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Technology-Driven Green Transformation in the Textile Industry: An Integrated Framework for Smart, Circular, and Sustainable Manufacturing

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ABSTRACT

Purpose - The textile industry is under pressure to reduce water, energy, chemical use, emissions, and waste while improving traceability and competitiveness. This article conceptualises technology-driven green transformation as the integration of digital capabilities, cleaner production, and circular-economy practices across the textile value chain, and develops an integrated framework for future empirical research. Design/methodology/approach - An integrative conceptual review synthesises from recent articles on artificial intelligence (AI), the Internet of Things (IoT), digital twins, 3D design and virtual prototyping, blockchain, digital product passports, advanced wet processing, and technology-assisted textile recycling. Findings - Technology does not automatically create sustainability. Environmental improvement occurs through intermediate capabilities: real-time visibility, prediction, optimisation, traceability, virtual experimentation, and closed-loop learning. These capabilities support resource efficiency, cleaner processing, waste prevention, circular design, recovery, and credible environmental disclosure. Practical implications - The study offers a phased implementation roadmap and measurable indicators suitable for textile firms, clusters, and small and medium-sized enterprises, including those in India and Kerala. Originality/value - The article moves beyond technology inventories by explaining the mechanisms through which technology drives green transformation and becomes measurable environmental performance, while presenting testable propositions for future research.

1. INTRODUCTION

The textile and apparel value chain connects fibre production, spinning, weaving or knitting, wet processing, garment manufacturing, distribution, use, and end-of-life management. Its environmental pressures therefore arise from multiple sources rather than from a single factory operation. Water- and chemical-intensive processing, energy demand, production defects, inaccurate forecasting, overproduction, complex supplier networks, and inadequate sorting and recycling all contribute to resource loss. These pressures are reinforced by a linear model in which products are designed, produced, sold, used, and discarded with limited recovery of material value.

Current sustainability policy increasingly treats textiles as a system requiring coordinated change. The United Nations Environment Programme (UNEP, 2023) identifies shifts in consumption, improved practices, and infrastructure investment as interdependent priorities for a circular textile sector. European policy similarly combines ecodesign, waste collection, product information, and producer responsibility. The Digital Product Passport (DPP) is especially significant because it transforms sustainability information from a voluntary communication exercise into structured lifecycle data that can support consumers, repairers, recyclers, firms, and regulators. In July 2026, the European Commission made the DPP Registry operational, while textile apparel remains a priority product group under the Ecodesign for Sustainable Products Regulation (European Commission, 2026).

Technology is frequently presented as the solution to these challenges. Sensors can measure water, steam, electricity, temperature, pressure, and chemical dosage; AI can detect defects and forecast demand; digital twins can simulate processes before physical execution; 3D tools can reduce physical sampling; blockchain and DPP systems can strengthen traceability; and automated sorting can improve the quality of recovered textile streams. However, a list of technologies is not a theory of green transformation. Firms may digitise inefficient processes, collect data without using it, or purchase equipment whose environmental burden exceeds the improvement it delivers. Technology creates green value only when it changes decisions, routines, incentives, and material flows.

This article therefore defines technology-driven green transformation as a coordinated organisational shift in which digital and advanced manufacturing technologies build capabilities for smart resource management, cleaner production, circular material flows, and verified sustainability performance. The paper contributes an integrated framework in which technologies generate digital capabilities; those capabilities support smart and green manufacturing practices; and those practices influence environmental, operational, circular, and market outcomes. This structure is useful for conceptual development, empirical testing, and managerial implementation.

1.1 Research Problem and Gap

Research on digitalisation and sustainable textiles is expanding, but three gaps remain. First, many studies focus on a single technology or process and therefore provide limited guidance on system-wide integration. Second, productivity improvements are sometimes treated as equivalent to environmental improvements even when resource and pollution indicators are not measured. Third, implementation studies often understate organisational factors such as managerial commitment, worker capability, supplier participation, data quality, and access to finance. The resulting knowledge gap is not whether AI, IoT, blockchain, or digital twins can be used in textiles; it is how a portfolio of technologies can be translated into verifiable, organisation-wide green transformation across firms of different sizes and capabilities.

2. OBJECTIVES AND RESEARCH QUESTIONS

1. To identify the principal technologies driving green transformation in textile production and supply chains.
2. To explain the digital capabilities through which these technologies support smart manufacturing, resource efficiency, cleaner production, and circularity.
3. To develop an integrated conceptual framework and testable propositions linking technology adoption, smart and green manufacturing practices, and sustainability performance.
4. To propose measurable indicators and an implementation roadmap relevant to textile firms and clusters in India, including Kerala.

RQ1. Which digital and advanced manufacturing technologies have the strongest potential to drive green transformation in textiles?

RQ2. Through which capabilities do these technologies influence environmental performance?

RQ3. Which organisational and institutional conditions strengthen or weaken technology-driven green transformation?

RQ4. How can firms measure implementation in a way that distinguishes real environmental improvement from symbolic digitalisation?

3. METHODOLOGY

The study uses an integrative conceptual review. This method is appropriate where a research problem spans multiple technical and managerial domains and the objective is to combine evidence into a new explanatory framework. The review considered literature published mainly from 2019 to July 2026, while retaining earlier work when it established an important concept. Search terms combined textile, apparel, fashion, green manufacturing, cleaner production, circular economy, AI, machine learning, IoT, Industry 4.0, digital twin, virtual prototyping, blockchain, traceability, DPP, wet processing, and recycling.

Priority was given to scopus indexed and peer reviewed journals on empirical studies, official regulations, and reports from recognised institutions. Sources were included when they (a) addressed a textile-specific application, (b) explained an environmental or circular mechanism, (c) presented empirical evidence or a transparent review method, or (d) established a relevant policy requirement. Evidence was coded into four categories: enabling technology, digital capability, green practice, and performance outcome. Barriers and enabling conditions were coded separately.

The approach is interpretive rather than meta-analytic. It does not estimate a pooled effect size and should not be described as a PRISMA systematic review. Its strength lies in theory integration and in the explicit translation of the literature into constructs, propositions, indicators, and managerial actions.

4. TECHNOLOGY LANDSCAPE FOR GREEN TRANSFORMATION

4.1 Artificial intelligence and Advanced Analytics

AI supports green practices when it reduces uncertainty or identifies patterns that are difficult to detect manually. In production, computer vision can identify yarn, fabric, colour, and stitching defects early, preventing defective material from moving to later stages where more energy, water, chemicals, and labour would be added. Predictive maintenance can identify abnormal machine behaviour before a breakdown causes rejects, leakage, or inefficient operation. Optimisation models can recommend settings for temperature, speed, pressure, liquor ratio, chemical dosage, and scheduling.

At the planning level, demand forecasting can reduce overproduction and deadstock when it is connected to disciplined production decisions. At end-of-life, AI combined with near-infrared or hyperspectral sensing can classify textiles by fibre composition, colour, or product condition. Faghih, Saki, and Moore (2025) show that automated textile sorting increasingly combines spectroscopy, imaging, and machine-learning methods. The environmental benefit depends on the quality of the input data, the availability of appropriate recovery routes, and the firm's willingness to use forecasts to limit production rather than merely accelerate it.

4.2 Internet of Things and real-time resource monitoring

IoT systems connect machines, meters, sensors, and software so that operating conditions and resource flows become visible in real time. In spinning and weaving, sensors can track power consumption, machine speed, vibration, humidity, and downtime. In wet processing, flow meters and chemical-dosing systems can monitor water intake, steam, bath temperature, pH, conductivity, and effluent parameters. This visibility enables control at the batch, line, machine, and product levels rather than relying only on monthly utility bills.

Petrillo, Rehman, and Baffo (2024) demonstrate the importance of IoT technologies in the digital and sustainable transition of textile manufacturing. Yet connectivity alone has limited value. Resource baselines, control limits, alerts, responsibility for corrective action, and management review must be defined. The important output is not the volume of sensor data but the frequency with which data prevents loss, improves process capability, or supports investment decisions.

4.3 Digital twins, Simulation, and Virtual Prototyping

A digital twin is a dynamic digital representation of a physical asset, process, or system. When linked to reliable operating data, it allows firms to test alternative settings, schedules, maintenance actions, or layouts before changing the physical process. Angelova (2025) argues that textile applications can extend beyond conventional equipment monitoring to energy optimisation, maintenance, process improvement, and decision support. Digital twins are particularly relevant where experimental changes are costly, resource-intensive, or risky.

At the product-development stage, computer-aided design, 3D garment simulation, digital colour management, and virtual sampling can reduce physical prototypes and accelerate collaboration between designers, buyers, and manufacturers. These tools also support design-for-circularity by allowing material composition, construction choices, durability, repairability, and disassembly to be considered before production. However, virtual sampling becomes environmentally meaningful only when it actually replaces samples, travel, or unnecessary iterations rather than adding another layer of activity.

4.4 Blockchain, Traceability, and Digital Product Passports

Traceability technologies address the information fragmentation of textile supply chains. Blockchain can create a shared, tamper-resistant record of transactions, certificates, and material movements, while IoT, barcodes, RFID, or QR codes provide the identification and data-capture layer. Ahmed and MacCarthy (2021) show that blockchain-enabled traceability can support product authentication and sustainability, although the scope and granularity of traceability must match the intended purpose. Alves et al. (2022) similarly connect blockchain, IoT, and digital twins to circular textile value chains.

The DPP provides a policy-driven structure for product information across the lifecycle. Relevant fields may include fibre composition, origin, chemicals of concern, repair guidance, durability, recycled content, environmental indicators, and end-of-life instructions. A DPP can improve the information available to recyclers and regulators, but it does not verify the truth of data by itself. Supplier assurance, standard definitions, auditability, access rights, and interoperability remain essential.

4.5 Smart Automation and Advanced Recycling

Automation can improve consistency in cutting, material handling, quality control, dosing, and sorting. Automatic marker planning and precision cutting reduce offcuts; robotic or guided handling reduces damage; and automated inspection prevents defect propagation. At end-of-life, mechanical opening, fibre separation, chemical recycling, and solvent-based recovery can retain greater material value when supported by accurate sorting and traceability. These technologies must be assessed through life-cycle thinking because a high-purity recycling process may require significant energy, chemicals, or capital. The preferred option is the one that delivers the best verified net environmental result for the specific material stream.

4.6 Cleaner Wet Processing and Process-Intensification Technologies

Wet processing remains a critical intervention point. Low-liquor-ratio dyeing, digital printing, foam application, enzymatic processing, ozone treatment, plasma treatment, supercritical carbon dioxide dyeing, membrane systems, wastewater recovery, and precise automated dosing can reduce water, energy, chemicals, or effluent. Catarino, Sampaio, and Gonçalves (2025) emphasise both the potential and the industrial limitations of emerging wet-processing options, including cost, scalability, compatibility, and process control.

Digitalisation strengthens these technologies by stabilising operating conditions and documenting results. For example, a low-water process can concentrate pollutants even as total water use falls; therefore, firms must track both absolute resource use and pollution intensity. Green evaluation should examine trade-offs across water, energy, chemicals, emissions, product quality, worker safety, and end-of-life compatibility.

Table 1. Technologies, transformation mechanisms, and performance indicators

Technology	Application	Green mechanism	Illustrative indicators
AI and analytics	Defect detection, forecasting, predictive maintenance, process optimisation *(Faghih et al., 2025; Monteiro et al., 2024)*	Prevents overproduction, rejects, downtime, and inefficient settings	Forecast error; defect rate; rework; deadstock; kWh per kg
IoT and sensors	Real-time metering of water, steam, electricity, pH, temperature, dosing, effluent *(Petrillo et al., 2024)*	Makes losses visible and enables rapid corrective control	Litres per kg; steam per batch; alert closure time; chemical variance
Digital twins and simulation	Virtual process trials, energy modelling, maintenance and layout decisions *(Angelova, 2025)*	Replaces resource-intensive trial and error and improves asset performance	Trials avoided; energy intensity; downtime; first-pass yield

Technology	Application	Green mechanism	Illustrative indicators
3D design and virtual sampling	Virtual garments, fit, colour, material and construction decisions *(Glogar et al., 2025; Swami et al., 2022)*	Reduces samples, travel, development waste, and late design changes	Samples per style; approval cycles; material used in development
Blockchain and DPP	Material identity, provenance, certificates, lifecycle and end-of-life information *(Ahmed & MacCarthy, 2021; European Commission, 2024, 2026)*	Supports responsible sourcing, compliance, repair, reuse, and recycling	Traceable volume; verified suppliers; data completeness; recovery rate
Automation and advanced recycling	Precision cutting, automated sorting, mechanical or chemical recovery *(Faghih et al., 2025; Glogar et al., 2025)*	Reduces offcuts and contamination and retains material value	Cutting yield; sorting purity; fibre-to-fibre recovery; waste diverted
Cleaner processing technology	Low-liquor dyeing, digital printing, enzymatic, ozone, plasma, membranes, ZLD *(Catarino et al., 2025)*	Reduces water, chemicals, energy, and discharge when life-cycle trade-offs are controlled	Water, COD, BOD, TDS, chemical and energy intensity; reuse percentage

5. INTEGRATED FRAMEWORK FORTECHNOLOGY-DRIVEN GREEN TRANSFORMATION

The integrated framework separates technology adoption from sustainability performance. This distinction is important because an installed system is only an input; sustainability depends on how the technology changes decisions and operations.

Technologies first generate digital capabilities such as visibility, prediction, optimisation, traceability, virtual experimentation, and closed-loop learning. These capabilities then support smart and green manufacturing practices, including resource-efficient production, cleaner processing, renewable-energy integration, waste prevention, circular product design, and material recovery.

Green practices directly influence environmental outcomes and may also improve quality, cost, resilience, compliance, and stakeholder trust. This layered relationship is consistent with frameworks connecting Industry 4.0, circular-economy capabilities, and sustainable manufacturing outcomes (Kristoffersen et al., 2020; Khan et al., 2021; Dal Forno et al., 2023).

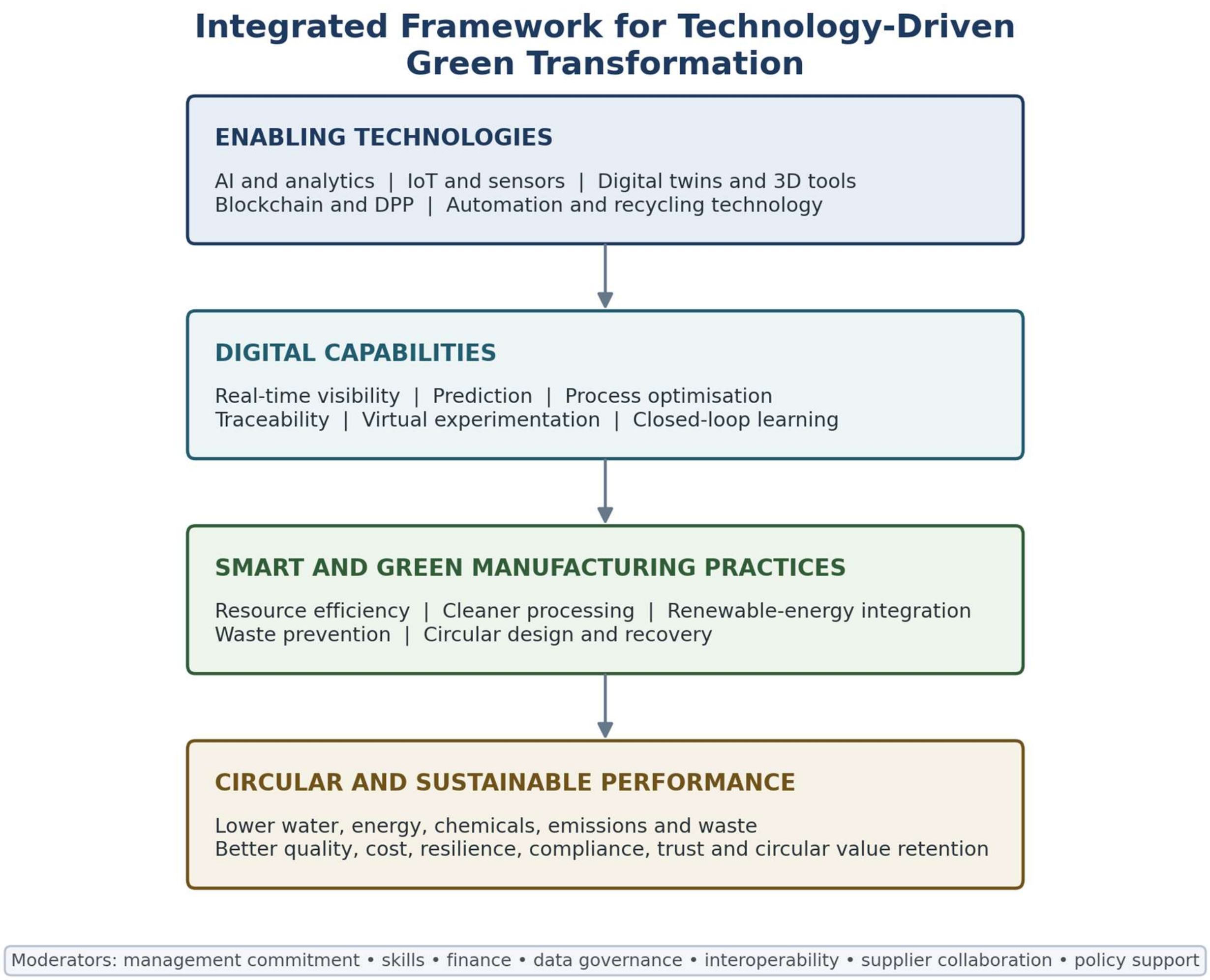

Figure 1. Integrated framework for technology-driven green transformation

Source: Developed by the author based on Barney (1991), Hart (1995), Teece (2007), Kristoffersen et al. (2020), Khan et al. (2021), and Dal Forno et al. (2023).

5.1 Theoretical Logic

The framework combines the resource-based view (Barney, 1991), dynamic-capabilities theory (Teece, 2007), and the natural-resource-based view (Hart, 1995).

Technology assets create value only when they are embedded in routines that allow a firm to identify environmental losses, act on improvement opportunities, and reconfigure operations. Green capabilities are therefore organisational rather than purely technical.

For example, a sensor is an asset. It becomes part of a capability when the firm routinely uses its data to detect abnormal water consumption, assign responsibility, correct the process, verify the result, and standardise the learning.

The framework also emphasises complementarity. IoT generates data, AI interprets patterns, digital twins test alternatives, and traceability systems connect product and supplier information. Digital circular-economy and textile value-chain research similarly stresses the value of combining these technologies (Kristoffersen et al., 2020; Alves et al., 2022).

An integrated portfolio can therefore create more value than isolated technologies. However, poorly connected systems may produce duplicate data, incompatible metrics, cybersecurity risks, and additional energy demand without delivering meaningful environmental improvement.

5.2 Research propositions

Code	Proposition	Explanation
P1	Real-time resource visibility generated by IoT and sensor systems is positively associated with the adoption and effectiveness of green production practices (Petrillo et al., 2024; Swami et al., 2022).	Visibility reduces information delay and supports operational control.
P2	AI-enabled prediction and optimisation reduce waste and environmental intensity through improved quality,	Green practices mediate the relationship between AI use and

Code	Proposition	Explanation
	maintenance, process settings, and demand alignment (Faghih et al., 2025; Monteiro et al., 2024).	sustainability performance.
P3	Digital twins and virtual prototyping reduce physical experimentation, sampling, and process loss when virtual outputs substitute for physical activities (Angelova, 2025; Glogar et al., 2025).	Substitution is the key boundary condition.
P4	Traceability capability strengthens circular practices by improving information on material composition, provenance, use, repair, and end-of-life options (Ahmed & MacCarthy, 2021; Alves et al., 2022).	Data quality and supplier participation moderate the effect.
P5	Integrated portfolios of complementary technologies have a stronger positive effect on green performance than isolated technology adoption (Kristoffersen et al., 2020; Khan et al., 2021; Dal Forno et al., 2023).	Interoperability and common data definitions enable complementarity.
P6	Management commitment, workforce capability, financial capacity, collaboration, and policy support positively moderate the technology-green performance relationship (Barney, 1991; Hart, 1995; Teece, 2007).	These conditions convert technical potential into sustained routines.

6. IMPLEMENTATION ROADMAP FOR TEXTILE FIRMS

Implementation should begin with environmental materiality rather than with technology availability. A firm should first identify the processes responsible for the largest water, energy, chemical, carbon, and waste burdens. It should then establish a baseline, choose a limited set of high-value use cases, and define who will act on the resulting information. This prevents technology-led projects from becoming disconnected from environmental priorities (UNEP, 2023; Catarino et al., 2025).

The roadmap below is intentionally phased. Each phase must produce a verified operational or environmental result before the next layer of complexity is added. Small firms can use shared cluster infrastructure, cloud platforms, leased sensors, common laboratories, and technical-assistance programmes to reduce the fixed cost of adoption (Kristoffersen et al., 2020; Khan et al., 2021).

Phase	Key actions	Decision
1. Diagnose and baseline	Map material, water, energy, chemical, effluent, and waste flows; identify hotspots and legal/buyer requirements (UNEP, 2023; Catarino et al., 2025).	Approved baseline; priority use cases; data owners
2. Instrument and standardise	Install or calibrate meters and sensors; define units, boundaries, product codes, and data-quality rules (Petrillo et al., 2024; European Commission, 2026).	Reliable machine/batch/product-level data
3. Control and improve	Use dashboards, alerts, statistical control, maintenance, and root-cause analysis (Petrillo et al., 2024; Monteiro et al., 2024).	Verified reduction in loss, defects, or intensity
4. Predict and simulate	Add AI, forecasting, optimisation, digital twins, and virtual development where data quality is adequate (Faghih et al., 2025; Angelova, 2025).	Improved prediction, fewer trials, lower deadstock and downtime
5. Connect the value chain	Integrate supplier data, product identity, DPP fields, certificates, repair, reuse, and recycling information (Ahmed & MacCarthy, 2021; European Commission, 2026).	Higher traceable volume and circular recovery
6. Verify and	Conduct life-cycle checks, independent assurance,	Sustained

Phase	Key actions	Decision
scale	benefit tracking, cybersecurity review, and replication (European Commission, 2024; UNEP, 2023).	performance and credible disclosure

Source: Author's synthesis of the sources cited within the table.

7. RELEVANCE TO INDIA AND KERALA

India's textile sector combines large export-oriented mills, processing clusters, garment factories, decentralised powerloom and handloom activity, and a broad MSME base. Current policy attention to organic fibres, safer chemicals, circular production, waste recovery, eco-labelling, and traceability creates a favourable environment for technology-driven green transformation (Press Information Bureau, 2026). At the same time, uneven digital maturity, capital constraints, older equipment, fragmented supplier data, and limited specialist skills make a uniform technology strategy unrealistic (Dal Forno et al., 2023; Monteiro et al., 2024).

For Indian firms, export-market readiness is an immediate driver. DPP and ecodesign requirements will increase demand for reliable product and material data (European Commission, 2024, 2026). Firms should therefore develop product coding, bill-of-material accuracy, chemical inventories, supplier verification, and machine- or batch-level resource records before investing in complex traceability platforms. The first competitive advantage is not blockchain itself; it is the ability to produce complete, consistent, and auditable data (Ahmed & MacCarthy, 2021; World Intellectual Property Organization, 2025).

In Kerala, a cluster-oriented approach is especially suitable for handloom, garment, and small-scale textile enterprises because the handloom base is geographically concentrated and predominantly cooperative (Kerala State Industrial Development Corporation, n.d.). Shared digital platforms can support production planning, energy monitoring, inventory visibility, common design libraries, QR-based provenance, and market access. For handloom products, digital identity can document fibre, artisan, location, design, natural-dye or process information, care, and authenticity. This can combine environmental communication with cultural and economic value, provided claims are verified (Kerala State Handloom Weavers' Co-operative Society Ltd., 2023; World Intellectual Property Organization, 2025).

A practical Kerala pathway would include green-digital audits through technical institutions; shared training in metering, data interpretation, eco-design, and traceability; affordable sensor and software packages for

MSMEs; renewable-energy and efficiency programmes; common testing and certification support; and producer-level dashboards linked to a small number of indicators (Kerala State Handloom Weavers' Co-operative Society Ltd., 2023; Press Information Bureau, 2026; United Nations Environment Programme, 2023). Enterprises without wet processing should prioritise materials, design, energy, inventory, quality, packaging, and product longevity, while wet-processing units should place water, chemicals, effluent, heat recovery, and process control at the centre of the intervention (Catarino et al., 2025).

8. DISCUSSION

The literature supports a twin-transition perspective: green and digital transformation are mutually reinforcing but not identical. Digital technology improves information, speed, coordination, and control; green management determines the environmental purpose, targets, trade-offs, and accountability. The combination is powerful because textile environmental impacts are distributed across processes and supply tiers. No single actor has complete visibility, and many losses are hidden within averages, inventories, quality failures, or downstream waste.

Three implications follow. First, measurement must move closer to the process and product. Monthly utility data are too aggregated for corrective action or product-level claims. Second, circularity requires both physical infrastructure and information infrastructure. Traceability without collection, sorting, repair, reuse, or recycling capacity produces data but not circular material flow. Third, rebound effects must be controlled. Faster design and production can increase total output; improved forecasting can be overridden by volume targets; and digital systems consume energy and equipment. Firms should therefore evaluate both intensity and absolute environmental outcomes.

The framework also clarifies why management commitment appears repeatedly as an implementation driver. Technology projects cross departmental boundaries. Production, maintenance, information technology, environment, quality, purchasing, design, marketing, and finance must agree on definitions, ownership, and performance priorities. Without governance, data remain fragmented and local improvements fail to scale.

9. MANAGERIAL AND POLICY IMPLICATIONS

9.1 Managerial implications

Managers should construct a portfolio of use cases ranked by environmental materiality, operational value, data readiness, cost, and scalability. Early projects should have short feedback loops, such as leak detection, automated dosing, defect prevention, compressed-air monitoring, heat-loss analysis, or cutting-yield improvement. Success should be defined before implementation through a baseline, target, time period, and verification method (UNEP, 2023; Petrillo et al., 2024; Catarino et al., 2025).

Technology procurement should include interoperability, data ownership, cybersecurity, maintenance, model transparency, worker usability, and exit conditions. Environmental teams should participate in system design, while operators should participate in defining alerts and work routines. Training must extend beyond software use to statistical reasoning, process knowledge, environmental interpretation, and problem solving (Kristoffersen et al., 2020; Dal Forno et al., 2023; OECD, 2018).

Green claims should be linked to evidence. A dashboard or DPP may communicate performance, but reliable claims require clear boundaries, consistent units, supplier validation, change control, and assurance. Where uncertainty is material, firms should communicate limitations rather than converting estimates into precise-looking but unreliable claims (Ahmed & MacCarthy, 2021; European Commission, 2024; OECD, 2018).

9.2 Policy implications

Policy should support the digital foundations of environmental improvement: interoperable standards, testing facilities, shared infrastructure, open technical guidance, verified eco-labels, and affordable finance. MSMEs need implementation assistance and common services, not only capital subsidies. Cluster-level resource monitoring, laboratories, wastewater and recycling infrastructure, digital traceability services, and training can spread fixed costs across many enterprises (UNEP, 2023; Dal Forno et al., 2023; Ministry of Micro, Small and Medium Enterprises, 2026).

Regulation should encourage outcome-based innovation while preventing burden shifting and greenwashing. Reporting rules should distinguish absolute impacts from intensity improvements, require credible product data, and support repairers and recyclers with relevant information (European Commission, 2022, 2024; OECD, 2018). Public procurement can accelerate demand for durable, repairable, traceable, and recycled-content textiles (European Commission, 2024).

10. RISKS, LIMITATIONS, AND FUTURE RESEARCH

Technology-driven green transformation faces technical, economic, organisational, and ethical risks. Legacy equipment may be difficult to connect; supplier systems may use incompatible codes; data may be missing or manipulated; AI models may drift; cyberattacks may interrupt operations; and workers may fear surveillance or job displacement (Kristoffersen et al., 2020; Dal Forno et al., 2023; Monteiro et al., 2024; OECD, 2018). Capital-intensive solutions can widen the gap between large firms and MSMEs (Khan et al., 2021; Dal Forno et al., 2023; Monteiro et al., 2024). These risks should be managed through proportionate governance, worker participation, staged investment, and independent verification (OECD, 2018; UNEP, 2023).

This article is limited by its conceptual and integrative design. It does not provide a meta-analysis, calculate life-cycle impacts for specific technologies, or test the proposed relationships. The technology landscape also changes rapidly. Future research should compare technology portfolios across spinning, weaving, wet processing, garment manufacturing, handloom, and recycling; test mediation and moderation in the proposed model; examine MSME and cluster adoption; measure rebound effects; and evaluate whether DPP data improve actual repair, reuse, sorting, and fibre-to-fibre recycling.

Longitudinal and quasi-experimental studies are particularly important. Researchers should measure resource and waste performance before and after implementation, use matched comparison units where feasible, and document concurrent changes in product mix, volume, quality, energy source, and regulation. Such designs would help distinguish genuine technology effects from general efficiency programmes or market changes.

11. CONCLUSION

Technology can help the textile industry move from periodic reporting and reactive control to continuous visibility, prediction, optimisation, traceability, and learning. AI, IoT, digital twins, virtual design, blockchain, DPP systems, automation, cleaner processing, and advanced recycling each address different information or material-flow problems. Their environmental value depends on how they are combined with green objectives and operational routines (Ahmed & MacCarthy, 2021; Petrillo et al., 2024; Angelova, 2025; Catarino et al., 2025).

The central conclusion is that digital adoption is an enabling condition, not the final outcome. Firms create sustainability performance when technology capabilities are translated into resource efficiency, cleaner processing, renewable integration, waste prevention, circular design, and recovery - and when results are measured against credible baselines. Management commitment, workforce skills, finance, data governance, interoperability, collaboration, and policy support determine whether this translation occurs (Kristoffersen et al., 2020; Khan et al., 2021; Dal Forno et al., 2023).

For India and Kerala, a practical path is phased and cluster-sensitive: establish reliable data, solve priority environmental problems, build shared capabilities, and then scale predictive, traceable, and circular systems. This aligns technological modernisation with environmental responsibility, competitiveness, and inclusive development (Kerala State Industrial Development Corporation, n.d.; Press Information Bureau, 2026; United Nations Environment Programme, 2023).

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