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A Study on Sustainable Textile Innovation through Circular Economy and Green Manufacturing Technologies

Shoaib Hanif

Department of Design Marketing and Merchandising, Asian Institute of Fashion Design, Iqra University, Karachi, Pakistan

Email: shoaib.2016432@gmail.com

ORCID ID: 0009-0007-5445-0962

Khadim Hussain

Department of Apparel Manufacturing and Merchandising, Textile Institute of Pakistan, Karachi, Pakistan

Email: Khadimhussain201788@gmail.com

Muhammad Waqas

Institute of Business & Management, University of Engineering and Technology, Lahore (UET), Pakistan

Email: M.waqas10855@gmail.com

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ABSTRACT

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Corresponding Author:

Shoaib Hanif

Email:

shoaib.2016432@gmail.com

The textile and apparel sector was a major source of employment and industrial value but also generated substantial environmental pressure through predominantly linear production and consumption systems. This paper examined the integration of circular-economy principles and green-manufacturing technologies to support sustainable textile value creation. A qualitative systematic/narrative literature review was conducted using peer-reviewed studies and authoritative institutional publications covering circular economy, sustainable materials, textile recycling, cleaner production, life-cycle assessment, Industry 4.0, artificial intelligence, the Internet of Things, blockchain, digital product passports, reverse logistics, and extended producer responsibility. The findings indicated that no single intervention achieved systemic sustainability. The most effective approach prioritized reduction, durability, repair, reuse, and remanufacturing before recycling, supported by life-cycle assessment and digital technologies. From the Pakistan and developing-economy perspective, resource constraints, fragmented supply chains, informal recovery, weak enforcement, financing gaps, and export-market pressures were identified as key challenges. The paper proposed an integrated framework connecting sustainable materials, eco-design, green and smart manufacturing, collection, sorting, reuse, remanufacturing, recycling, and renewed production. It concluded that circular textile innovation required coordinated participation from industry, workers, consumers, regulators, recyclers, technology providers, and communities.

Introduction

Textiles are indispensable to everyday life, yet their production and consumption embody a substantial concentration of material, chemical, water, energy, labor, and logistics decisions. The sector includes fiber cultivation and production, spinning, weaving or knitting, dyeing and finishing, garment assembly, distribution, use, care, collection, and end-of-life management. Environmental impacts are distributed across this chain rather than confined to the factory gate. Fiber choice affects land, feedstock, chemicals, durability, and recyclability; wet processing affects water, energy, effluent, and chemical exposure; product design determines repairability and sorting; and consumer practices influence use-phase energy, washing, longevity,

and disposal. Reviews of fashion and textile sustainability consequently emphasize the need to examine the entire life cycle rather than isolated factory improvements [1] [2] [3].

The conventional model is frequently described as “take–make–use–dispose.” In this model, value is created primarily through throughput: more virgin material is extracted, transformed into more units, sold more quickly, and replaced more frequently. Fast-fashion business models intensify this dynamic through short trend cycles, low prices, and incentives for volume. The environmental price includes resource depletion, greenhouse-gas emissions, wastewater, hazardous substances, microfiber release, and growing post-consumer waste. The social price includes occupational risks, unequal value distribution, precarious work, and exposure of producing regions to pollution. The circular economy offers a different organizing principle: retain the utility and value of products and materials for as long as possible, prevent waste at source, and regenerate natural systems where feasible [4] [5].

Circularity, however, is not equivalent to recycling alone. A hierarchy of interventions places prevention, durability, reuse, repair, sharing, and remanufacturing above material recycling because these options usually preserve more of the embedded product and material value. Recycling remains essential for unavoidable waste, but it can be energy- and chemical-intensive, can reduce fiber quality, and can become a justification for continued overproduction if interpreted narrowly. Recent textile reviews show that recycling and reuse benefits depend on collection quality, transport distances, sorting yields, substitution assumptions, product lifetimes, energy mixes, and the fate of residues [6] [7]. Thus, the central challenge is not whether a technology is “green” in isolation, but whether it contributes to a credible, measured, and socially just system transition.

Green manufacturing complements circular economy by reducing the impacts of processes that remain necessary. It includes cleaner production, resource-efficient machinery, closed-loop water systems, safer chemistry, renewable energy, waste prevention, heat recovery, process optimization, and environmental management. Digital technologies extend this capability by making products, machines, materials, and flows more visible. IoT sensors can measure water, energy, temperature, pressure, quality, and machine condition in real time. AI and machine vision can support demand forecasting, defect detection, and fiber sorting. Blockchain can provide tamper-evident records where governance and data quality are adequate. DPPs can connect product identity, composition, repair instructions, and recycling information across the lifecycle [8] [9] [10].

Research problem

Despite extensive scholarship on sustainable fashion and cleaner production, implementation remains fragmented. Studies often examine material innovation, eco-design, recycling, digitalization, or supply-chain governance as separate topics. This fragmentation creates three problems. First, improvements in one stage may shift impacts to another: a recycled fiber may require complex processing; a water-saving dyeing process may consume more electricity; or a biodegradable material may be incompatible with existing sorting and recycling systems. Second, the literature is richer in conceptual claims and pilot projects than in evidence of scaled, financially viable, and socially inclusive deployment. Third, research and policy discussions often privilege high-income-country infrastructures and technologies, while manufacturing economies such as Pakistan face different capital costs, institutional capacities, energy reliability, informal-sector dynamics, and export requirements.

The research problem is therefore defined as follows: the textile sector lacks an integrated and context-sensitive model that connects circular-economy strategies with green and digital manufacturing technologies across the full textile lifecycle, while accounting for life-cycle trade-offs, developing-economy constraints, and the SDG agenda.

Research gap

Four gaps motivate this study. The first is an integration gap. Circular strategies, green manufacturing, Industry 4.0, and reverse logistics are frequently discussed in parallel rather than as a mutually dependent architecture. The second is an evaluation gap. LCA is widely recommended, but studies differ in functional units, system boundaries, allocation rules, durability assumptions, and treatment of social impacts; consequently, apparent environmental superiority cannot be generalized without methodological care [11] [12]. The third is a governance gap. DPPs, blockchain, and AI are presented as enablers, but their value depends on standards, interoperability, privacy, verification, affordability, and accountability. The fourth is a contextual gap concerning Pakistan and comparable developing economies, where the combination of export dependence, resource stress, informal recovery, small and medium enterprises, and uneven regulation changes the feasibility of circular interventions [13] [14] [15].

Aim and objectives

The aim of this paper is to critically synthesize evidence on sustainable textile innovation and propose an integrated framework that combines circular-economy principles, green manufacturing, smart technologies, and enabling governance.

The objectives are to:

- Examine the environmental, economic, and social rationale for circular transformation in textiles.
- Critically compare sustainable materials, eco-design, reuse, repair, remanufacturing, and textile-recycling pathways.
- Analyze green-manufacturing technologies for water, energy, chemical, carbon, and waste efficiency.
- Assess the contribution and limitations of LCA, AI, IoT, blockchain, DPPs, and other Industry 4.0 tools.
- Synthesize the requirements of closed-loop textile supply chains, reverse logistics, EPR, standards, and policy.
- Develop a Pakistan/developing-economy perspective on barriers, enablers, and transition priorities.
- Map the integrated pathway to SDGs 6, 7, 8, 9, 12, and 13 and formulate actionable recommendations.

Research questions

1. What environmental, economic, and social problems are associated with the prevailing linear textile system?
2. Which circular-economy strategies and sustainable-material innovations offer the strongest potential, and what trade-offs constrain them?
3. Which green-manufacturing technologies can reduce water, energy, chemical, and waste impacts in textile production?
4. How can Industry 4.0 technologies improve circular design, process control, traceability, sorting, and reverse logistics?
5. What organizational, infrastructural, financial, policy, and social barriers impede closed-loop textile systems?
6. How do these barriers and opportunities differ in Pakistan and other developing economies?
7. How can an integrated framework align textile innovation with SDGs 6, 7, 8, 9, 12, and 13?

Significance and scope

The paper contributes a synthesis for researchers, textile manufacturers, brands, policymakers, technology providers, recyclers, and development agencies. It does not claim to provide primary measurements from a particular mill or to establish universal impact coefficients. Rather, it interprets existing scholarship and identifies conditions under which innovations are likely to create environmental and economic value. The scope covers fibers, textile processing, apparel and household textiles, post-industrial and post-consumer flows, digital technologies, policy, and selected social dimensions. The geographical analysis is global with a dedicated focus on Pakistan as a manufacturing and cotton-producing developing economy.

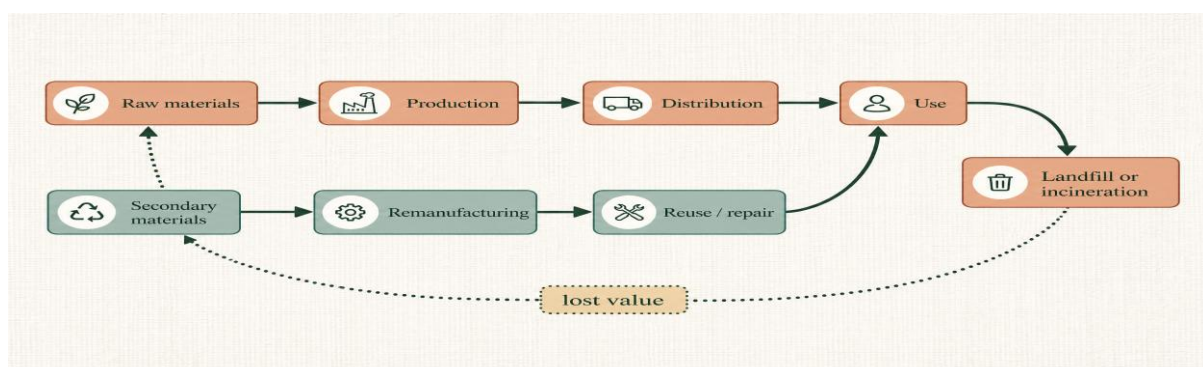


Figure 1. Linear versus circular textile economy. Source: Author's conceptualization.

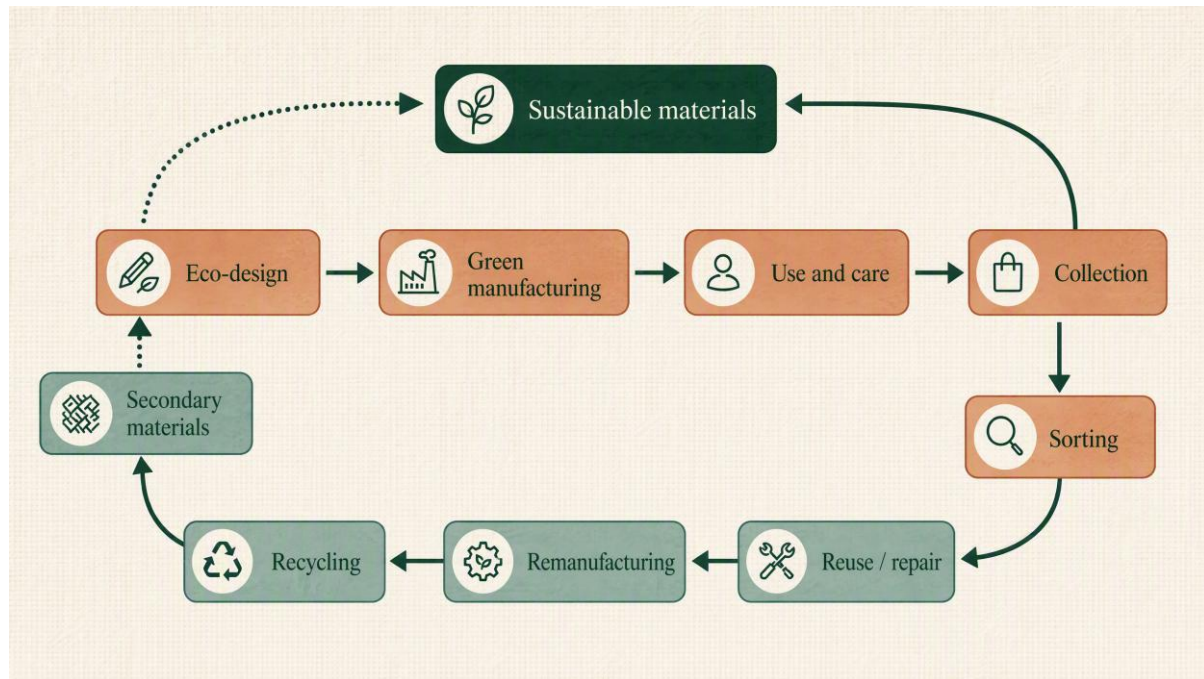


Figure 2. Circular textile lifecycle. Source: Author's conceptualization.

Literature Review

Circular economy as a textile transition

Circular economy is best understood as a set of principles and strategies rather than a single business model. Foundational work distinguishes narrowing resource flows through efficiency, slowing flows through longer product life, and closing flows through recovery and recycling [4] [5]. In textiles, narrowing can involve lightweighting, waste-minimizing cutting, and lower-liquor processing; slowing includes durability, repair, resale, rental, and emotional attachment; closing includes fiber-to-fiber recycling, polymer recovery, and industrial symbiosis. A strong circular strategy must also ask whether material flows are safe, renewable, socially fair, and economically viable.

The textile literature increasingly recognizes that circularity is a systems issue. A garment's recyclability does not guarantee recycling because collection, identification, sorting, de-trimming, and markets for recovered outputs are also required. Likewise, recycled content does not automatically reduce impact if it compromises durability or causes additional processing. Systematic reviews report that reuse, repair, reduction, and recycling are the most frequently discussed strategies, but adoption is constrained by consumer incentives, service access, technology, cost, and policy [16] [17]. This evidence supports a portfolio approach in which product-life extension is prioritized while recycling capacity is developed for residual streams.

Table 1 summarizes major impact domains. The table intentionally avoids presenting a single sector-wide percentage because the literature reports divergent values depending on geography, fiber mix, system boundary, and production technology.

Table 1. Environmental and social impact domains in textile value chains

Domain	Main pressure points		Mechanisms and consequences		Circular/green response
Materials	Virgin agricultural, or feedstocks	fossil, or forest	Resource pressure, biodiversity	depletion, chemical inputs, loss of	land Recycled, bio-based, renewable, durable, and mono-material options assessed with LCA
Water	Fiber dyeing, finishing	cultivation, washing,	Freshwater wastewater, eutrophication, local scarcity	withdrawal, salinity,	Low-liquor processes, water reuse, safer chemistry, wastewater treatment, water-risk mapping

Energy and climate	Spinning, heating, logistics	drying, cooling,	Direct and indirect greenhouse-gas emissions; exposure to unreliable energy	Efficiency, heat recovery, electrification, renewable energy, production optimization
Chemicals	Dyes, auxiliaries, finishes, solvents		Toxicity, worker exposure, persistent substances, effluent contamination	Chemical substitution, ZDHC-style control, enzymatic and digital processes, closed-loop recovery
Waste	Cutting scraps, rejected goods, post-consumer textiles		Landfill, incineration, microfiber release, lost material value	Prevention, reuse, repair, remanufacturing, sorting, mechanical/chemical recycling
Labor and communities	Low wages, occupational exposure, informal recovery		Health risks, inequality, exclusion from formal value chains	Decent work, safer plants, formalization, skills, worker participation and social auditing
Consumption	Short use periods, washing, drying, replacement		Higher throughput and use-phase energy; premature disposal	Durable design, care guidance, repair, resale, sharing, demand moderation

Note. Source: Author's synthesis of [1] [2] [3] [6] [18].

Linear and circular systems: critical comparison

The linear model is operationally simple because responsibility ends close to the point of sale. Circular systems are more complex because value chains must coordinate forward and reverse flows. They require product information, collection channels, quality grading, secondary-material markets, and contractual alignment. The circular model can create new revenues through repair, resale, remanufacturing, material recovery, and service-based models, but it can also increase coordination costs and expose firms to uncertain supply and demand.

Table 2. Linear and circular textile systems compared

Dimension	Linear system	Circular system	Critical implication
Value proposition	Sell more units and replace quickly	Deliver utility, durability, services, and recovered value	Circularity challenges volume-based growth assumptions
Material input	Predominantly virgin or low-cost mixed fibers	Recycled, renewable, durable, and design-compatible materials	Material choice must anticipate end-of-life pathways
Product design	Aesthetic, cost, and speed optimized	Durability, repairability, modularity, mono-materiality, disassembly	Design decisions determine downstream recovery costs
Production	Throughput and unit cost focused	Resource efficiency, cleaner chemistry, renewable energy, traceability	Green manufacturing reduces the footprint of necessary production
Consumer relationship	Transaction at sale	Use, care, repair, resale, take-back, and data relationship	Firms need service and reverse-flow capabilities
Waste	Externalized to municipalities or informal actors	Managed as a resource with prevention hierarchy	EPR and market design are needed to internalize responsibility
Information	Limited composition and process transparency	Lifecycle information and chain-of-custody data	DPPs help only when data are accurate and interoperable

Performance measure	Sales, cost, speed	Lifetime utility, impact per use, recovery yield, worker welfare	Metrics must avoid rebound and burden shifting
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Note. Source: Author's synthesis of [4] [5] [16] [19].

Sustainable materials and eco-design

Sustainable material innovation spans recycled fibers, bio-based fibers, regenerated cellulose, agricultural residues, engineered fibers, and improved conventional materials. Recycled polyester can reduce dependence on virgin feedstock when collection and processing are credible, while recycled cotton can reduce demand for virgin cotton but may have shorter fibers and therefore require blending or quality adjustments. Regenerated cellulose and bio-based fibers may offer renewable feedstocks, but their impacts depend on land use, forest governance, chemicals, energy, and end-of-life behavior. The literature therefore rejects simple material rankings. A material is sustainable relative to a defined alternative, service performance, production route, use period, and recovery pathway [20] [21] [22].

Eco-design is the point at which many circular possibilities are either enabled or blocked. Design for durability reduces replacement demand; design for repair supports disassembly and spare parts; mono-material construction simplifies sorting and recycling; compatible trims and removable components reduce contamination; and digital identification preserves information after products leave the original manufacturer. Design trade-offs remain real. Blends can improve comfort, stretch, or performance but complicate separation. Durable finishes can extend life but introduce chemical concerns. Lightweighting can reduce material use but harm durability. LCA, material passports, wear testing, and stakeholder review should therefore be combined rather than relying on labels or material claims alone.

The strongest design principle is not “design for recycling” in isolation but design for the highest feasible value-retention option. A durable, repairable, and desirable product that remains in use for a long time can outperform a theoretically recyclable product that is discarded quickly. This principle aligns circular strategies with consumer behavior and business models rather than treating technology as a substitute for demand-side change.

Textile recycling technologies

Textile recycling is commonly grouped into mechanical, chemical, and biological or biochemical routes. Mechanical recycling involves sorting, cutting, shredding, opening, and re-spinning. It is comparatively established and can be suitable for clean mono-material or post-industrial waste, but repeated processing can shorten fibers and reduce quality. Chemical recycling dissolves or depolymerizes polymers and can potentially regenerate higher-quality outputs, yet it requires chemical management, energy, capital, feedstock purity, and reliable offtake. Biological routes use enzymes or microorganisms to break down selected polymers or components and are promising for targeted streams, although scale, reaction time, contamination, and cost remain constraints [23] [24] [25].

Table 3. Textile recycling technologies and their trade-offs

Route	Typical feedstock	Strengths	Limitations and risks	Best-fit condition
Mechanical fiber recycling	Cotton, wool, polyester, clean production scraps	Lower complexity; established equipment; useful for pre-consumer waste	Fiber shortening, quality loss, color contamination, downcycling	Clean, sorted, compatible feedstock with stable demand
Thermo-mechanical polymer recycling	Thermoplastic polyester and selected synthetics	Can recover polymer value without full chemical depolymerization	Sensitive to blends, additives, dyes, degradation, and contamination	High-purity thermoplastic streams
Chemical depolymerization	Polyester, polyamide, selected polymers	Potential for near-virgin-quality monomers or polymers	Chemical, energy, solvent, safety, and capital requirements	Large aggregated streams with strong process control
Dissolution/regeneration	Cellulosic or blended materials	Can separate or regenerate components;	Solvent recovery, purity, additives, and scale-up challenges	Designed-for-recycling materials

	under chemistry	suitable	supports textile ambition	textile-to-		and verified solvent loops
Enzymatic/biological recycling	Selected polyester, or blended fractions	cellulose, or	Potentially lower-temperature pathways	selective and	Reaction enzyme contamination, industrial scale	rate, cost, and Targeted streams supported by research and controlled inputs
Reuse and remanufacturing	Garments, household textiles, industrial textiles		Preserves value and production	embodied avoids new	Quality hygiene, demand, intensity	grading, logistics, and labor Durable products with accessible collection and markets

Note. Source: Author's synthesis of [6] [23] [24] [25] [26].

A critical synthesis reveals that recycling technology cannot compensate for poor upstream design. Mixed fiber products, elastane, coatings, prints, buttons, zippers, and unknown chemical treatments reduce sorting accuracy and process yield. Conversely, standardized composition, accessible product data, low contamination, and aggregation can improve economics. The best recycling pathway is consequently a value-chain decision beginning at design and ending with a market for secondary material.

Green manufacturing, water, energy, and dyeing

Green manufacturing seeks to prevent pollution and resource loss while maintaining product quality and competitiveness. In textiles, the largest operational opportunities often occur in wet processing, where dyeing, washing, bleaching, printing, and finishing require water, heat, chemicals, and wastewater treatment. Low-liquor-ratio dyeing, foam and air-assisted application, digital printing, plasma and ozone treatments, enzymatic preparation, supercritical carbon dioxide dyeing for suitable applications, and improved dosing can reduce selected burdens. Their performance must nevertheless be evaluated with process-specific LCA because lower water use may increase electricity demand, capital expenditure, or maintenance complexity [27] [28].

Energy efficiency includes efficient motors, variable-speed drives, insulation, boiler optimization, heat recovery, steam management, drying control, renewable electricity, and electrification where feasible. Renewable energy can reduce operational emissions, but it does not remove the need for efficiency; inefficient plants powered by renewables still consume materials and create wastewater. Energy management also has a competitiveness dimension in Pakistan and other developing economies because energy price volatility and reliability affect production planning, quality, and export compliance.

Safer chemistry is equally important. Substitution is preferable to end-of-pipe treatment when hazardous dyes, auxiliaries, or finishes can be avoided. However, chemical substitution requires performance testing, procurement control, worker training, laboratory capacity, and credible verification. Digital printing may reduce overproduction and application losses for some products, but ink chemistry, substrate preparation, curing energy, and equipment utilization must be included in the assessment. "Waterless" claims should therefore be treated as bounded process claims, not as proof of overall sustainability.

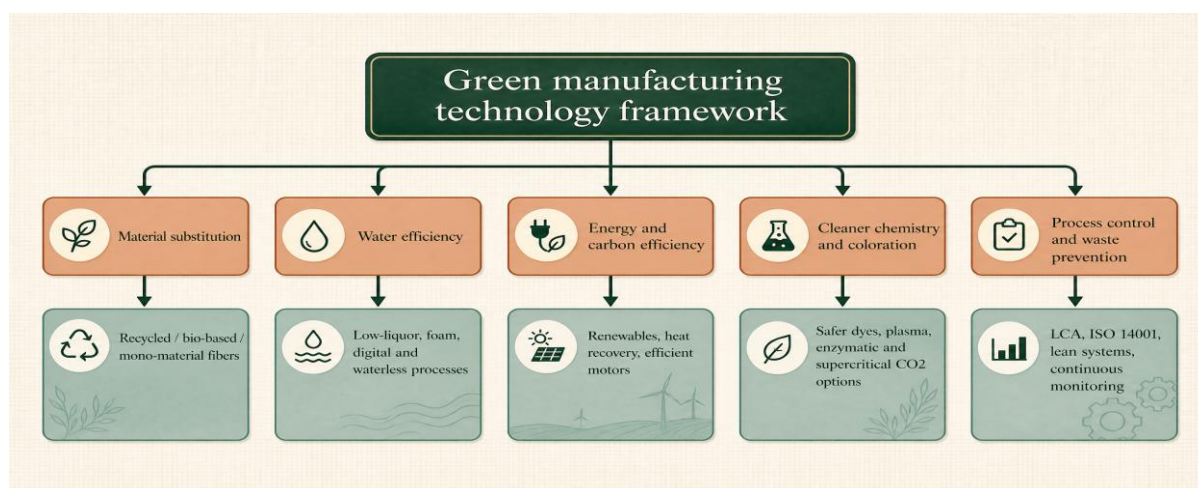


Figure 3. Green manufacturing technology framework. Source: Author's conceptualization.

Table 4. Green manufacturing technologies and expected contributions

Technology or practice	Primary resource or impact target	Enabling condition	Main caution
Low-liquor and optimized dyeing	Water, chemicals, heat	Recipe control, compatible machinery, skilled operators	Capital cost and quality consistency
Digital textile printing	Water, chemicals, sampling waste	Suitable inks, substrates, curing, high equipment utilization	Energy and ink impacts must be included
Enzymatic processing	Chemicals, temperature, wastewater load	Stable enzymes, process control, trained staff	Substrate-specific performance and scalability
Plasma, ozone, and advanced surface treatment	Water, chemicals, finishing time	Safety systems and validated product quality	Electricity, equipment, and application boundaries
Heat recovery and efficient drying	Energy and emissions	Thermal integration and maintenance	Payback depends on operating profile
Renewable electricity and electrification	Scope 1 and 2 emissions	Grid access, storage, finance, reliable equipment	Upstream materials and process heat may remain fossil-based
IoT metering and process control	Water, energy, defects, downtime	Sensors, data infrastructure, worker capability	Data quality, cybersecurity, and maintenance
Cleaner production and lean methods	Material loss, rejects, time	Management commitment and continuous improvement	Efficiency gains can increase output unless governed
Closed-loop water and wastewater treatment	Freshwater withdrawal and pollution	Adequate treatment, monitoring, sludge management	Concentrate and sludge require responsible handling

Note. Source: Author's synthesis of [27] [28] [29] [30].

LCA and sustainability assessment

LCA provides a structured method to compare products and processes across defined life-cycle stages. It is valuable for testing claims about recycled materials, reuse, repair, dyeing, and energy systems. Yet LCA is not a neutral answer machine. Results depend on the functional unit, system boundary, allocation, temporal assumptions, use-phase behavior, recycling method, substitution credit, electricity mix, and data quality. For textiles, “per kilogram,” “per garment,” and “per wear” can generate different conclusions. A durable garment may have higher production impacts but lower impact per use if it is worn much more often. Reuse may be beneficial, but washing, transport, quality loss, and rebound demand need consideration [11] [12] [31].

The literature supports combining environmental LCA with life-cycle costing, social-LCA or decent-work indicators, material-flow analysis, circularity indicators, and sensitivity analysis. A circularity metric that counts recycled content without measuring lifetime, toxicity, recovery yield, and secondary-material substitution can reward superficial interventions. Robust assessment should report assumptions transparently and test alternative scenarios rather than presenting a single deterministic ranking.

Industry 4.0, AI, IoT, blockchain, and DPPs

Digitalization can support circularity in four connected ways. First, it improves visibility: sensors and enterprise systems can identify resource losses, quality defects, machine condition, and batch composition. Second, it improves prediction: AI can forecast demand, optimize cutting, detect defects, and support automated sorting. Third, it improves coordination: digital platforms connect brands, manufacturers, repair providers, collectors, recyclers, and consumers. Fourth, it improves accountability: DPPs and blockchain can record product attributes, certifications, transactions, and chain-of-custody events [8] [9] [32].

The literature also warns against technological determinism. AI models are only as good as training data, labels, lighting conditions, fiber complexity, and maintenance. IoT produces value only when data are interpreted and translated into operating

decisions. Blockchain cannot verify facts entered incorrectly at the source. DPPs may create reporting burdens for small suppliers if data fields, software, and financing are not standardized. Digital systems also consume energy and raise questions about privacy, commercial confidentiality, worker surveillance, interoperability, and cybersecurity. The appropriate principle is **digital sufficiency**: deploy the minimum reliable digital architecture that solves a defined circular problem, then scale it through open standards.

Table 5. Digital technologies and circular capabilities

Digital technology	Circular capability	Textile application	Limitation governance	requiring
IoT sensors	Real-time measurement and control	Water, energy, temperature, humidity, machine health, effluent monitoring	Sensor connectivity, skills	calibration, cybersecurity,
AI and machine vision	Classification, prediction, optimization	Fiber sorting, defect detection, demand forecasting, cutting optimization	Bias, training data, explainability, maintenance	
Digital twins	Scenario simulation and process optimization	Test process changes, maintenance, energy and water scenarios	Model fidelity and data integration	
Blockchain/distributed ledgers	Shared traceability and transaction records	Chain-of-custody, recycled-content claims, supplier events	Energy, governance, data-entry integrity, interoperability	
Digital product passports	Lifecycle information and product identity	Composition, repair, care, dismantling, recycling instructions	Standardization, cost, privacy, access for SMEs	
Cloud platforms and marketplaces	Coordination of dispersed actors	Take-back, resale, repair booking, secondary-material trading	Platform power, data ownership, inclusion	
Robotics and automation	Consistent handling and productivity	Automated sorting, cutting, inspection, material handling	Capital intensity and employment transition	

Note. Source: Author's synthesis of [8] [9] [10] [32] [33] [34].

Closed-loop supply chains and policy

A closed-loop textile supply chain links forward production with reverse collection, sorting, reuse, repair, remanufacturing, and recycling. Reverse logistics is difficult because flows are dispersed, uncertain, low-density, heterogeneous, and quality-sensitive. Collection costs can exceed material value, especially where municipalities or firms lack aggregation infrastructure. Quality grading must distinguish wearable products from repairable products, fiber-recyclable products, and contaminated residues. Partnerships among brands, retailers, municipalities, social enterprises, informal collectors, and recyclers are therefore essential.

EPR can change incentives by assigning producers financial or operational responsibility for post-consumer products. Properly designed EPR can fund collection, sorting, reuse, recycling, data systems, and worker formalization. Poorly designed EPR may create administrative burdens, encourage low-value recovery, or exclude small producers and informal workers. Policy should combine eco-design requirements, minimum information standards, safe-chemical controls, procurement, recycled-content demand, landfill restrictions where appropriate, and transparent reporting [35] [36].

Pakistan and developing-economy perspective

Pakistan is an important textile and apparel manufacturing economy with capabilities in cotton, spinning, weaving, processing, home textiles, and garments. Its transition conditions differ from those in high-income consumer markets. The sector faces pressure from water scarcity, wastewater pollution, energy reliability and cost, aging equipment, fragmented supplier networks, limited finance for SMEs, and uneven enforcement. At the same time, local capabilities in repair, reuse, informal recovery, low-cost entrepreneurship, and export-oriented compliance can provide foundations for circularity [13] [14] [15] [37].

The developing-economy perspective changes the sequence of priorities. High-cost automation or advanced chemical recycling may not be the first intervention for many firms. Metering, preventive maintenance, boiler and motor efficiency, wastewater monitoring, cleaner chemistry, modular product design, production-scrap segregation, and industrial symbiosis may deliver more immediate benefits. Digital systems should be designed for incremental adoption, mobile access, shared service providers, and interoperable data fields rather than assuming that every SME can maintain sophisticated proprietary software.

Social inclusion is particularly important. Informal collectors and sorters may already recover value but remain exposed to unsafe conditions and excluded from formal policy. A circular transition that formalizes access, improves safety, recognizes skills, and shares value can support SDG 8 while strengthening supply reliability. Conversely, automation that eliminates livelihoods without retraining or protection can undermine social sustainability. Pakistan therefore requires a just-transition lens combining industrial upgrading, environmental enforcement, worker voice, and inclusive enterprise development.

Research Methodology

Research design

This study uses a qualitative systematic/narrative literature-review design. The systematic component provides an explicit search logic, inclusion criteria, thematic coding, and evidence-tracking approach. The narrative component is necessary because the literature is heterogeneous: it includes conceptual CE studies, process engineering research, LCA comparisons, technology reviews, supply-chain studies, policy analyses, and developing-economy case studies. A meta-analysis would be inappropriate because the studies do not share sufficiently comparable outcomes, functional units, system boundaries, or experimental designs.

The review follows the spirit of transparent review practice by defining the question, searching multiple source types, screening relevance, extracting evidence, and synthesizing patterns and contradictions. It is not presented as a registered PRISMA review because the paper's purpose is an integrative framework rather than a statistical estimate. The review includes peer-reviewed journal articles, scholarly book chapters where directly relevant, and authoritative institutional reports for policy and sector context. Search concepts included "textile circular economy," "sustainable textile manufacturing," "textile recycling," "life-cycle assessment fashion," "sustainable dyeing," "Industry 4.0 textile," "digital product passport," "closed-loop textile supply chain," and "Pakistan textile sustainability."

Inclusion and exclusion criteria

Included sources had to address at least one of the following: textile or apparel environmental performance; CE strategy; fiber, garment, or textile recycling; sustainable material innovation; cleaner textile processing; LCA; digital technology supporting circularity; reverse logistics or EPR; or Pakistan/developing-economy textile transition. Priority was given to 2020–2026 scholarship, while earlier seminal works were retained where they define CE, LCA, or textile impact concepts. Sources were excluded when they lacked identifiable authorship and publication information, made unsupported commercial claims, duplicated another publication, or addressed sustainability only tangentially.

Search and evidence handling

The evidence base was assembled through scholarly search interfaces, publisher pages, open-access repositories, and bibliographic metadata services. Bibliographic records were checked for author names, year, title, journal or publisher, volume and issue where available, and DOI or stable URL. Search results were treated as discovery aids rather than evidence; claims were based on article abstracts, full texts, publisher metadata, or institutional documents. Because publication dates and citation counts can change, the review does not use citation counts as evidence of quality.

A structured extraction sheet recorded: study purpose; geography; sector stage; method; technology or strategy; environmental, economic, and social outcomes; limitations; and relevance to the integrated framework. Themes were refined through constant comparison. For example, "recycling" was split into collection, sorting, process technology, product quality, and market demand

rather than coded as one undifferentiated category. “Digitalization” was split into measurement, prediction, traceability, coordination, and governance.

Analytical procedure

The analysis proceeded in four stages. First, descriptive mapping identified the dominant themes and the relative emphasis on materials, processes, use, end-of-life, digital systems, and policy. Second, critical comparison examined where findings converged and where outcomes depended on assumptions. Third, causal synthesis connected upstream decisions with downstream feasibility. Fourth, the framework was constructed by placing value-retention strategies in hierarchical order and overlaying enabling technologies and governance mechanisms.

The synthesis used five evaluation lenses: environmental effectiveness; economic feasibility; technical maturity; institutional and infrastructural requirements; and social justice. An intervention was considered strongly supported only when it performed plausibly across multiple lenses or when limitations were clearly bounded. This approach avoids treating a laboratory breakthrough, a single pilot, or a marketing claim as evidence of system-level transformation.

Quality, reflexivity, and limitations

Quality was supported through source triangulation, preference for peer-reviewed studies, explicit separation of evidence from conceptualization, and cautious reporting of quantitative claims. Reflexivity is necessary because circular economy is normatively attractive and may encourage confirmation bias. The analysis therefore asked not only how a technology can reduce impact, but also whether it creates rebound, transfers burdens, depends on unrealistic collection rates, or worsens labor conditions.

The methodology has limitations. It is qualitative and cannot estimate a pooled effect size. The publication record may overrepresent successful innovations and well-resourced regions. English-language searches can underrepresent local knowledge and non-English research. Rapid changes in DPP policy, AI tools, and recycling investment mean that some technologies may evolve faster than peer-reviewed evidence. Finally, Pakistan-specific evidence is less extensive than evidence from Europe, China, India, and global fashion markets; conclusions for Pakistan are therefore analytical and strategic, not a substitute for plant-level audits or national material-flow data.

Results, Analysis & Discussion

Result 1: Circularity is a hierarchy, not a technology checklist

The first result is that circular textile innovation is best organized as a hierarchy of value retention. Prevention and reduction come first because the least harmful product is often the one not produced, especially when demand is speculative or products are underused. Durability and repair come next because they extend service life while preserving the highest share of embodied material and labor value. Reuse and resale can distribute products to additional users, although transport, cleaning, quality, and rebound effects require assessment. Remanufacturing can recover functionality and identity for selected garments, uniforms, technical textiles, and household products. Recycling is essential for residual streams but should be optimized for textile-to-textile or high-value outputs where feasible.

This hierarchy answers Research Question 2 by showing that no universal “best” material or technology exists. The strongest potential comes from combinations: eco-design that enables durability and separation; green processing that lowers burdens; collection and sorting that preserve quality; and recycling technologies matched to feedstock. It also addresses Objective 2 by reframing innovation from a race for novel fibers toward a portfolio of product, process, business-model, and system innovation.

A key tension is between scale and quality. Reuse can retain more value but requires labor, inspection, hygiene, style relevance, and accessible markets. Mechanical recycling is comparatively available but may downcycle materials. Chemical recycling can deliver higher-quality outputs but demands scale, purity, investment, and environmental controls. The strategic implication is to avoid sending every collected textile to the same process. Sorting should route products according to the highest feasible value pathway.

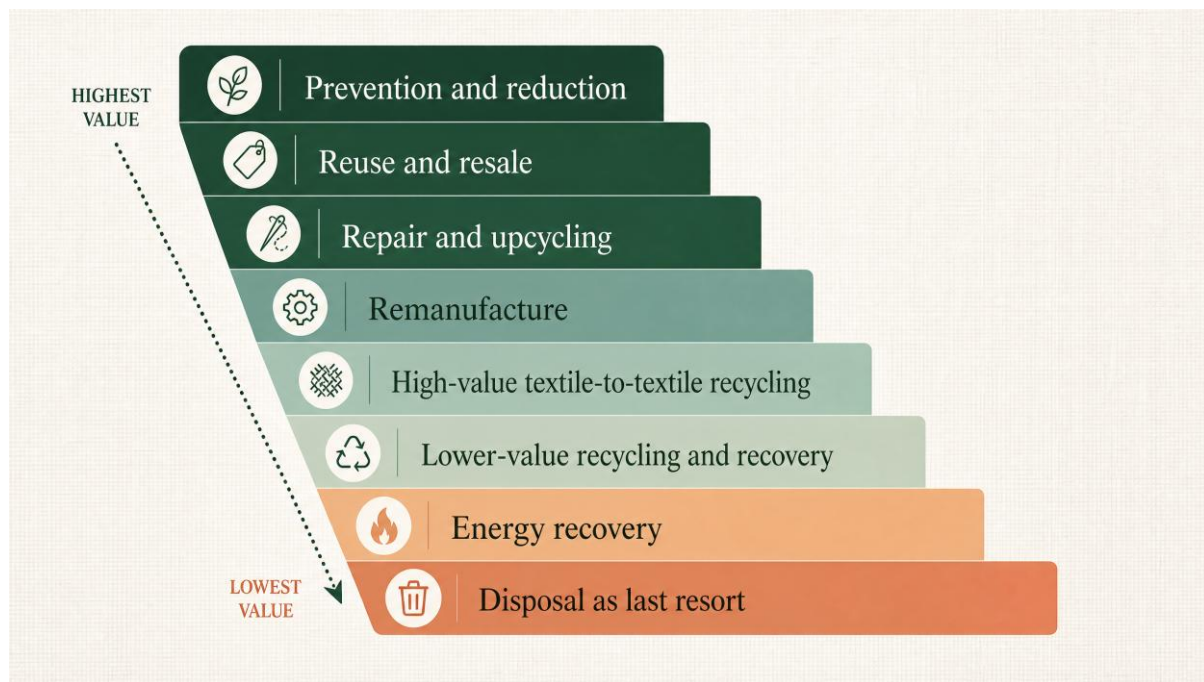


Figure 6. Textile waste management hierarchy. Source: Author's conceptualization.

Result 2: Green manufacturing produces the most immediate operational gains

The second result is that green manufacturing is the near-term bridge between circular ambition and factory-level action. Material circularity can take years to scale because collection, standards, and recycling infrastructure are required. Energy, water, chemical, and waste-efficiency measures can often begin with audits, metering, maintenance, operator training, and targeted equipment upgrades. The literature consistently indicates that process conditions matter: production rejects, rework, overdosing, inefficient drying, steam leakage, and poorly controlled recipes represent both environmental loss and financial loss [27] [29] [30].

Research Question 3 is answered by identifying five high-priority technology clusters. First, measurement and control reduce invisible losses. Second, efficient thermal and electrical systems reduce energy demand. Third, low-liquor, digital, enzymatic, plasma, ozone, and other cleaner coloration or finishing options can reduce selected water and chemical burdens. Fourth, wastewater treatment and water reuse control pollution and freshwater demand. Fifth, renewable energy and heat integration lower operational emissions. The appropriate sequence is measurement, prevention, efficiency, substitution, recovery, and renewable supply—not renewable supply as a substitute for process discipline.

The analysis also identifies a measurement problem. Many papers report water savings for a particular machine or step, but sector decisions need whole-system accounting. A lower-water process may involve more electricity, more cleaning chemicals, or lower throughput. LCA and process-level monitoring should therefore be used together. Plants should report intensity indicators such as water, energy, chemicals, rejects, and emissions per functional output, while also tracking absolute production and total impacts to detect rebound.

Result 3: Digital technologies are coordination infrastructure

The third result is that Industry 4.0 technologies matter less as isolated gadgets than as coordination infrastructure. IoT supports measurement, AI supports interpretation, DPPs support product memory, blockchain can support shared records, and reverse-logistics platforms support transactions. Figure 5 shows the relationship between these functions.

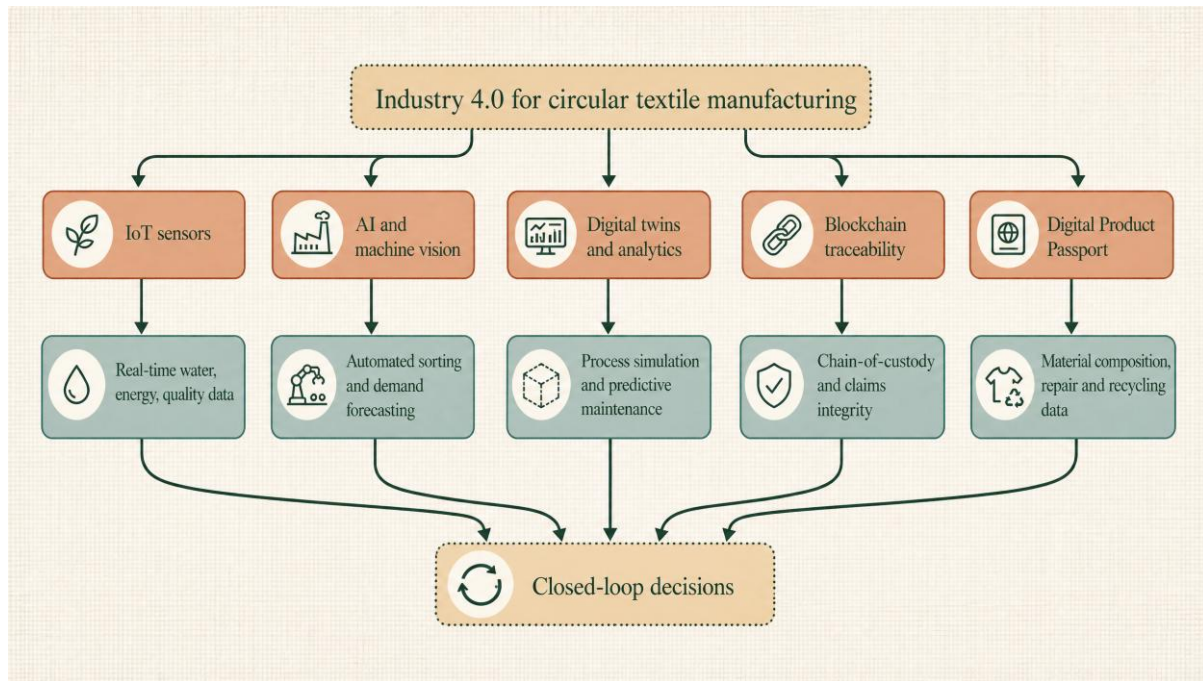


Figure 5. Industry 4.0 for circular textile manufacturing. Source: Author's conceptualization.

Research Question 4 is therefore answered conditionally. AI can improve sorting only when products are collected, presented, and labeled in ways that allow reliable classification. IoT can reduce resource use only when managers act on the data and machines are maintained. Blockchain can increase traceability only when upstream data are verified and participants agree on governance. DPPs can enable repair and recycling only when composition, treatments, and disassembly information are complete, accessible, and standardized.

The DPP is especially important because textiles lose information as they move through fragmented value chains. A passport can include fiber composition, material proportions, finishes, care guidance, repair history, recycled content, and end-of-life instructions. Yet information must be proportionate to risk and value. A micro-enterprise should not be forced to purchase a complex platform when a standardized, interoperable data service can provide the required fields. Public policy should define minimum data requirements, access rights, verification, and liability while allowing implementation flexibility.

Result 4: Closed-loop supply chains require reverse-flow economics

The fourth result is that reverse logistics is the practical bottleneck in circular textiles. Forward supply chains move predictable volumes from suppliers to consumers. Reverse flows are uncertain in timing, location, condition, composition, and quantity. This creates a coordination problem: recycling plants need consistent feedstock, collectors need aggregation and payment, brands need reliable data, and consumers need convenient take-back channels.

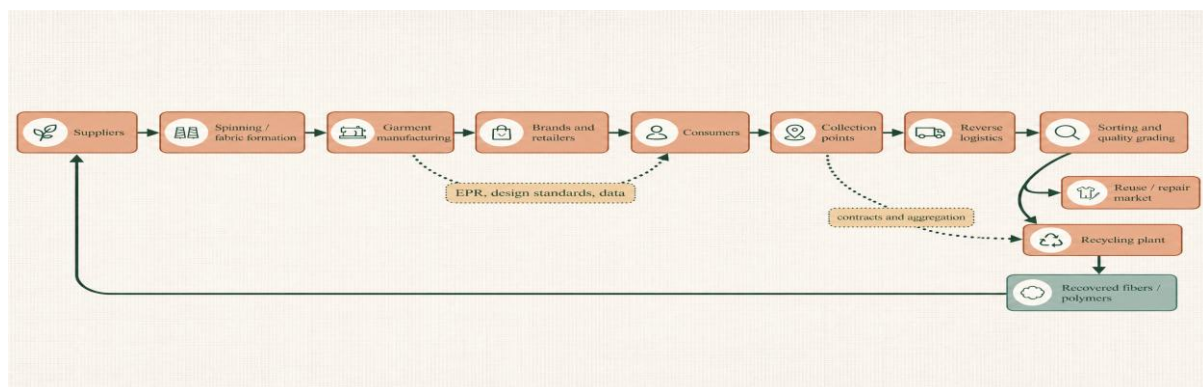


Figure 4. Closed-loop textile supply chain. Source: Author's conceptualization.

Research Question 5 is answered by identifying barriers across five layers. At the product layer, mixed fibers, trims, finishes, and low durability reduce recovery. At the operational layer, firms lack meters, skills, capital, and stable secondary-material markets. At the network layer, collection and sorting are fragmented. At the institutional layer, policy, standards, enforcement, and data governance are uneven. At the social layer, consumers may not repair or return products, while informal workers may be excluded from formal systems.

Closed-loop economics improves when products are designed for predictable routes, collection is aggregated, secondary material has committed buyers, and EPR or procurement creates demand. The business case should include avoided disposal, compliance, resilience, energy and water savings, brand value, new services, and risk reduction—not only the sale of recovered fiber. Public or blended finance may be justified where infrastructure creates environmental benefits that private actors cannot capture alone.

Table 6. Barriers and enablers, with developing-economy implications

Barrier	How it appears in textile systems	Enabler or intervention	Developing-economy priority
Fragmented value chains	Small suppliers, informal collectors, weak coordination	Producer platforms, cooperatives, shared facilities, contracts	Build aggregation and shared services before high-cost automation
Limited finance	High cost of efficient machinery, sensors, treatment, and recycling	Green credit, guarantees, concessional finance, pay-as-you-save	Link finance to verified resource and social outcomes
Poor data	Unknown composition, missing process records, inconsistent metrics	DPP minimum fields, metering, interoperable standards	Mobile-first, low-cost data systems and training
Mixed and contaminated waste	Blends, trims, finishes, moisture, and dirt	Eco-design, source segregation, AI sorting, quality grading	Begin with clean industrial scraps and priority product categories
Weak policy enforcement	Uneven wastewater, chemical, labor, and waste compliance	EPR, inspections, disclosure, procurement, standards	Combine enforcement with technical assistance for SMEs
Skills gap	Lack of LCA, maintenance, digital, repair, and recycling expertise	TVET, university-industry programs, worker upskilling	Treat skills as infrastructure, not an optional add-on
Informal-sector exclusion	Unrecognized recovery work and occupational risk	Formal contracts, PPE, cooperatives, fair payment	Upgrade rather than displace existing recovery capabilities
Consumer behavior	Low repair demand, low return rates, rapid replacement	Guarantees, repair networks, take-back incentives, education	Use trusted local networks and affordable service models
Technology uncertainty	Pilots do not scale or lack markets	Demonstration programs, standards, offtake agreements	Select robust, maintainable technologies before frontier options

Note. Source: Author's synthesis of [13] [14] [15] [35] [37] [38].

Result 5: Pakistan requires a staged, inclusive transition

Pakistan and comparable developing economies should not be treated as delayed versions of high-income markets. Their textile sectors often combine export manufacturing, domestic markets, informal recovery, labor-intensive production, and resource constraints. Research Question 6 is answered through a staged transition model.

Stage one is measurement and compliance. Mills should establish water, energy, chemical, wastewater, reject, and maintenance baselines. This stage creates visibility and reduces losses without requiring radical product change. Stage two is efficiency and safer production. Investments in motors, boilers, steam, heat recovery, dosing, wastewater treatment, renewable electricity, and operator capability reduce cost and environmental risk. Stage three is circular product and network design. Firms can prioritize mono-material or separable products, production-scrap segregation, repair services, take-back pilots, and partnerships with recyclers. Stage four is digital and advanced recycling scale-up. Once data, volumes, skills, and markets exist, AI sorting, DPPs, digital twins, and chemical or biological recycling can be deployed selectively.

This sequencing is important because premature investment in advanced technology may fail when collection volumes, quality standards, power reliability, spare parts, or trained personnel are absent. It is also important for employment. Repair, sorting, quality grading, maintenance, wastewater operation, and remanufacturing can generate work if standards and finance support decent conditions. Industrial policy should connect environmental performance with export competitiveness while preventing compliance costs from being shifted onto low-paid workers or small suppliers.

Pakistan also has an opportunity to connect circularity with cotton and agricultural value chains. Cotton waste, cutting scraps, and selected agricultural residues may support material or energy recovery, but each pathway requires LCA, contamination control, and food-versus-fiber safeguards where relevant. The country's established textile clusters can support shared wastewater facilities, testing laboratories, recycling hubs, and training centers. Export buyers and emerging product regulations can provide demand for verified performance, but local policy should ensure that compliance data also improve domestic environmental outcomes rather than serving only as paperwork for international buyers.

Result 6: The framework aligns sustainability with the SDGs

Research Question 7 is answered by mapping the integrated framework to the requested SDGs. SDG 6 is supported through water efficiency, wastewater treatment, chemical substitution, and watershed-sensitive production. SDG 7 is supported through energy efficiency, renewable electricity, heat recovery, and electrification. SDG 8 is supported through decent work, safe chemistry, repair and remanufacturing employment, worker skills, and formalization of recovery work. SDG 9 is supported through cleaner industrial infrastructure, innovation, digital systems, and resilient supply chains. SDG 12 is the central goal because prevention, sustainable materials, eco-design, responsible consumption, EPR, and circular production directly address production and consumption patterns. SDG 13 is supported by reducing energy demand, fossil dependence, transport inefficiency, and waste-related emissions.

The SDG mapping should not be used as a branding exercise. Progress in one goal can create conflict with another. Automation may improve productivity while displacing workers. Waterless processing may shift burden to energy. Recycling may reduce virgin inputs while increasing chemical risk. Export compliance may improve data while excluding small suppliers. Integrated governance is therefore required to monitor co-benefits and trade-offs.

Table 7. Research objectives and synthesized findings

Objective		Synthesized finding
Examine impacts		Textile impacts are distributed across materials, wet processing, energy, use, waste, and labor; no single stage explains sustainability performance
Compare strategies	circular	Prevention, durability, repair, reuse, and remanufacturing generally retain more value than recycling, but recycling is essential for residual streams
Analyze manufacturing	green	Measurement, efficiency, cleaner chemistry, water management, heat recovery, and renewable energy offer complementary operational gains

Objective	Synthesized finding
Assess Industry 4.0	Digital tools enable measurement, prediction, traceability, and coordination but require standards, data quality, skills, and governance
Examine closed loops	Reverse logistics, sorting, quality grading, offtake markets, EPR, and product information are essential to close material loops
Address Pakistan	A staged transition beginning with measurement, compliance, efficiency, skills, and shared infrastructure is more feasible than technology leapfrogging
Map SDGs	Integrated action can support SDGs 6, 7, 8, 9, 12, and 13, provided trade-offs and distributional effects are measured

Note. Source: Author's synthesis of the reviewed literature.

Proposed integrated framework

The proposed framework integrates the core lifecycle demanded by the research problem: Sustainable Materials → Eco-Design → Green Manufacturing → Smart Manufacturing → Use → Collection → Sorting → Reuse/Repair → Remanufacturing → Recycling → Secondary Materials → Manufacturing. It overlays AI, IoT, LCA, DPPs, blockchain, renewable energy, reverse logistics, EPR, and policy. Each overlay has a different role. LCA tests decisions and trade-offs. IoT measures and controls processes. AI improves prediction, inspection, and sorting. DPPs carry product information. Blockchain can support shared records where appropriate. Renewable energy reduces operational emissions after efficiency. Reverse logistics moves products and materials. EPR finances and governs post-use responsibility. Policy establishes minimum standards, incentives, accountability, and worker protection.

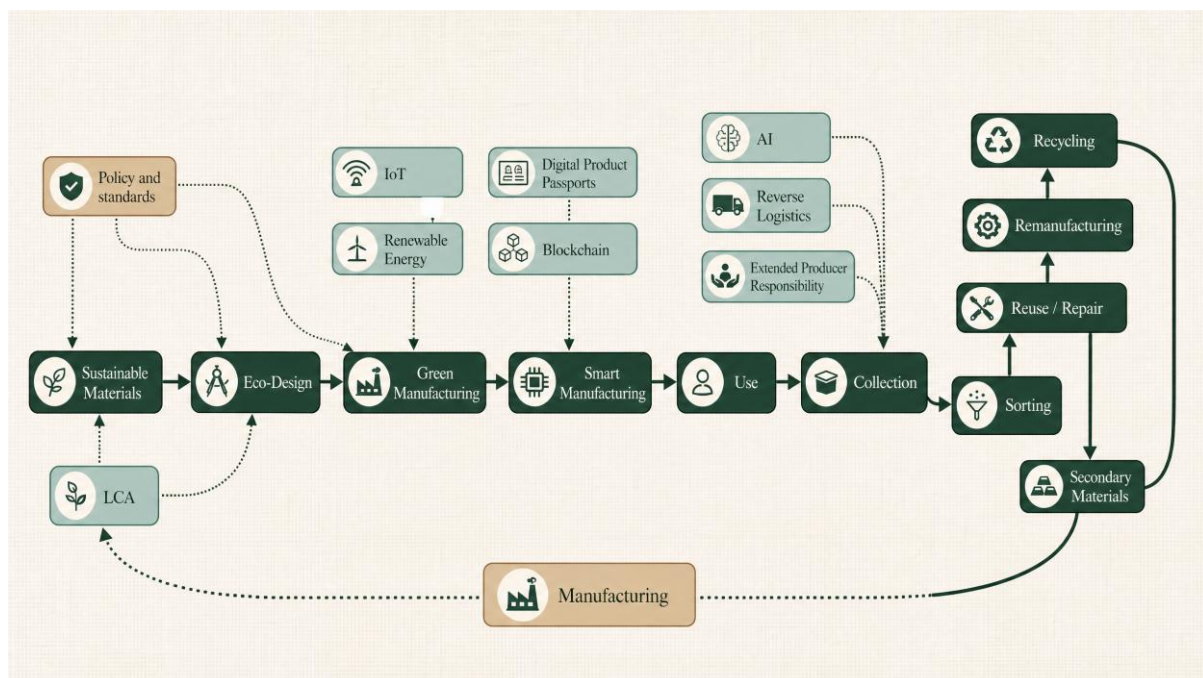


Figure 7. Proposed integrated circular economy and green manufacturing framework. Source: Author's conceptualization.

The framework's central proposition is that circularity is an engineered and governed system, not an end-of-pipe activity. Upstream design and manufacturing determine the quality and cost of downstream recovery. Downstream collection and recycling determine whether sustainable materials can be supplied back to manufacturing. Digital technologies connect the two sides, but governance determines whether their information is trusted and useful. The framework is therefore recursive: production learns from returned products, returned products inform design, and design determines future recovery performance.

Table 8. Research questions and answers

Research question	Answer from the synthesis
RQ1: What are the problems of linear textiles?	Resource depletion, water and chemical pollution, energy and climate impacts, waste, short use periods, labor risks, and value loss across fragmented chains
RQ2: Which circular strategies are strongest?	Prevention, durability, repair, reuse, and remanufacturing generally rank above recycling; the best option depends on product, use, collection, and LCA assumptions
RQ3: Which green technologies help?	Metering, efficient machinery, low-liquor and cleaner coloration, enzymatic/surface treatments, heat recovery, wastewater control, renewables, and process optimization
RQ4: How does Industry 4.0 help?	It provides measurement, prediction, traceability, product memory, quality sorting, and reverse-flow coordination, subject to data and governance conditions
RQ5: What blocks closed loops?	Poor design, fragmented collection, mixed waste, weak markets, finance gaps, skills shortages, weak policy, limited data, and exclusion of informal workers
RQ6: What differs in Pakistan/developing economies?	Capital, infrastructure, energy, enforcement, SME, export, informal-sector, and skills conditions require staged and inclusive transition strategies
RQ7: How can SDGs be aligned?	Water, energy, decent work, innovation, responsible production, and climate action can be co-optimized through the integrated framework and transparent metrics

Note. Source: Author's synthesis of the reviewed literature.

Conclusion & Recommendations

Conclusion

This paper examined sustainable textile innovation through circular economy and green manufacturing technologies using a qualitative systematic/narrative literature review. The central conclusion is that textile sustainability cannot be achieved by adding a recycling facility, replacing one fiber, or installing one digital platform while leaving the linear business logic intact. The transition requires a connected system in which sustainable materials, eco-design, cleaner production, smart manufacturing, longer use, collection, sorting, repair, remanufacturing, recycling, and secondary-material markets reinforce one another.

The first objective was addressed by demonstrating that textile impacts include materials, water, energy, chemicals, emissions, waste, consumption, labor, and community effects. The second objective was addressed through a hierarchy that prioritizes prevention, durability, repair, reuse, and remanufacturing before recycling. The third objective was addressed by identifying green-manufacturing technologies for water, energy, chemical, carbon, and waste efficiency and by emphasizing the need for process-level and life-cycle evaluation. The fourth objective was addressed by showing that AI, IoT, DPPs, blockchain, digital twins, and platforms are enabling infrastructure rather than stand-alone solutions. The fifth objective was addressed through closed-loop supply-chain analysis, with reverse logistics, EPR, standards, markets, and product information identified as essential. The sixth objective was addressed through a staged Pakistan/developing-economy pathway. The seventh objective was addressed through SDG mapping.

The research gap is therefore answered with an integrated conceptual framework. Its distinctive contribution is to place value retention at the center, green manufacturing around the production stage, digital technologies across information-intensive interfaces, and policy and EPR around the system. The framework also recognizes that environmental gains must be tested with LCA and that social gains require decent-work, inclusion, and just-transition measures.

Recommendations for policymakers

Policymakers should establish a coherent textile circularity roadmap linking eco-design, EPR, chemical safety, waste collection, recycled-content quality, DPPs, wastewater enforcement, renewable-energy access, and worker protection. EPR systems should finance collection, sorting, reuse, repair, and recycling according to the waste hierarchy rather than rewarding only the cheapest disposal route. Regulations should define interoperable minimum product-information fields, allowing SMEs to participate through shared digital services.

Public procurement should create demand for durable, repairable, recycled, and responsibly produced textiles. Incentives should be conditional on verified resource, emissions, chemical, and social performance. Governments should support shared wastewater treatment, testing laboratories, recycling hubs, reverse-logistics aggregation, and demonstration plants. In Pakistan, industrial clusters and export associations can host shared services that individual SMEs cannot finance alone.

Policy should also recognize informal workers and small enterprises. Formalization should provide safer conditions, fair payment, access to training, and participation in design of collection systems. Enforcement should be paired with technical assistance, phased compliance, and affordable finance; otherwise, standards may simply push pollution and work into less visible segments.

Recommendations for textile firms and brands

Firms should begin with a material and process baseline covering fiber composition, water, energy, chemical inputs, rejects, wastewater, labor conditions, and post-use pathways. They should then prioritize high-return measures such as preventive maintenance, efficient motors and boilers, dosing control, heat recovery, process optimization, water reuse where safe, and renewable electricity. Capital decisions should use LCA and life-cycle costing rather than relying on one-dimensional claims.

Brands and manufacturers should create design standards for durability, repairability, separability, and verified material information. Product teams should identify the intended highest-value recovery pathway before finalizing fiber blends, trims, finishes, and labels. Take-back pilots should be measured by return rate, quality grade, reuse share, repair share, recycling yield, residue, and downstream destination. Contracts should include offtake commitments so that recovered materials have a credible market.

Digitalization should follow a business problem. IoT should target high-loss processes; AI should target classification, defects, and demand uncertainty; DPPs should carry information needed for care, repair, sorting, and recycling; and blockchain should be used selectively where shared records and verification justify the added complexity. Firms should publish boundaries, assumptions, and verification methods for sustainability claims.

Recommendations for Pakistan and developing economies

A practical national strategy should use four phases. The first phase should establish environmental and social measurement, basic compliance, and cluster-level technical support. The second should scale resource and energy efficiency, safer chemistry, wastewater treatment, and renewable-energy access. The third should develop product-design standards, repair and reuse networks, production-scrap markets, and formalized collection. The fourth should scale digital passports, AI sorting, advanced recycling, and secondary-material manufacturing where feedstock and markets justify investment.

Skills policy is central. Universities, technical and vocational institutions, industry associations, and development agencies should establish programs in LCA, industrial energy management, wastewater operation, textile chemistry, repair, sorting, maintenance, data management, and circular business models. Technology transfer should prioritize maintainability, spare parts, local service capacity, and worker training. Green finance should include concessional loans, credit guarantees, leasing, and pay-as-you-save models for SMEs.

Pakistan can also develop regional circular textile hubs connecting mills, garment factories, municipalities, collectors, repair enterprises, recyclers, and buyers of secondary material. These hubs can reduce reverse-logistics costs and create shared testing and data infrastructure. Any national circularity claim should distinguish pre-consumer production waste from post-consumer textile waste, report recovery yields rather than collection alone, and include labor and environmental safeguards.

Recommendations for future research

Future research should prioritize longitudinal, plant-level, and comparative studies that measure before-and-after performance rather than describing pilot intentions. Researchers should report functional units, system boundaries, allocation rules, electricity mixes, durability assumptions, transport, recycling yields, and uncertainty in LCA. More research is needed on social-LCA, informal-sector inclusion, gendered labor effects, and distribution of circular-economy value.

Pakistan-specific research should develop national and cluster-level material-flow analyses, wastewater and energy baselines, reverse-logistics maps, and techno-economic assessments of mechanical, chemical, and biological recycling. Studies should compare centralized and decentralized models and examine how EPR, export requirements, and domestic policy interact. Digital research should test low-cost, interoperable, multilingual, and mobile-first DPP architectures, especially for SMEs.

Finally, future work should examine rebound and sufficiency. Efficiency can lower cost and stimulate more production; recycling can reduce virgin demand but also legitimize disposability; resale can expand access but may increase consumption. Circular innovation should therefore be assessed against absolute resource use, total emissions, product lifetime, worker welfare, and ecological limits—not only efficiency ratios or recycled-content percentages.

Final statement

Sustainable textile innovation is feasible, but it is not automatic. It depends on aligning design, technology, infrastructure, markets, information, policy, and social institutions. The most credible pathway begins by preventing unnecessary production and extending useful life, then makes remaining production cleaner and smarter, and finally recovers unavoidable waste through appropriately matched technologies. For Pakistan and other developing economies, the transition should be staged, financeable, skills-intensive, and inclusive. When governed in this way, circular economy and green manufacturing can move textiles from a linear throughput model toward a resilient system that supports water security, clean energy, decent work, industrial innovation, responsible production, and climate action.

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