modern smart and digitally connected textile systems (Akhtar et al., 2022; Jeong, 2023).

2.1. Understanding industry 4.0: A new era of manufacturing

In the year 2000, the Fourth Industrial Revolution began, which is popularly known as Industry 4.0 (Nagesh, 2022). It entails a shift from conventional, labor-intensive production methods to smart manufacturing techniques such as automation, real-time data exchange, interconnected and intelligent systems, decentralized decision- making. Industry 4.0 has brought the 'smart factory' into existence in which smart digital services are networked and they communicate with raw materials, semi-finished products, machines, tools, etc (Frank, 2019).

Prior to industry 4.0, manufacturing systems relied heavily on centralized control and manual supervision. But now the system has become automatic. The adoption of Industry 4.0 within textile manufacturing not only improves operational efficiency but also aligns with the increasing consumer demand for sustainable, high-quality products. Despite these benefits, practical adoption in textile remains limited, highlighting a gap between conceptual readiness and industrial implementation (Haq, 2025).

3. Industry 4.0 technologies in cotton spinning

One of the key components of Industry 4.0 in spinning is the integration of digital technologies throughout the production process.

3.1 IoT (Internet of Things)

The Internet of Things abbreviated as IoT. Within IoT technology, a network of physical devices, referred to as "things" linked to the internet. Devices with processors, sensors and communication hardware gather, exchange data through edge computing, facilitating seamless interaction with other systems. IoT is one of the nine pillars that make up the Industry 4.0 (I4.0) revolution, according to Boston Consulting Group (BCG) (Nagesh, 2022). IoT connects devices and machinery to monitor and control operation in real-time throughout the production process this data is then analyzed to enable automation, improve efficiency, enhance quality control and facilitate data driven decision making (Sabareesh, 2024). Real time IoT data analytics coupled with machine learning can enable predictive maintenance, process optimization and improved operational performance in manufacturing environments by continuously monitoring sensor data and identifying inefficiencies before they escalate into downtime or quality issues (Kurkute, 2024). Global bibliometric analysis reveals that IoT and RFID technologies are among the most intensively researched aspects of Industry 4.0 in textile and apparel industries, while additive manufacturing and AR remain underexplored (Deepthi, 2022).

3.2 Robotics and Automation

Robots are used in tasks that require precision, consistency, or speed (Sabareesh, 2024). Robotics streamlines repetitive tasks such as spinning, weaving, and dyeing, leading to higher efficiency and less waste. Robotics has emerged as a highly dependable technological domain that exhibits remarkable responsiveness in adapting to dynamic changes. In contrast to other modes of automation, robots possess a high degree of adaptability (S.K, 2023). Robot technology is being implemented and developed rapidly for reducing cost and improving automation of manufacturing. Robots are introduced in inventory management by well-known brands like Zara and Nike (Ooi, Lee, Tan, Hew, & Hew, 2018).

Automation is particularly impactful in repetitive, labor-intensive tasks, enhancing productivity and reducing human error (Sabareesh, 2024). Automated processes in quality control, packaging, and logistics further enhance productivity. Automation in spinning has taken place in various processes. Cotton mixing has been automated so that the uniformity can be achieved in the Yarn. Automation is recently done to separate out the contamination of any colour, size and nature in the fibre thus improving the overall quality of the final yarn produced.

Automation has been achieved through sensor-based monitoring, auto piecing, auto doffing, and digital control systems integrated into modern spinning machines. Robotic automation significantly reduces human dependency in repetitive textile operations while improving consistency and production speed (Lázár, 2024).

3.3 Artificial Intelligence AI

Role of Artificial Intelligence is to describe the ability of machines to imitate the human working mentality and required functions. It also marks the differentiation of demarcation between robotics and machine learning. Adopting AI technologies offers the potential for optimizing processes. Pattern inspection, flaw identification, and color matching are some of the most often used AI applications in textile manufacturing (Sabareesh, 2024). AI facilities interaction between machines, humans, software systems and products through the. AI-driven systems analyze vast datasets for process optimization, quality control, and predictive maintenance. AI enhances efficiency and adaptability in textile manufacturing by processing complex datasets to support decisionmaking. AI-driven software suggests improvements in textile design based on consumer trends and material properties. AI models predict market demand, enabling just-in-time manufacturing. AI supports the creation of personalized textiles by analyzing individual customer preferences (Textile, 2010).

3.4 Big Data Analytics

Big data analytics is where advanced analytic techniques operate on big data sets. Big Data can be turned into useful insights which in turn can be converted into knowledge. This proves to be helpful in identifying trends, patterns and relationship between inputs, processes and outputs, enabling improvements to be made across a number of manufacturing units (Russom, 2011). Textile manufacturing generates massive data from production metrics to quality control readings. Big Data Analytics transforms raw data into actionable insights for Predictive Maintenance, Quality Assurance and Process Optimization (Textile, 2010).The proper data acquisition and processing are crucial as incorrect mapping or fault data can lead to flawed analytics. The technique ensures various benefits including new revenue opportunities, more effective marketing, better customer services, improved operational efficiency and competitive advantages (Aljehani, 2024). Big data analytics allows textile manufacturers to identify complex relationships between raw materials, machine parameters, and yarn quality outcomes (Wang, 2016).

3.5 Cloud Computing

One of the top emerging technologies is cloud computing. It can improve manufacturing industries in terms of operational, management and strategic efficiency (Ooi, 2018). Platform as a service (PaaS) cloud services make it possible for industries to adopt different emerging technologies at a low cost. Cloud computing supports the distributed manufacturing across multiple locations and remove major barriers such as labor, material cost and environmental conditions. Cloud platforms allow companies to manage data from multiple sources, enabling centralized control and analysis (Ahmad, 2020).

3.6 Digitalized Spinning Systems

Compact spinning represents a significant advancement in spinning technology and aligns strongly with the principles of Industry 4.0. As a modified form of conventional ring spinning, compact spinning eliminates the spinning triangle through controlled fiber condensation, resulting in improved yarn strength, reduced hairiness, and enhanced uniformity. The process relies on precise mechanical design, pneumatic control, and automated drafting systems, making it a digitally optimized spinning solution rather than a purely mechanical one.

Modern compact spinning machines incorporate sensor-based airflow regulation, automated drafting adjustments, and real-time monitoring of yarn formation parameters. The use of negative pressure airflow, lattice aprons, and controlled condensing zones enables consistent fiber alignment and minimizes fiber loss. These digitally controlled mechanisms improve reproducibility, reduce waste, and enhance overall production efficiency, reflecting the core objectives of smart manufacturing under Industry 4.0 (Saty, 2024).

4. Applications of Industry 4.0

To illustrate practical applications, advanced sensors and monitoring systems have been implemented across various spinning stages. The waste sensor installed in the blowroom monitors the quality of waste at the cleaners, and this data is subsequently used for the automatic adjustment of the cleaning elements. Waste and performance sensors play a crucial role, as the system actively regulates the cleaning elements instead of merely reporting information to management for manual intervention through alerts. Trutzschler reports savings of approximately 320 cotton bales per year due to improved recovery of good fibers, typically resulting in a yield improvement of about 0.4%. With a cotton price of 63 cents per pound, installing this system leads to estimated savings of US $210,900.

The performance camera used in the blowroom consists of five components: the F-Module for detecting colored or dark foreign matter, the P-Module for transparent foreign particles, the UV-Module for fluorescent contaminants, the G-Module for shiny foreign materials, and LED lighting for identifying small or thin foreign parts. At ITMA 2019, enhancements to the F and P sensors improved the reliability of detecting strip- and thread-shaped foreign materials, enabling simultaneous identification of small, highcontrast particles and relatively large, low-contrast contaminants. Data obtained from the performance camera supports preventive maintenance activities and helps assess the quality of incoming raw materials.

T-CON, a contact sensor installed on the carding machine, is used to measure the gap between carding elements and to compare individual machines or groups of machines, providing alerts to management when deviations occur. At ITMA 2019, Trutzschler introduced the TC19i Card, which enables automatic gap correction up to 3/1000th of the distance using data from T-CON. Acting as an electronic feeler gauge, TCON can also be retrofitted to older machines such as the TC03 carding machine introduced in 2003.

The Nep Sensor is utilized to identify issues related to machine settings or components, such as bent teeth, and to compare the performance of multiple machines. For instance, if data from all machines deteriorates at the same time, the issue is likely related to raw material quality. However, if only one machine shows declining performance, a maintenance alert is automatically generated. Additionally, a temperature sensor is employed at the card to prevent cold starts of carding machines. (Manglani, 2019)

In draw frames and combing machines, the DISC Leveller provides information on carded sliver quality and fluctuations in lap batt weight, while the DISC Monitor sends signals to the control system to adjust the draft and ensure uniform sliver production. Overall, extensive T-Data sensor technology is applied throughout the blowroom, carding, combing, drawing, and roving stages of production. (Mahmood, 2020)

Ring spinning development has historically focused on fiber-strand control to reduce hairiness and improve yarn quality. Compact spinning, siro-spinning, solo-spinning, air-jet/air-suction spinning, and Nu-torque spinning are recognized as key advanced ring-spinning methods. Advanced spinning methods improve yarn quality by mechanical, pneumatic, or twist-distribution control, but often increase cost and energy consumption (Xia, 2013).

5. Research Gap

Although Industry 4.0 technologies are increasingly being adopted across manufacturing sectors, their holistic and system-level implementation in textile production, particularly across interconnected spinning processes, remains underexplored. Existing research mainly concentrates on conceptual models and readiness frameworks for Industry 4.0 adoption, with limited emphasis on real-world, integrated applications. Furthermore, there is a lack of empirical studies that evaluate how digitally connected spinning systems influence operational performance, efficiency, quality, and decision-making in textile manufacturing. This gap highlights the need for further research focusing on practical implementation and measurable outcomes of integrated digital transformation in the textile industry.

6. Opportunities and Challenges

4.0 technologies particularly automation enhance the working efficiency and product quality. Automation brings in quality and also improves the productivity in the mills. Productivity increase because of automation has resulted in reduction in the overall manpower in the textile industry. While the adoption of automation and smart manufacturing offer compelling benefits, spinning mills also face challenges in implementing these technologies. The challenges include initial investment costs, integration complexities, data security concerns, and workforce upskilling requirements. Addressing these challenges requires a strategic approach, investment in training and education, and collaboration with technology partners and industry stakeholders. The future of textile spinning lies in continuous innovation, collaboration, and adaptation of emerging technologies and market trends.

Figure 1

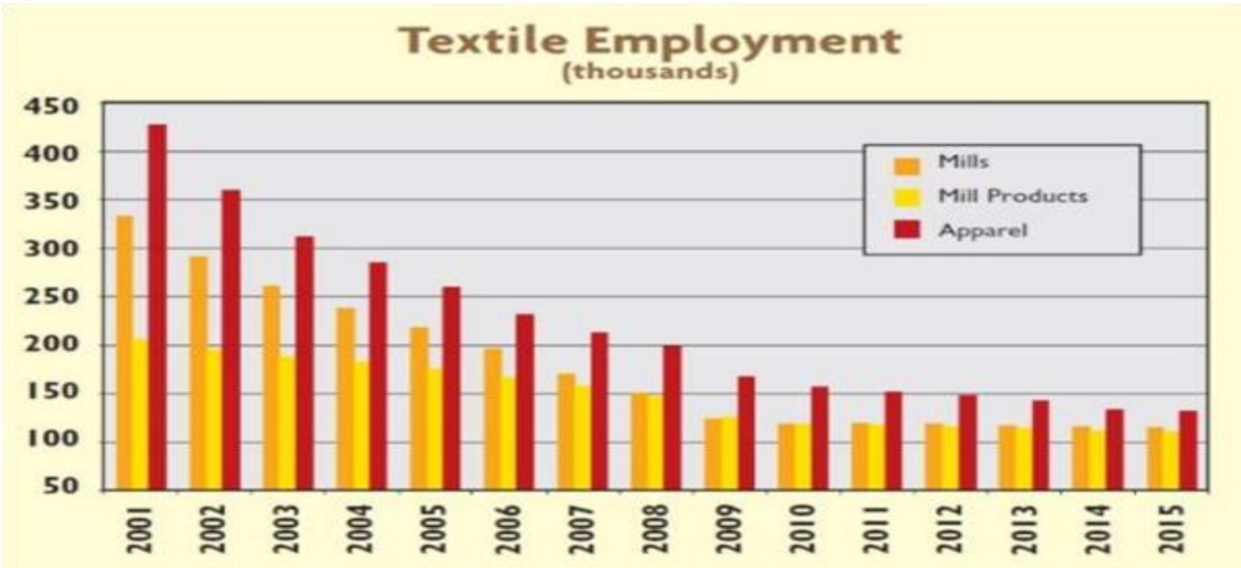

Figure 1 shows the overall decline in the manpower in Mills and Mills Products in last 15 Years. Automation has contributed to reduction in workforce requirements, leading to structural changes in employment patterns within textile industry. While challenges such as high initial costs, legacy system integration, and a skills gap exist, the long-term economic and environmental benefits are undeniable. Embracing Industry 4.0 will empower textile manufacturers to remain competitive and meet the evolving demands of modern consumers.

Conclusion

Industry 4.0 is poised to redefine textile manufacturing by incorporating IoT, AI, robotics, and big data, enhancing efficiency, quality, and sustainability. Key advancements like IoT-enabled sensors, AI-driven quality control, and automated systems offer profound improvements, reducing human error, optimizing resource use, and supporting sustainable practices.

Digitalization has evolved from an optional strategy to a fundamental requirement for modern spinning mills enabling higher automation, connectivity and competitiveness. While the adoption of smart manufacturing technologies offers significant benefits, challenges such as high initial investment costs, complex system integration and the need for skilled manpower continue to limit widespread implementation. Addressing these challenges through strategic planning, workforce training and supportive polices will be essential for realizing the full potential of Industry 4.0 in cotton spinning. Overall, smart factory concept provides a strong foundation for the future development of a competitive and technologically advanced textile industry.

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