PAGE PARTNERSHIP FOR ACTION ON GREEN ECONOMY

वस्त्र मंत्रालय MINISTRY OF TEXTILES

UNIDO

BASELINE ASSESSMENT REPORT

Development of a Roadmap towards Inclusive and Green Transformation of the Textile Manufacturing Sector in India

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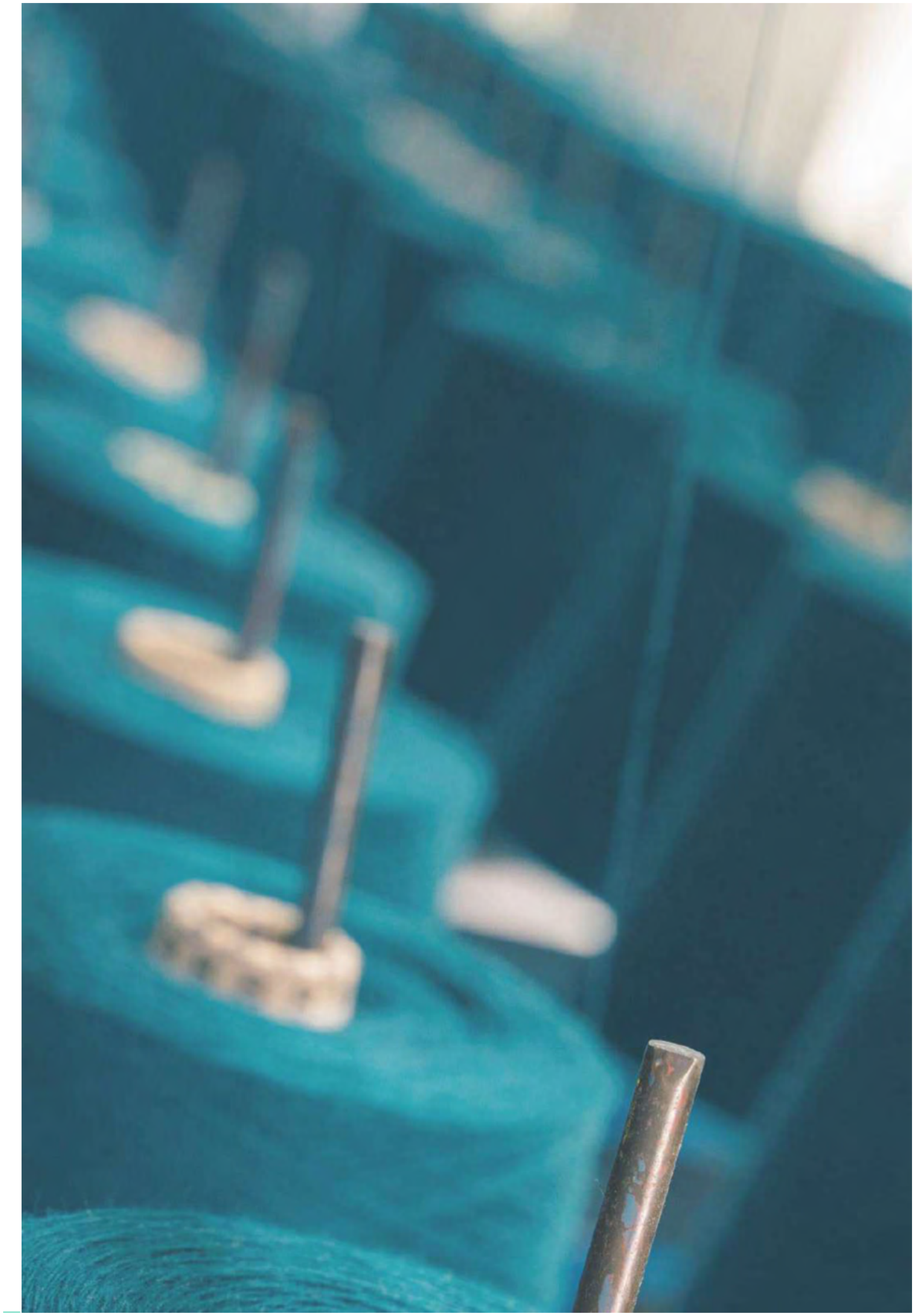
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List of Abbreviations

Abbreviation	Full Form
AEPC	Apparel Export Promotion Council
ATDC	Apparel Training & Design Centre
ATUF	Amended Technology Upgradation Fund Scheme
BAT	Best Available Techniques
BCI	Better Cotton Initiative
BOD	Biochemical Oxygen Demand
BREF	Best Available Techniques Reference Document
CAD/CAM	Computer-Aided Design / Computer-Aided Manufacturing
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CEA	Central Electricity Authority
CETP	Common Effluent Treatment Plant
CFC	Common Facility Centre
CITI	Confederation of Indian Textile Industry
COD	Chemical Oxygen Demand
CPCB	Central Pollution Control Board
D2C	Direct-to-Consumer
DPP	Digital Product Passport
DSIR	Department of Scientific and Industrial Research
DTG	Direct-to-Garment
ERP	Enterprise Resource Planning
ESG	Environmental, Social and Governance
ETP	Effluent Treatment Plant
EU	European Union
FDI	Foreign Direct Investment
FTA	Free Trade Agreement
GI	Geographical Indication
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GOTS	Global Organic Textile Standard
GPCB	Gujarat Pollution Control Board
HTHP	High Temperature High Pressure
HVAC	Heating, Ventilation and Air Conditioning
IBEF	India Brand Equity Foundation
IE3/IE4	International Efficiency Class 3 / Class 4 (Motor Standards)
ILO	International Labour Organization
IoT	Internet of Things
IP	Intellectual Property
ISM	Individual Spindle Monitoring
ITI	Industrial Training Institute
ITMA	International Textile Machinery Association (Exhibition)
ITMF	International Textile Manufacturers Federation
LLR	Low Liquor Ratio
LR	Liquor Ratio
MMF	Man-Made Fibre
MoEFCC	Ministry of Environment, Forest and Climate Change
MoT	Ministry of Textiles
MRSL	Manufacturing Restricted Substances List
MSME	Micro, Small and Medium Enterprises
NHDP	National Handloom Development Programme
NIFT	National Institute of Fashion Technology
NTTM	National Technical Textiles Mission
OECD	Organisation for Economic Co-operation and Development
PAGE	Partnership for Action on Green Economy
PC	Poly-Cotton
PIB	Press Information Bureau
PLC	Programmable Logic Controller
PVA	Polyvinyl Alcohol
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU Regulation)
RFID	Radio Frequency Identification
RMG	Ready-Made Garment
RO	Reverse Osmosis
ROI	Return on Investment
RSL	Restricted Substances List
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable Development Goal
SECO	State Secretariat for Economic Affairs (Switzerland)
SEDEX	Supplier Ethical Data Exchange
SIDA	Swedish International Development Cooperation Agency
SIMA	Southern India Mills' Association
SPCB	State Pollution Control Board
TDS	Total Dissolved Solids
TEXPRO-CIL	Cotton Textiles Export Promotion Council
TFH	Thermic Fluid Heater
TMMA	Textile Machinery Manufacturers' Association
TNPCB	Tamil Nadu Pollution Control Board
TRA	Textile Research Association
TSDF	Treatment, Storage and Disposal Facility
TUFS	Technology Upgradation Fund Scheme
ULR	Ultra-Low Liquor Ratio
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organization
UNITAR	United Nations Institute for Training and Research
USA	United States of America
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
ZDHC	Zero Discharge of Hazardous Chemicals
ZLD	Zero Liquid Discharge

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1. Executive Summary

1. Executive Summary

India's textile and apparel sector is one of the country's most economically vital industries — the 6th largest exporter globally, contributing 8.21% of total national exports (FY 2023-24) and employing over 45 million people directly and more than 100 million indirectly. The sector spans the complete value chain from raw fibre to finished garment, providing unique competitive advantages rooted in scale, diversity, and skilled labour.

This Baseline Assessment Report has been prepared under the Partnership for Action on Green Economy (PAGE) India programme. This joint UNIDO-ILO work package started with an inventory and appraisal of policy issues and macro-level levers for inclusive and green manufacturing transformation, expected to set the stage for deep dives for technology and innovation roadmaps for key manufacturing sectors (led by UNIDO) and green jobs and just transition policy and preparedness (led by ILO). The textile and apparel sector had been proposed as the first target sector as the first phase of UNIDO work package of developing a Technology and Innovation Roadmap for India's textile sector aligned to the Vision India @ 2047 framework for the development of a sustainable technology and innovation roadmap. It systematically documents the current state (2026) of technology adoption across five manufacturing segments — Spinning, Weaving, Knitting, Wet Processing, and Ready-Made Garments (RMG) — to establish an evidence base for the roadmap's 2030 milestones and 2047 vision.

45M+	Direct jobs
6th	Global Exporter Rank
$34.4B	FY24 T&A Exports
8.21%	Share of India Exports

Approach and Methodology

The assessment adopts a diagnostic-to-strategic framework structured across three phases:

1. Current State Diagnostic
2. Gap Analysis and Benchmarking
3. Roadmap Development

This report covers phase 1 findings and lays the groundwork for phases 2–3. A multi-method qualitative approach was employed, integrating:

- **Secondary research:** Government reports (MoT Annual Report 2024-25), industry data (AEPC, CITI, TEXPROCIL), international BAT references (EU BREFs, OECD, UNIDO case studies).
- **Structured stakeholder consultations** with textile manufacturers, technology suppliers, industry associations, government bodies, and international experts.
- **Comprehensive questionnaires** for validation across the value chain; and
- **Cluster-based geographic analysis** across major textile hubs including Tirupur, Ahmedabad, Surat, Ludhiana, Bhiwandi, Bengaluru, and Panipat.

Technology benchmarking compared India's adoption status against global best available techniques (BAT), leading exporters (China, Vietnam, Bangladesh, Turkey), and international sustainability requirements (NDCs, SDGs, ZDHC mandates, EU CBAM).

Technology Gap Summary:

Spinning
54.48M Spindles
2nd Globally

Scale Advantage:
- Low auto-doffing & ISM penetration in MSMEs
- Limited rotor & air-jet spinning vs global leaders
- <40% high-efficiency motors & VFDs in older mills
- ERP & IoT adoption nascent outside large exporters

Weaving
28L Handlooms
25L Powerlooms

World's largest:
- 60–70% still on slow shuttle looms
- Only 15–20% mills have digital monitoring
- IoT deployment <2%; AI design systems absent
- Bhiwandi rapier looms show viable upgrade path

Knitting
Tirupur INR 40,000 crore
55% exports

Export Momentum:
- Seamless & 3D knitting virtually absent
- Warp knitting <5%; limits technical textiles
- Machine vintage 8–12 yrs; quality gap widens
- IoT smart factory systems <5% active use

Wet Processing
70-80% of textile water pollution

Tirupur ZLD Model
- Liquor ratio 1:8–1:12 vs BAT target 1:3–1:4
- Waterless dyeing virtually absent in India
- Digital printing only ~1% of total printing
- Manual dosing & limited real-time monitoring

RMG
Apparel exports +35% since October 2024

Full Value Chain
- Sewing highly manual; robotic sewing absent
- 72% capacity in small units; CAD limited
- Industry 2.0–3.0 overall; few 4.0 pockets
- Bangladesh 20–30% lower labour cost pressure

Way Forward

Based on the baseline findings, five priority imperatives define India's technology transformation agenda towards Viksit Bharat 2047.

1. Selective Automation:
   20-30% productivity gain without displacing 45M+ jobs

2. Resource Efficiency:
   50% water - 40% energy reduction in wet processing by 2030

3. Quality and Value Addition
   Premium market access through in-line QC and 3D design

4. Digital Integration:
   IoT - AI/ML - ERP - Blockchain traceability at scale

5. Innovation and R&D
   - Raise R&D from <0/5% to 2% of turnover.
   - Cut import dependency

This baseline assessment establishes a comprehensive evidence base for the roadmap phases. The sector's transformation pathway is structured across three-time horizons. India's textile sector possesses the scale, diversity, and institutional capacity required to execute this transformation.

The sector's employment significance (45 million+ direct jobs), strategic export role, and domestic market depth makes it a priority vehicle for inclusive and green industrial transformation.

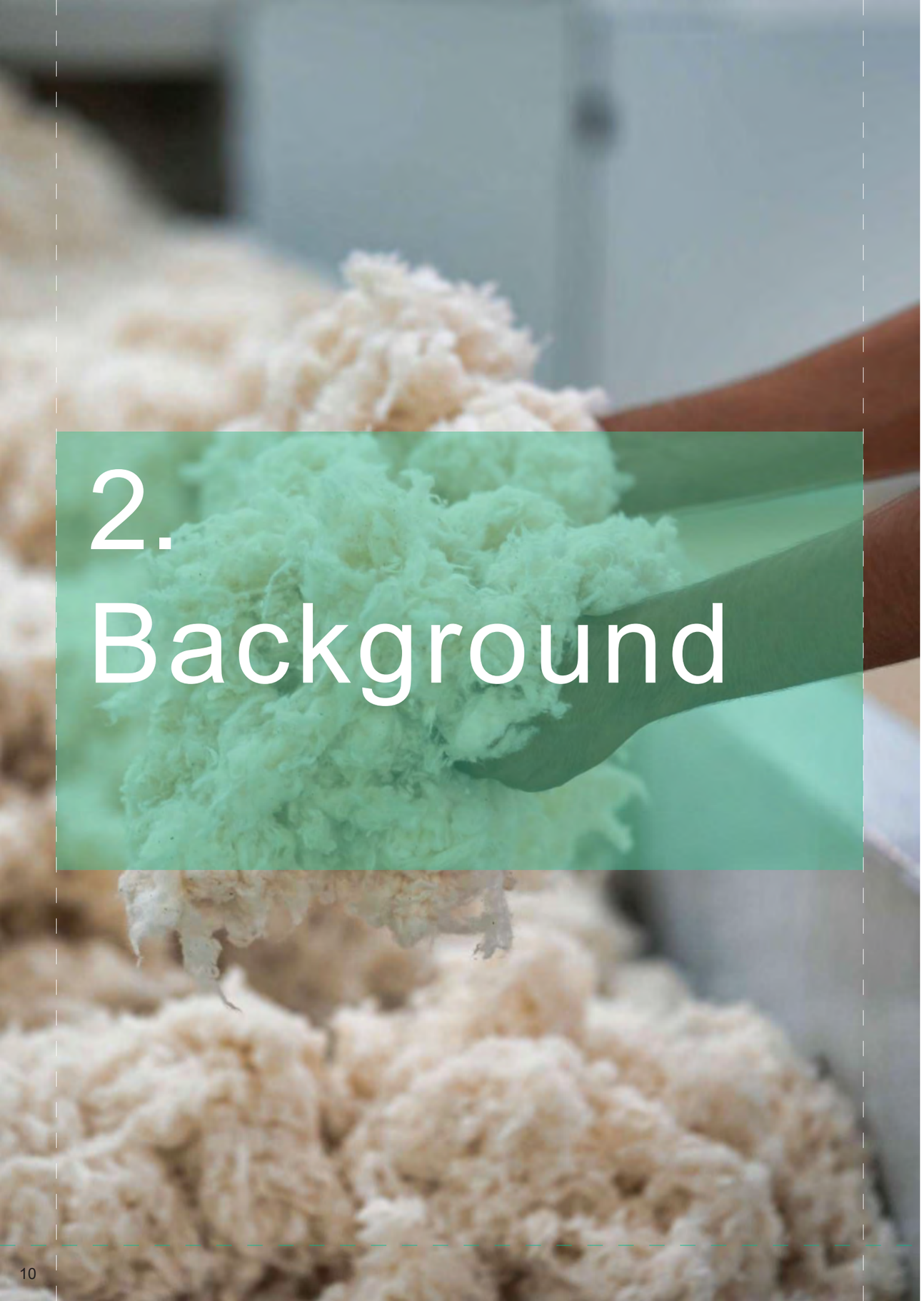
The roadmap phase will translate this baseline evidence into:
— actionable technology pathways
— investment requirements
— phased targets and
— coordinated institutional mechanisms
to guide India's textile sector toward technology excellence, sustainability leadership, and global competitiveness by 2047.

2026
Scale Proven Tech:
- Energy and Water efficiency,
- Renewables,
- Digital Foundations

2030
Commercialise emerging Tech:
- ULR dyeing,
- Recycled fibres,
- Advanced automation

2047
Net-zero and Circularity:
- Sustainable technology leader
- Viksit Bharat Vision





2. Background

2. Background

2.1 PAGE Initiative in India

The Partnership for Action on Green Economy (PAGE) is a United Nations inter-agency initiative that brings together the expertise of five UN agencies—UNEP, ILO, UNIDO, UNDP, and UNITAR. Launched in 2013 following the Rio+20 Conference, PAGE currently supports 22 partner countries through integrated policy advice, capacity development, and analytical tools.

The primary goal of PAGE is to assist countries in creating enabling policy conditions, incentives, business models, and partnerships to catalyse greater action and investment in green technologies and natural, human, and social capital.

By 2018, the Government of India had already embraced large-scale, integrated economy-wide approaches including resource efficiency, circular economy, and sustainable consumption and production to achieve the Sustainable Development Goals (SDGs) and Nationally Determined Contributions (NDCs).

A national green economy stocktaking exercise identified resource efficiency as the main entry point for PAGE support. In India, PAGE is overseen by the Ministry of Environment, Forests and Climate Change (MoEFCC), and coordinated by the United Nations Environment Programme (UNEP).

The United Nations Industrial Development Organization (UNIDO) and the International Labour Organization (ILO) work together under PAGE India on strategies, opportunities and challenges for inclusive and green manufacturing milestones and 2047 vision.

This joint UNIDO-ILO work package started with an inventory and appraisal of policy issues and macro-level levers for inclusive and green manufacturing transformation, expected to set the stage for deep dives for technology and innovation roadmaps for key manufacturing sectors (led by UNIDO) and green jobs and just transition policy and preparedness (led by ILO). The textile and apparel sector had been proposed as the first target sector for the development of a sustainable technology and innovation roadmap.

PAGE India Focus Areas	Institutional Partners
Circular economy frameworks and business models	Ministry of Environment, Forest and Climate Change (MoEFCC) – Lead ministry
Eco-labelling (strengthening India's Eco-mark Scheme)	National Institution for Transforming India (NITI Aayog)
Green manufacturing with initial focus on textiles	Ministry of Textiles
Sustainable public procurement	Ministry of Finance

Key Milestones

2018
India joins PAGE; Policy Brief on Resource Efficiency launched

2019
Task Force on Environmental Sustainability formed for Indian Railways

2022
Policy dialogue on "Unlocking Inclusive & Green Manufacturing" convened; assessment of technology status in textile value chains.

2023
Assessments published on green jobs, just transition readiness, and textile sector opportunities

2024
New Eco-Mark Certification Rules notified (October 2024),

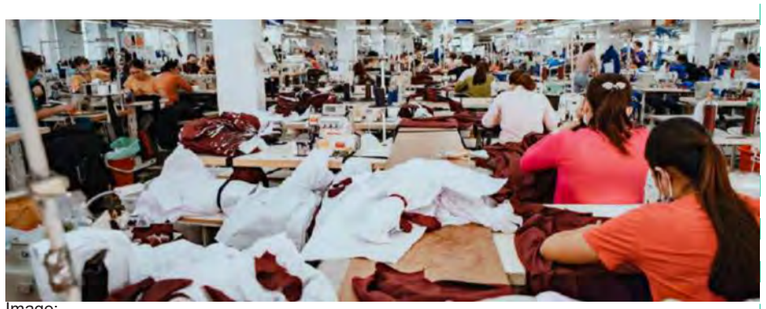


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https://www.unido.org/sites/default/files/unido-publications/2025-12/DPP-Report-V_1.6-lr.pdf

The textile sector was prioritized for PAGE India's green manufacturing interventions due to its

1. Economic significance
- 45+ million direct employment
- 6th largest exporter globally)

2. Environmental impact
- Resource-intensive with high water and energy consumption

3. Transformation potential
- Proven green technologies available

4. Policy momentum
- Industry associations advocating for green transition,
- cluster initiatives like Tirupur's ZLD achievement

2.2 Project Overview

Inclusive and green manufacturing represents a fundamental departure from business-as-usual industrial development. It entails transformation from a future industry that can be extrapolated based on current trends to one that must be back-casted from the inclusive and sustainability requirement, this future industry needs to meet—such as circularity, carbon neutrality, and resource efficiency.

Creating and strengthening incentives for this transformation will generate the motivation, capacity, momentum, and agency to drive change. However, incentives alone do not suffice to create a shared vision of plausible futures in terms of technology, products and services, markets and business models, and the research, innovation, market changes, and policy development required to realize these technologies.

The inclusive and green manufacturing transformation therefore benefits from visioning, expert and stakeholder consultations, partnerships, and transformation management—approaches already utilized globally within carbon-neutral energy transformation frameworks. Transformation planning and management can start with technology road mapping, an established tool for technology and product planning that aims to identify, define, and map strategies, objectives, and actions related to innovation and commercialization.

Popularized by Motorola Company in the 1970s to align technology development with product planning, technology road mapping is a process tool to build agreement around plausible product and technology futures, identify key technologies a sector needs to succeed, and define steps required to develop and implement those technologies.

The road mapping process typically involves five steps:

1. Scoping
Definition of the search area

2. Forecasting
Analysis of trends, needs, and potential

3. Back-casting
Projecting possible visions of the future back to the present

4. Roadmap Creation
Developing the roadmap itself

5. Transfer
Implementation through collaborative research, innovation, transformation projects, and partnerships.

Stakeholder and expert consultations are essential to this process, enabling participation and co-creation. This flexible approach allows for customization and has been applied successfully to both sustainability and circularity-focused roadmaps.

Vision India@2047 and Textile Sector Alignment

India will celebrate 100 years of independence in 2047. Through Vision India@2047, the Government aims to foresee 22 years of growth and development to become a modern and industrialized country by its Centenary of Independence.

Vision India@2047 is being operationalized through time-tabled actions covering short-term (2026), medium-term (2030), and long-term (2047) horizons. Within the framework of sustainable technology and innovation for the textile and apparel sector, this translates to:

Promote and scale up application of and investments in already feasible sustainable technologies through known techniques and practices for energy and water efficiency, renewable energy, and chemicals management

Medium-term (by 2030)
Fast-track development and commercialization of emerging sustainable technologies to achieve widespread application, including waterless dyeing and printing, alternative (renewable or recycled) textile materials, 3D printing, and other innovations

Long-term (by 2047)
Identify plausible sustainable textile innovations capable of achieving net-zero and other sustainability targets, conduct research and development, and achieve widespread commercial application.

2.3 Objectives

Under PAGE in India, UNIDO has undertaken to develop, through a participatory process with key technology and industry experts, a vision for a low-carbon and circular textile and apparel sector in India with specific performance targets aligned to the 2047 timeframe and plausible sustainable technology solutions for achieving these targets.

This Technology and Innovation Roadmap aims to:

1. Establish a comprehensive baseline of current technology adoption across spinning, weaving, knitting, wet processing, and garment manufacturing segments, including capacity, technology types, automation levels, resource efficiency, and competitive positioning

2. Identify technology and innovation gaps relative to global best practices, sustainability requirements, and India's commitments under NDCs and SDGs

3. Define a shared vision for India's textile sector in 2047—a low-carbon, circular, competitive, and inclusive industry aligned with Viksit Bharat aspirations

4. Chart phased technology pathways (2026, 2030, 2047) that balance competitiveness, employment generation, resource efficiency, and environmental sustainability

5. Propose enabling mechanisms—financial instruments, policy frame works, institutional arrangements, and capacity-building programs—to accelerate the green transition.

6. Provide actionable recommendations for government, industry, technology providers, financial institutions, and development partners to catalyse

2.4 Approach & Methodology

2.4.1 Approach

This baseline assessment adopts a diagnostic-to-strategic framework commonly employed in industrial transformation roadmaps. The approach follows three phases:

• Phase 1: Current State Diagnostic (Where We Are)

Comprehensive assessment of existing technology adoption, capacity, resource efficiency, and competitive positioning across India's textile value chain. This establishes the baseline against which progress will be measured.

• Phase 2: Gap Analysis and Benchmarking (Where We Need to Be)

Systematic identification of technology, infrastructure, skills, policy, and financial gaps through comparison with:

- Global best practices (EU BAT, leading exporters: China, Vietnam, Bangladesh, Turkey)
- Sustainability requirements (India's NDCs, SDGs, ZLD mandates, energy efficiency targets)
- Market standards (Export compliance requirements for USA, EU, UAE markets)

•Phase 3: Roadmap Development (How We Get There)

Translation of gaps into phased technology pathways (2026-2030-2047) with enabling mechanisms, investment requirements, and implementation frameworks.

This methodology report presents Phase 1 findings (Sections 2-7: Baseline Assessment) to inform Phase 2-3 (Sections 8-14: Roadmap).

2.4.2 Methodology

This baseline adopts a multi-method qualitative approach to capture the diversity of India's textile sector:

1. Analysis of literature and secondary research such as government reports (MoT Annual Report 2024-25, production/export statistics), industry reports (AEPC, TEXPROCIL, CITI data), technology documentation (machinery specifications, ITMA data), international best practices (EU BREFs, OECD reports, UNIDO case studies), and regulatory documents (CPCB/GPCB BREF).

2. Structured discussions with stakeholders:
   - Textile manufacturers across large mills, medium enterprises, MSMEs, export vs. domestic units, technology leaders vs. conventional operators.
   - Technology suppliers (machinery manufacturers, automation providers, chemical suppliers, ETP developers);
   - Industry associations (CITI, AEPC, SIMA, TEXPROCIL, cluster associations);
   - Government and research bodies (Ministry of Textiles, CPCB/SPCBs, textile research associations, technical institutes);
   - International experts (UNIDO specialists, GIZ advisors, technology consultants).

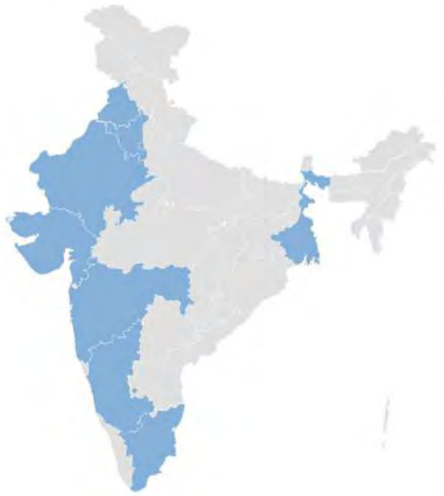
3. Comprehensive structured questionnaires (following UNIDO framework) deployed across value chain to capture: equipment inventory and specifications, resource consumption patterns (water, electricity, steam, chemicals), technology modifications and retrofits (VFDs, sensors, heat recovery), resource savings achieved, CAPEX ranges and government support utilized, operational challenges and technology needs. Coverage: Spinning (17 equipment types), Weaving (14), Knitting (11), Wet Processing (26), Garmenting (20), ETP & Utilities (26), Digital Systems (20).

4. Cluster-Based Geographic Analysis: Assessment covers major clusters with distinct characteristics. Each cluster analysed for fibre type, value chain stage, scale of operations, technology adoption patterns, environmental compliance, and infrastructure availability.

5. Multiple sources ensure reliability: Primary data (consultations, questionnaires, site visits), secondary data (government statistics, industry reports, vendor studies, research), cross-verification across sources, expert validation, stakeholder feedback on findings.

Textile Clusters in India

City	State	Primary Focus
Tirupur	Tamil Nadu	Knitwear (Integrated)
Mumbai	Mahashtra	Textile Machinery & Trade
Bangalore	Karnataka	Garmenting (Wovens)
Delhi (NCR)	Delhi	Garmenting (Fashion)
Ludhiana	Punjab	Hosiery & Woolens
Surat	Gujarat	Synthetic Textiles
Coimbatore	Tamil Nadu	Machinery & Spinning
Ichalkaranji	Maharashtra	Weaving
Ahmedabad	Gujarat	Wet Processing & Denim
Bhilwara	Rajasthan	Suiting & Processing
Perundurai	Tamil Nadu	Wet Processing (Green)
Panipat	Haryana	Recycling & Home Textiles
Kolkata	West Bengal	Garmenting (Children Wear)



Scope and Limitations:

Focus on manufacturing technologies (not agricultural/ logistics/retail), organized/ semi-organized sectors (limited informal coverage), representative sampling (not exhaustive census),qualitative characterization (not detailed engineering specifications).

Methodology provides strategic insights for roadmap development, establishing evidence-based foundation for priority technology interventions from baseline through 2030 milestones to 2047 vision.





3. Context Setting

3. Context Setting

The Partnership for Action on Green India's textile and apparel sector stands at a transformative juncture. As the 6th largest global exporter (3.9% of global trade), the sector contributes 8.21% to India's total exports (FY 2023-24) and provides employment to 45 million people directly and over 100 million indirectly, making it vital for women's participation and rural livelihoods.

For Viksit Bharat 2047, this sector must evolve from labour-intensive, resource-heavy operations into a technology-enabled, sustainable manufacturing hub. The Technology and Innovation Roadmap project establishes this baseline to assess technology availability and adoption, identify gaps against global benchmarks, and chart the path to 2030 milestones and the 2047 vision.

This roadmap provides a strategic framework for India's textile and apparel sector stakeholders—including policymakers, industry associations, manufacturers, financial institutions, technology providers, and buyer industries—to accelerate the transition toward a low-carbon, circular, and competitive textile ecosystem.

It addresses four critical enablers:

- industrial capability and competitiveness
- human capital and entrepreneurial competencies
- technology access and adoption
- financing mechanisms and policy frameworks.

By 2018, the Government of India had already embraced large-scale, integrated economy-wide approaches including resource efficiency, circular economy, and sustainable consumption and production to achieve the Sustainable Development Goals (SDGs) and Nationally Determined Contributions (NDCs).

A national green economy stocktaking exercise identified resource efficiency as the main entry point for PAGE support.

In India, PAGE is overseen by the Ministry of Environment, Forests and Climate Change (MoEFCC), and coordinated by the United Nations Environment Programme (UNEP). The United Nations Industrial Development Organization (UNIDO) and the International Labour Organization (ILO) work together under PAGE India on strategies, opportunities and challenges for inclusive and green manufacturing milestones and 2047 vision.



3.1.1 India's textile and apparel sector: Strengths and Positioning

India's textile and apparel sector represents one of the world's most complete and diversified manufacturing ecosystems, spanning from raw material production through finished garments. This comprehensive value chain positioning provides unique competitive advantages while also presenting distinct opportunities for technology-driven transformation.

As international markets increasingly shift toward synthetic and blended fabrics—driven by performance requirements, cost competitiveness, and functionality—India's continued reliance on cotton-dominated production risks market share erosion in high-growth segments. Major competitors (China, Vietnam, Bangladesh) have aggressively scaled MMF capacity with advanced technology, creating quality and cost advantages that threaten India's export competitiveness.

MMF segment requires focused attention on improving technical textiles and performance fibres exports, capacity expansion, quality improvement to match international specifications, and sustainable practices including recycled polyester and bio-based synthetics.[1]



Fibres	India Advantage
Cotton - The White Gold of India	Cotton dominates India's fibre landscape. India holds the first position globally in cotton acreage with 113.60 lakh hectares (36% of world area), supporting annual consumption of 326 lakh bales (170 kg each). The crop sustains 6 million cotton farmers and 40-50 million people in related activities. Production is split between 62% rain-fed and 38% irrigated lands, with current productivity at 448 kg/ha (2024-25), indicating room for technology-driven improvement.[1]
Jute	India is the world's largest producer (90 lakh bales, 16 lakh MT annually), concentrated in eastern states. The industry provides direct employment to 0.40 million workers and supports 4 million farm families.[1]
Silk	As the second-largest global producer, India's sericulture spans multiple varieties—mulberry, tasar, eri, muga—providing unique positioning in luxury and specialized segments
Synthetic and Semi-synthetic Fibres	India has substantial capacity in polyester, nylon, acrylic, and viscose. Man-made textiles exports grew 12.89% recently, demonstrating robust demand. However, India's man-made fibre (MMF) sector lags behind global demand trends, where MMF now accounts for ~ 60% of global fibre consumption[2] compared to natural fibres.

[1] Ministry of Textiles - Annual Report 2024-2025

[2] Materials Market Report 2025, Textile Exchange

3.1.2 Manufacturing Capabilities: Complete Value Chain Strength

Spinning:

India operates one of the world's largest spinning capacities, producing cotton, blended, polyester, and specialty yarns. The sector ranges from traditional ring spinning to modern compact, rotor, and air-jet spinning. However, significant technology heterogeneity exists—large mills operate modern high-speed automated equipment while substantial capacity remains in older-generation machinery with lower productivity and higher resource consumption. This technology gap presents the primary opportunity for targeted intervention.

Weaving, Knitting, and Fabric Formation:

India's fabric production spans handlooms (cultural heritage, rural employment), power looms (backbone of production), and modern shuttle-less looms (air-jet, rapier) in organized mills. Knitting infrastructure includes circular knitting, flat knitting, and warp knitting. This diversity enables production from commodity grey cloth to technical textiles, catering to both mass markets and premium segments.

Wet Processing:

Dyeing, printing, and finishing operations distributed across clusters (Tirupur, Ahmedabad, Surat, Bhilwara, Perundurai, Bhiwandi, Ludhiana).This segment represents the critical intervention point for environmental sustainability. Technology adoption here—water-efficient dyeing, digital printing, plasma treatment, enzymatic processes, zero-liquid discharge—directly impacts India's ability to meet international sustainability requirements.

Garment Manufacturing:

India's apparel sector shows exceptional momentum. Apparel exports surged 35.06% in October 2024 with cumulative growth of 11.60% (April-October FY 2024-25), reaching $8.732 billion3. The sector spans large organized export-oriented units with compliance certifications to small job-work units. Technology needs vary significantly large exporters adopt CAD/CAM, automated cutting, RFID tracking while smaller units operate with basic equipment.

Textile Manufacturing Resource Intensity

Stage	Water	Energy	Labour
Fiber / Yarn Spinning	Low	High	Low
Fabric Weaving	Medium	High	Medium
Fabric Knitting	Low	High	Medium
Wet Processing Dyeing and Finishing	Very High	Very High	High
Garment Mfg. Cut, Make, and Trim	Medium	Low	Very High

3.1.3 Market Performance: Strong Export Rebound

After FY 2023-24 decline (-3.24%, total: $34.430 billion), India's textile and apparel exports staged strong recovery. April-October FY 2024-25 reached $20.721 billion (+7.08%). Textiles grew 4.01% to $11.988 billion, while apparel surged 11.60% to $8.732 billion.[3]

Geographic Markets: USA and EU account for ~47% of exports (USA alone ~27%). India is gaining US market share while competitors decline (China -1.3%, Bangladesh -11.9% during Jan-May 2024). FTA markets show robust growth, indicating strategic diversification. The robust domestic market (1.4 billion population, rising middle class) provides demand stability, particularly for cotton textiles and value-segment apparel.

3.2 Baseline Study Scope

3.2.1 Value Chain and Fibre Coverage

Manufacturing Stages Assessed:

1. Spinning: Blow room, carding, drawing, roving, spinning, yarn processing

2. Fabric Formation: Weaving (shuttle, rapier, air-jet), knitting (circular, flat, warp), non-wovens

3. Wet Processing: Pre-treatment, dyeing, printing, finishing

4. Garment Manufacturing: Pattern making, cutting, sewing, finishing, quality control

5. Supporting Systems: Utilities (steam, compressed air), digital systems (ERP, IoT)

Fibre Types: Natural (Cotton), Synthetic (Polyester, Nylon), Semi-Synthetic Cellulosic (Viscose)

3.2.2 Technology Definition and BAT Alignment for Textile Sector

This baseline assessment defines "technology" in alignment with internationally recognized Best Available Techniques (BAT) frameworks:

> International BAT Definition (EU Industrial Emissions Directive 2010/75/EU): "The most effective and advanced stage in the development of activities and their methods of operation, indicating the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where this is not practicable, to reduce emissions and the impact on the environment as a whole." which has similar adoption in OECD BAT Framework and Indian Context - CPCB/GPCB Framework.

Techniques as defined by these frameworks include both:

- Technology used: Equipment, machinery, systems
- Operational methods: How equipment / machinery are maintained and operated



For this assessment, "technology" encompasses four dimensions:

1. Manufacturing Technologies: Machinery, equipment, and production systems—including automation levels, resource savings. This includes both new installations and modifications/ retrofits to existing equipment (such as VFD additions, sensor installations, heat recovery systems, inverter drives).

2. Process Technologies: Methods, techniques, and protocols for material transformation—including chemical formulations, treatment sequences, operating parameters, quality standards, and cleaner production practices.

3. Digital Technologies: Information systems, sensors, analytics, and control systems enabling monitoring, optimization, and decision-making across operations (ERP, SCADA, PLC, IoT sensors, AI/ML applications, traceability systems).

4. Sustainability Technologies: Systems and interventions specifically designed for resource efficiency, waste reduction, emission control, and circular economy implementation (zero-liquid discharge systems, renewable energy integration, waste heat recovery, material recycling).



3.2.3 Assessment Framework

The baseline evaluates:

Current Adoption: Technologies deployed, penetration rates, equipment specifications and vintages across different segments (MSMEs & large players)

Adoption Gaps: India vs. international best practices, explaining factors (awareness, cost, skills, policy, market structure), cases of high availability but low adoption

Benchmarking evaluates:

- What resource consumption levels (water, energy, chemicals, steam per unit output) do BAT-compliant facilities achieve?
- What enabling factors (policy, finance, skills, technical support) facilitate BAT adoption internationally and in leading Indian facilities?

3.2.4 From Baseline to Roadmap

This assessment establishes the foundation for a comprehensive roadmap that will:

1. Identify Priority Technologies: Maximum impact on sustainability, competitiveness, employment for India's context

2. Define Adoption Pathways: Realistic timelines and mechanisms from current state to 2030 milestones to 2047 vision

3. Address Enablers: Policy, finance, skills, infrastructure needed for technology scaling

4. Set Targets: Measurable indicators for technology penetration, resource efficiency, quality, competitiveness

5. Align Stakeholders: Shared vision and coordinated action across government, industry, technology providers, financial institutions, development partners

[3] Fibre2Fashion - India's T&A exports sustain momentum in Oct 2024



4. Spinning

4. Spinning

4.1 Overview: Spinning in India's Textile Value Chain

Spinning represents the foundational manufacturing stage where all textile fibres—natural, synthetic, and blends—converge into yarn, the building block for all subsequent textile production. India's spinning sector operates one of the world's largest installed capacities, serving both domestic textile manufacturing and international yarn markets.

India's spinning industry is characterized by massive scale and structural diversity, operating across a spectrum from large integrated mills with tens of thousands of spindles to small family-owned units with a few hundred spindles, from state-of-the-art automated facilities to decades-old conventional equipment.

4.1.1 Current Performance Snapshot

India's spinning sector demonstrates significant technology heterogeneity, with capacity distributed across large, medium, and small mills.

Cotton spinning dominates installed capacity, concentrated in Tamil Nadu (Coimbatore, Tirupur), Gujarat (Ahmedabad, Surat), and Maharashtra (Vidarbha).

Synthetic spinning (polyester, nylon) represents a growing segment in Gujarat and Maharashtra, while blended yarn production serves diverse end-use applications. Specialty spinning (organic cotton, recycled fibres) remains an emerging niche.

Global Competitive Context

India's spinning sector operates in a highly competitive international environment.

China dominates globally with over 110 million spindles representing more than 50% of global spinning capacity as of 2024, achieving approximately 78.5% capacity utilization. The Xinjiang region alone operates 29.1 million spindles, exceeding many countries' entire spinning capacity.[4,5]

Turkey has positioned itself as a technology-forward hub for cotton and specialty yarns, leveraging European market proximity with higher automation penetration than India's average, though at smaller overall scale.

Bangladesh, Pakistan, and Vietnam have developed spinning capacity primarily supporting their garment sectors with varying technology sophistication.

Table 1: Spinning Mills Technology Overview

Mill Capacity	Technology View	Location
Large mills (>25000 spindles)	Modern equipment, higher automation, export focus	Majority of installed capacity, predominantly in Tamil Nadu, Gujarat, Maharashtra
Medium mills (10,000-25,000 spindles)	Mix of conventional and upgraded technology	Distributed across textile clusters
Small mills (<10,000 spindles)	Predominantly conventional equipment, domestic market focus	Scattered presence, often family-owned

[4] ILO - Responsible Business Conduct in China Textile Industry

[5] USDA Foreign Agricultural Service - Cotton and Products Annual China

4.2 Spinning Technology Landscape in India

The spinning process transforms loose fibres into continuous yarn through a sequence of cleaning, opening, drawing, and twisting operations. Each stage employs specific technologies with varying levels of automation, productivity, and resource consumption. Its strategic significance for this roadmap stems from three factors:

1. Energy Intensity

Accounting for approximately 35-45% of total textile manufacturing energy consumption (excluding wet processing).[6] Efficiency improvements can directly impact India's carbon footprint reduction targets.

2. Quality Gateway

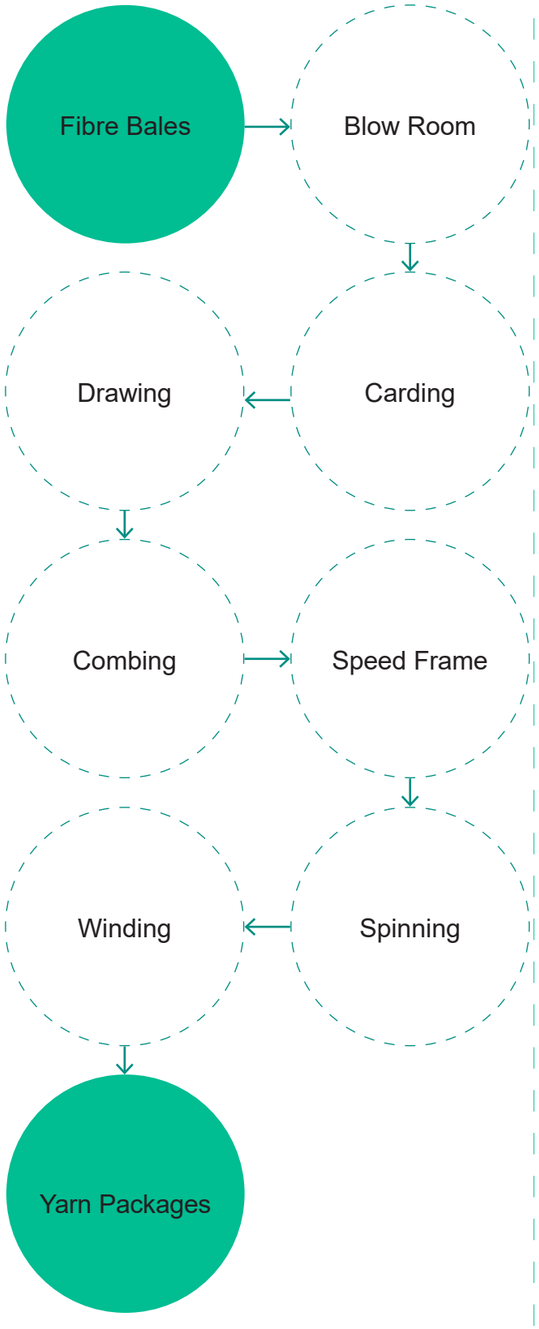
Yarn parameters (strength, evenness, imperfections) established during spinning determine fabric quality, dyeing uniformity, and garment performance, making technology gaps here cascade into downstream defects and export rejections.

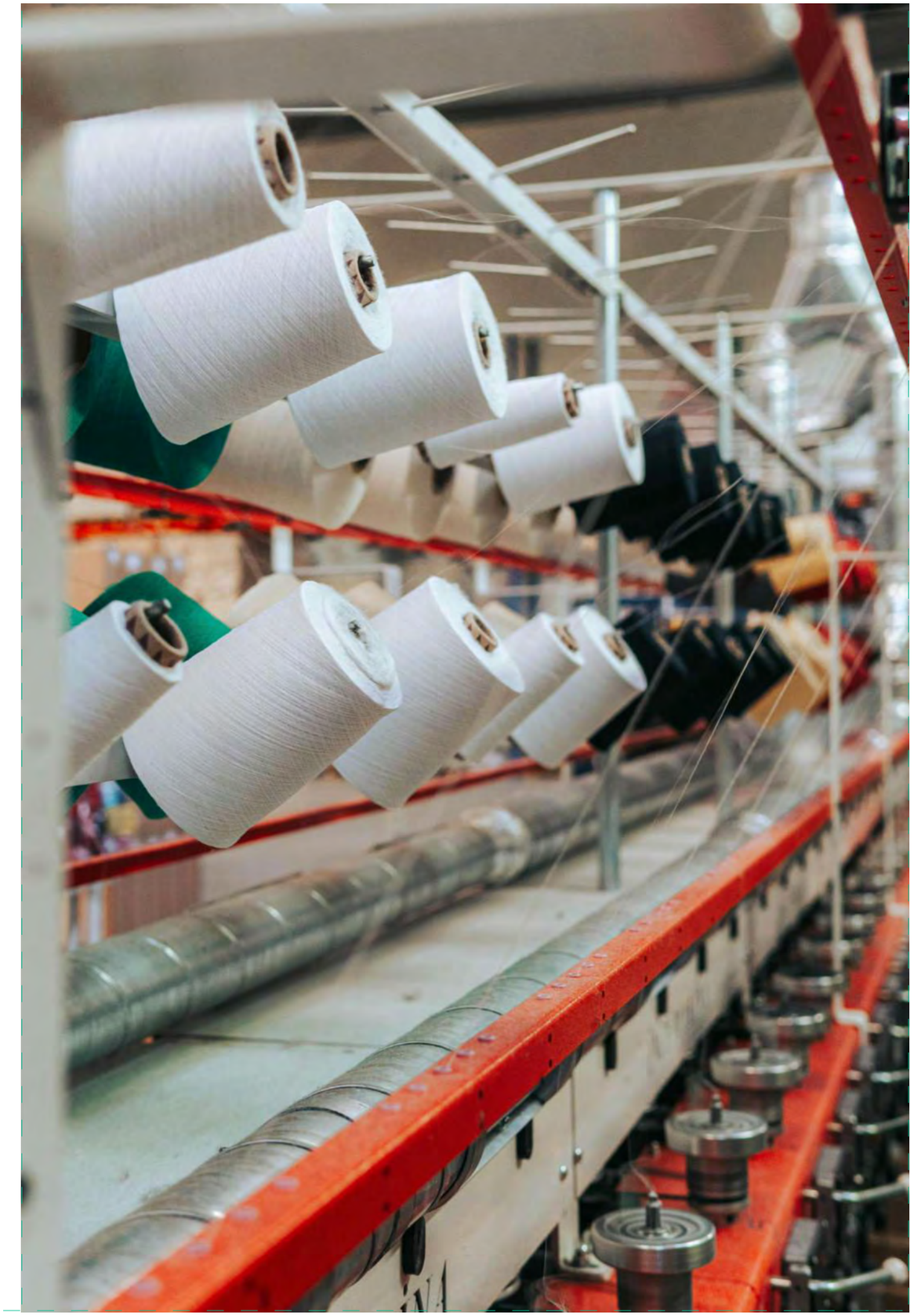
3. Upstream Influence on Value Chain:

As the entry point for manufactured textiles, spinning technology influence weaving/knitting machinery selection, dyeing recipes, and finishing treatments.

Given India's position as the world's second-largest spinning capacity (54.48 million spindles)[7], technology transformation in this segment is critical for achieving the roadmap's 2030 milestones and 2047 vision of a competitive, sustainable, and inclusive textile sector.

4.2.1 Spinning Process Overview





6. Textile Insights - Domestic Textile Industry Actively Moving Over to Renewable Energy

7. Department of Textiles, Govt of Tamil Nadu

Table 2: Spinning Processes Equipment and Technology Adoption

Stage	Equipment Category	Technology range available (global)	India adoption (2026)
Blow Room	Bale opening & chute-feed systems	Automated bale handling, contamination control, chute-feed integration	Medium – integrated chute-feed and semi-auto-mation in organized mills; low penetration in MSMEs due to capex + space
	Contamination control / bale sorting	Vision-based contamination detection & selective removal systems	Low–Medium – used mainly by export-quality mills seeking raw material consistency; adoption linked to premium yarn production
	Cleaning & dust extraction	Integrated pneumatic systems with monitoring	Medium–High in organized mills; retrofits driven by dust control and environmental compliance motivations
	Mixing & blending	Automated blending with ratio control	Medium – more common in mills producing blends/ synthetics for export consistency; manual mixing still widespread in cotton-dominant mills
Carding	High-production cards	High-speed cards with auto-levelling / monitoring	Medium–High – increasingly standard in greenfield/modernized installations; mixed base due to legacy card popu-lation
	Standard / legacy cards	Mechanical levelling / older generation	High (installed base) – large installed base still operational; modernization occurs via selective replacement & VFD-driven improvements
Carding	Electronic auto-levelling	Servo-controlled drafting + real-time monitoring	Medium – strong in new installations; lower diffusion in older mills due to mainte-nance skill gaps
	Mechanical/Manual levelling	Basic levelling / manual adjustment	High in older & MSME mills – maintains acceptable operation but leads to higher variability and quality loss
Drawing	Draw frames with auto-levelling	Multi-point monitoring + electronic levelling	Medium–High – adopted by quality-conscious mills (combed/premium segment); part of modernization packages
	Mechanical drafting / levelling	Mechanical levellers	High – remains dominant in older/ medium mills due to lower capex and simpler maintenance
	Automated can handling	Robotic transport + auto-positioning	Low – limited to a few high-automation greenfield projects; capex + space constraints restrict penetration
	Manual can transport	Trolley/manual handling	High – dominant across MSMEs and many medium/ large mills even where spinning is modernized
Combing	High-speed combers	Modern high-speed combers (quality + productivity)	Medium–High – premium count/combed yarn producers upgrade first; adoption driven by export quality requirements
Combing	Conventional combers	Lower speed legacy combers	Medium – still present due to cyclic combed-yarn demand and replacement cost
Speed Frame (Simplex / Roving)	Servo/electronic draft + automation	Servo drives, electronic drafting, auto-doffing options	Medium for servo/ electronic draft; Low for auto-doffing (limited installations). Upgrade linked to productivity + labour dependence reduction
	Mechanical drive + manual doffing	Legacy simplex systems	High – large installed base; replacement happens gradually due to retrofit feasibility and payback uncertainty
	Energy efficiency	modern drives reduce power demand	Upgrade narrative aligns with TUFS-style modernization benefits (productivity gains, energy/ resource efficiency). (NITI Aayog)

4.2.1.1 Supporting Systems:

- **Humidification plants:** Maintain optimal humidity (60-70% RH)
- **Compressor systems:** Compressed air for pneumatic transport and rotor spinning
- **Overhead cleaners:** Extract fly waste and maintain air quality
- **Material handling systems:** Automated transport of cans, bobbins, packages



4.2.2 Automation and Digitalisation Status

Automation Levels:

- **Material handling:** Limited to large mills, predominantly manual / semi-manual in most facilities
- **Process monitoring:** Growing adoption for critical parameters (humidity, temperature, production rates)
- **Quality control:** Electronic yarn clearers common in winding, limited automated testing upstream
- **Robotic systems:** Minimal presence, confined to demonstration installations

Digitalization Adoption:

- **ERP systems:** Adopted by large, organized mills, limited in medium/ small mills
- **Manufacturing Execution Systems (MES):** Emerging adoption linking production to management
- **IoT sensors:** Limited deployment for machine monitoring and predictive maintenance
- **Data analytics and AI/ML:** Nascent stage, few mills experimenting with predictive quality control

4.2.3 Global Comparison

Table 3: Global Spinning Gap Comparison

Category	India status (2026)	Global BAT (leaders)	Gap severity	Strategic priority / why it matters
Blow room automation	Medium in organized mills; Low in MSMEs	High automation (chute feed integration, bale management, contamination control)	High	Material handling productivity + raw material consistency + dust reduction
High-production cards	Medium (in new/ modernized mills; legacy base still large)	High-speed cards with auto levelling + monitoring are standard	High	Productivity + sliver uniformity + lower kWh/kg
Electronic auto levelling (cards/ drawing)	Medium–High in new installs; Medium overall	Electronic levelling as default in modern prep lines	Med. –High	Quality consistency (CV% reduction), fewer downstream defects
Automated can handling	Low	Automated handling / smart material movement systems	High	Labour efficiency + quality preservation (less sliver damage/contamination)
Servo / energy-efficient speed frames	Medium	Servo drives + electronic drafting widely adopted	High	Power savings + productivity + yarn quality stability
High-speed ring frames	Medium	Higher spindle speeds with optimized automation	Med. –High	Productivity uplift and consistent high output
Auto-doffing (ring frames)	Low	Medium–High adoption in high-labour-cost markets	High	24/7 operations + labour productivity + reduced downtime
Individual spindle monitoring (ISM)	Low	Increasingly standard in advanced mills	Critical	Waste reduction + real-time quality control + defect prevention
Compact spinning	Low–Medium (niche premium segment)	Higher penetration in premium yarn ecosystems	Medium	Access to premium export yarn markets
Rotor (open-end) spinning share	Lower relative penetration vs global leaders	Higher rotors share where synthetics/recycled/denim yarn dominates	Critical	Strategic alignment with MMF + recycled fibre trends (cost + productivity advantage)
Auto-coners with yarn clearers	Medium–High in export mills; Medium overall	High adoption (quality + contamination control)	Med. –High	Export-quality requirement; reduces faults and claims
Automated package handling / traceability	Low	Automated package logistics + digital traceability	High	Traceability readiness + digital reporting; reduces mix-ups and claims

4.3 Global Technology Benchmarking

India imports approximately 30% of textile machines from China , with many machines over 10 years old especially in weaving and smaller spinning units. The Indian machinery sector needs focus on shuttle-less looms, advanced processing mechanisms, and market-driven product development.

The Indian machinery sector needs focused development in these critical technology areas and market-driven product innovation to reduce import reliance and provide cost-appropriate solutions for the domestic textile industry.

4.3.1 Technology Availability vs. Adoption in India

Readily Available: Ring spinning equipment (domestic and imported) across full range, standard carding and draw frames, conventional winding and twisting machinery, component suppliers for spares, established service networks for major brands.

4.3.1.1 Available Internationally, Limited Indian Adoption:

- High-speed rotor spinning: Technology exists but limited deployment despite productivity advantages. Barriers include higher capital cost, perceived quality differences, preference for ring-spun yarn, and cotton fibre characteristics requiring specific handling.

- Air-jet spinning: Minimal presence despite very high productivity. Very high capital cost limited suitable applications in Indian yarn mix, and technical expertise requirements limit adoption.

- Comprehensive automation: Robotic handling, automated doffing, integrated digital monitoring available but capital intensity, lack of skilled personnel, and uncertain ROI perception limit adoption.

- Advanced digital integration: IoT platforms, AI-driven quality control, predictive maintenance systems face barriers of digital infrastructure gaps, lack of in-house IT capabilities, and ROI uncertainty.

- Recycled fibre spinning technology: Emerging need given EU sustainability requirements. Limited domestic technology availability. China has decades of experience processing recycled content (rotor spinning with 47% short fibre content vs. 25% in virgin cotton).[8]

4.3.1.2 Technology Gap Analysis

Gaps between India and global leaders characterized by:

1. Generation gap: Average installed equipment vintages older than China, Turkey; many machines over 10 years old

2. Automation gap: Lower penetration of automated material handling and quality control vs. China's advancing automation

3. Digital gap: Limited IoT, data analytics, AI deployment; nascent Industry 4.0 adoption

4. Speed/productivity gap: Lower average machine speeds and output per unit

5. Energy efficiency gap: Higher energy consumption per kg yarn from older motors and drive systems

6. Quality consistency gap: Greater yarn quality variation from equipment heterogeneity and limited automated monitoring

[8] TMMA Part-1: Technology Gap Analysis

4.4. Resource Efficiency and Sustainability Considerations

4.4.1 Energy Consumption in Spinning

Spinning is energy-intensive, with electricity representing significant operational costs.

Energy is consumed across:

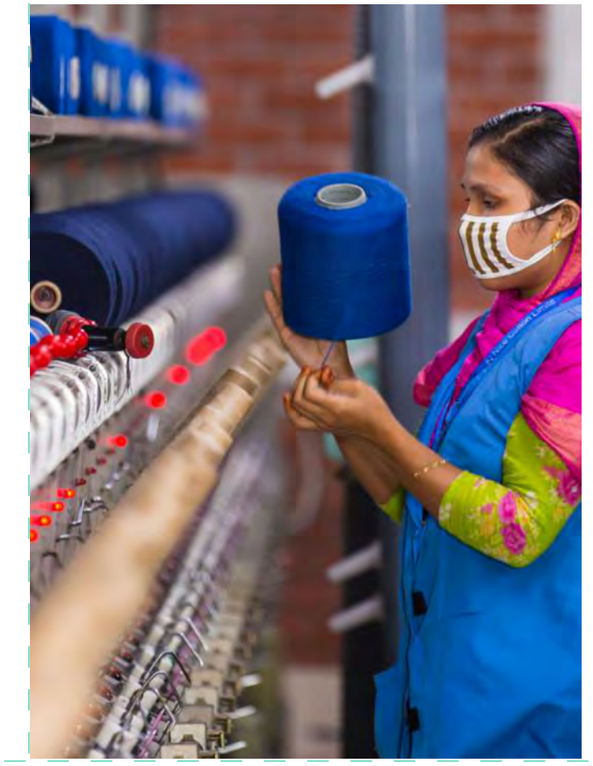
1. Blow room and Carding
- Motors
- Pneumatic transport

2. Drawing and Roving
- Draft mechanisms

3. Spinning
- Spindle drives - major consumer in ring spinning

4. Winding:
- Package Formation

5. Supporting systems:
- Humidification for water heating/cooling
- Compressed air,
- Overhead cleaning



4.4.1.1 Energy Efficiency Drivers

Energy efficiency in spinning has become critical due to three converging factors:

- Rising Power Tariffs: Industrial electricity costs in major spinning clusters have increased 8-12% annually over the past five years. With energy representing 15-20% of yarn production costs, every 10% efficiency improvement translates to 1.5-2% reduction in total yarn cost.

- Carbon Intensity and Export Compliance: India's grid carbon intensity (0.71 kg CO_2/MWh, 2023)[9] creates significant Scope 2 emissions. Export buyers—particularly EU brands facing Carbon Border Adjustment Mechanism (CBAM) requirements—increasingly demand carbon footprint disclosure. Mills unable to demonstrate efficiency improvements or renewable energy adoption face supplier de-listing risk.

- Competitive Disadvantage: Other countries spinning achieves lower energy consumption per kg yarn through modern equipment and automation. India's energy efficiency gap translates to cost disadvantage in commodity yarn exports, eroding competitiveness.

Absolute consumption benchmarks (kWh/kg yarn) vary significantly based on yarn count, fibre type, spinning technology, machine vintage, and operational practices. Publicly available comparative data across countries is limited.

Note: Comprehensive quantitative benchmarking of energy consumption (kWh/kg yarn) and productivity (kg/spindle/day) across countries is limited in publicly available sources, requiring primary data collection or proprietary reports.

[9] Central Electricity Authority (CEA), Ministry of Power, Government of India. "CO_2 Baseline Database for the Indian Power Sector." 2023

4.4.2 Energy Efficiency and Technology Interventions

Table 4: Energy Efficiency and Technology Interventions in Spinning

Technology Intervention	Energy Saving Potential	India Adoption (2026)	Investment Payback	Key Barrier
Variable Frequency Drives (VFDs) on motors	20-35% per machine[10]	Medium	2-3 years	Capital cost (₹2-5L per installation)
High-efficiency motors (IE3/IE4)	5-15% per motor[11]	30-40% of capacity	2-3 years	Replacement timing, upfront cost
Humidification upgrades (pad vs. spray systems)	20-30% in HVAC energy[12]	35-40% modern systems	3-5 years	High capital (₹50L-2Cr), space constraints
Compressed air optimization (leak detection, pressure control)	10-20% in air consumption[13]	<20% systematic programs	1-2 years	Lack of awareness, monitoring systems

4.4.2.1 Water Consumption

Spinning has relatively low direct water consumption vs. wet processing. Primary uses: humidification systems (maintaining atmospheric moisture), machine cooling (bearings, motors), and limited auxiliary processes. Efficiency improvements focus on closed-loop humidification (water recycling in pad systems), cooling system optimization (recirculation and heat recovery), and condensate recovery (utilizing waste heat condensate).



4.4.2.2 Waste Generation and Circularity

Spinning generates significant fibre waste at various stages:

Table 5: Waste Generation in Spinning

Stage	Waste Type	Characteristics
Blow room	Trash, dust, short fibres	Heavily contaminated, lowest value
Carding	Flat strips, licker-in waste	Short fibres, neps
Combing	Noil (combed yarn only)	Short fibres, cleanest waste stream
Spinning	End breaks, cleanings	Process waste

Data source: Industry consultations with spinning mills across Coimbatore, Ludhiana, Ahmedabad, and Tirupur clusters (2024-2025), cross-verified with equipment manufacturer specifications (Rieter, Trützschler). Ranges reflect variation by fibre quality, machine settings, and yarn count.

- **Waste utilization:**
Sale as low-grade fibre for non-woven/filling applications, limited internal recycling in blow room, and emerging processing into recycled yarn (requires suitable equipment).

- **Circular economy opportunities:**
Post-industrial textile waste recycling into new yarn (rotor spinning well-suited), equipment designed for higher recycled content processing, and partnerships between garment manufacturers (cutting waste) and spinners.
Global trends show increasing focus on recycled content yarns meeting brand sustainability targets (EU mandates from 2025 onward). Indian spinning sector faces both opportunity (becoming recycled yarn supplier) and technology challenge (equipment suitability for recycled fibre processing).

- **Post-Industrial Waste Recycling:**
For this, rotor spinning technology handles recycled fibre effectively (47% short fibre tolerance vs. 25% in ring spinning).

4.5 Spinning Sector Baseline 2026

India's spinning sector in 2026 demonstrates a paradox of scale and technology. Operating one of the world's largest installed capacities serving significant domestic and export markets, the sector shows substantial technology gaps compared to global leaders, particularly China and advanced European manufacturers.

*Estimates from structured assessments across clusters. Cross-verified with equipment suppliers (TMMA members) and industry associations (SIMA, CITI). Indicative sector patterns; actual distribution varies by cluster and mill size.

Table 6: Technology Profile in Spinning Industry

Equipment Vintage	Technology Profile	Typical Mill Type
Modern	High-speed (≈18,000 RPM+), electronic controls, digital-ready	Large, organized mills (>25k spindles)
Upgraded	Mid-speed (≈14,000–16,000 RPM), VFD retrofits, mixed mechanical + electronic systems	Medium/large mills
Older	Low speed (<14,000 RPM), limited automation, higher energy intensity	Small mills/MSMEs (<10k spindles)

[10] ABB, "Transforming textiles"

[11] Benefits of Using IE3 & IE4 High-Efficiency Motors: A Comprehensive Guide for the Indian Market

[12] Energy Savings in textile industry

[13] Textile mills need to give priority to compressed air savings

Strategic Gaps

The sector's technology advancement from this 2026 baseline will directly impact downstream weaving, knitting, and garment sectors' global competitiveness, forming the foundation of India's textile value chain transformation toward Viksit Bharat 2047.

Table 7 - Global Technology Benchmarking in Spinning

Dimension	India (2026)	Global leaders / benchmark	Gap severity
Rotor spinning penetration	Installed rotor capacity exists but diffusion is relatively limited vs ring spinning in India;	Rotor modernization and rotor investments are higher in countries optimizing for productivity and MMF/recycled segments[19]	Critical
Modernization trajectory (spinning)	India shows strong modernization momentum in spinning relative to global averag-es	China is the main peer benchmark; modernization stronger than most countries	Medium–High
Machinery import dependence	Import dependence remains high; domestic textile engineering industry supplies a limited share of demand[8]	Global leaders have deeper domestic machine manufacturing ecosystem	High
Digital textile printing penetration	Digital printing penetration is very low (~1% of textile printing in In-dia) (reported), despite growth	Higher penetration in leading markets; faster adoption trajectory	High
Automation scale (macro competitiveness)	Automation adoption is uneven across India (organized vs MSME); not fully comparable via official % datasets	China is scaling manufacturing au-tomation aggressively (robots, smart factories)[34]	High
ERP / digital systems (large mills)	Adoption concentrated in large exporters; still limited diffusion overall	Higher adoption in advanced ecosystems	High





5. Weaving

5. Weaving

5.1 Overview: Weaving in India

Weaving represents the critical manufacturing stage where yarn is converted into fabric through the interlacement of warp and weft threads. Fabric production directly determines the value addition potential of the entire textile chain, serving as the bridge between spinning (upstream) and processing/garment manufacturing (downstream).
India's weaving sector is characterized by its unique duality—maintaining one of the world's largest handloom sectors while simultaneously modernizing with advanced shuttleless looms, creating a distinctive position in global textile manufacturing.

Weaving is central to this roadmap for three reasons:

- Technology Diversity and Modernisation Imperative
- Value Chain Linkage
- Export Competitiveness and Market Access

• Technology Diversity and Modernization Imperative:
India maintains the world's largest handloom sector (28 lakh looms, 32 lakh workers)[14] alongside 26 lakh powerlooms[15], creating unique scale diversity. Weaving technology choices directly impact fabric quality, production speed, energy consumption, and market access—making modernization critical for 2030-2047 transformation.

• Value Chain Linkage:
Weaving specifications dictate upstream yarn requirements (count, strength, twist) and downstream processing capabilities (dyeing uniformity, finishing potential). Technology gaps in weaving—limited shuttleless penetration, older loom vintages, minimal automation—constrain the entire value chain's ability to compete in premium fabric markets and meet speed-to-market demands of global buyers.

• Export Competitiveness and Market Access:
Global weaving machinery markets show rapid technology transition — India's limited shuttleless penetration (estimated 28-40% of powerlooms vs. >70% in major manufacturing countries) and slower modernization pace create competitive disadvantages in productivity, energy efficiency, and premium fabric production.

Given India's position as one of the world's largest fabric producers and weaving's role in employing millions across handlooms and powerlooms, technology transformation in this segment is essential for achieving the roadmap's 2030 milestones and 2047 vision.

[14] CMoT, Fourth All India Handloom Census Report
[15] IBEF, Powerloom Industry and Exports in India

5.1.1 Current Performance Snapshot

India's weaving industry operates across an extraordinary spectrum of technology and scale, from traditional hand-operated looms in rural clusters to automated high-speed shuttleless looms in integrated mills.



Fibre and Fabric Diversity:
Cotton weaving dominates both handloom and power loom sectors (grey fabrics, shirting, bed linen). Synthetic weaving concentrated in Surat (polyester, nylon), primarily water-jet looms for filament yarns. Growing blended fabrics across polycotton, polyester-viscose. Traditional silk handloom (Varanasi, Kanchipuram, Mysore) with limited mechanization. Emerging technical textiles for automotive, geotextiles, filtration applications.

Table 8 - Cluster wise Weaving Capacity Distribution

Loom Category	Estimated Capacity	Key Characteristics	Geographic Concentration
Handlooms	28 lakhs[14]	Manual operation	West Bengal, Assam, Odisha, Tamil Nadu, Gujarat
Powerlooms (Total)	25 lakhs[16]	Decentralized production	Bhiwandi, Surat, Erode, Ichalkaranji
Shuttleless looms	1.3 lakh[16]	2-3x productivity	Organized mills across India

5.1.2 Global Competitive Context

Turkey's weaving sector demonstrates high technology integration with automated jacquard looms, AI-integrated design systems, and laser-cutting equipment. Over 65,000 textile companies operate with vertically integrated facilities covering spinning through garment assembly, enabling rapid speed-to-market for European brands.[17]

India's weaving sector competes on scale diversity like handloom heritage + modern technology, cost competitiveness in power loom segment, and growing shuttleless loom adoption.

However, technology gaps exist in automation penetration limited, many looms over 10 years old is plaguing the industry.

[16] PIB, Powerloom Sector

[17] FashionatingWorld - Turkey Report 2024

The industry still relies on import of second-hand textile machineries leading to concentration on conventional shuttle/older power looms limiting competitiveness in premium fabrics and speed-to-market.[5]

5.1.3 Handloom vs. Powerloom—India's Dual Weaving Identity

India's weaving sector is unique globally in maintaining two parallel weaving ecosystems:

1. The world's largest handloom sector alongside
2. A substantial powerloom base.

This duality reflects India's commitment to preserving cultural heritage and artisan livelihoods while simultaneously pursuing industrial modernization and productivity growth. Understanding the distinctions, complementarities, and strategic positioning of both sectors is essential for the roadmap's 2030-2047 vision.

India's weaving roadmap must recognize that handloom and powerloom serve different strategic purposes and are not in direct competition for most product segments:

1. Handloom Positioning

- Cultural heritage preservation: UNESCO recognition of handloom traditions (Banarasi, Kanchipuram), GI-tagged products
- Livelihood security: 43.3 lakh weavers (predominantly BPL category, rural, women) depend on handloom for subsistence
- Artisanal premium market: Growing global demand for "slow fashion," handmade, sustainable textiles

2. Powerloom Positioning:

- Industrial fabric production: Base fabrics for domestic garment manufacturing and export
- Volume and speed: Meeting time-sensitive fashion cycles, large order fulfilment
- Economic engine: Powerloom clusters employ 50-55 lakh, contribute significantly to fabric exports
- Technology modernization pathway: Shuttleless adoption enables global competitiveness





Table 9 - Aspect wise Comparison between Handloom & Powerloom

Aspect	Handloom	Powerloom
Scale & Employment	• 31 lakh looms employing 43.3 lakh weavers and allied workers—world's largest handloom sector preserving traditional weaving heritage.[1]	• 25 lakh looms forming India's decentralized fabric production backbone with significant technology heterogeneity across clusters[1]
Technology	• Manual operation dominant: Frame looms, pit looms, traditional fly-shuttle handlooms across 23 states • Limited mechanization: Jacquard handlooms for brocades and intricate designs in silk clusters (Varanasi, Kanchipuram) • Semi-automatic looms: Progressive clusters with improved shuttle mechanisms	• Large, organized mills: Higher shuttleless penetration (50-70%), mix of air-jet, rapier, water-jet based on product • Medium powerloom units: Selective shuttleless adoption (20-40%), primarily rapier for versatility • Small powerloom units: Predominantly conventional shuttle/older powerlooms, limited capital for shuttleless investment
Challenges	• Geographic dispersion: Scattered presence across states limiting economies of scale • Capital constraints: Limited financial resources for basic upgrades • Generational decline: Younger generation migrating away from traditional craft • Market competition: Powerlooms competition	• Technology obsolescence: 60-70% capacity still conventional shuttle looms • Capital barriers: Small units unable to invest ₂25-60L for shuttleless looms • Import dependency: Limited domestic shuttleless manufacturing; reliance on Chinese/European imports • Energy cost pressures: Rising electricity tariffs eroding margins
Modernization Scheme	• NHDP (National Handloom Development Programme): ○ Ergonomic improvements (seating, lighting, workspace design) ○ Better shedding mechanisms for reduced drudgery ○ Productivity enhancement tools ○ Design development support	
Sustainability	• Inherently sustainable: ○ Human-powered (zero fossil fuel use) ○ Often uses organic cotton, natural dyes ○ Minimal carbon footprint ○ Low environmental impact ○ Preserves traditional ecological knowledge	• Modernization pathway: ○ Adoption of energy-efficient shuttleless looms ○ VFD adoption reducing motor energy ○ Compressed air optimization ○ Growing renewable energy adoption

5.2 Weaving Technology Landscape and Value Chain

Weaving involves preparatory processes followed by fabric formation. Each stage employs specific technologies with varying mechanization, automation, and resource efficiency levels.

5.2.1 Pre-Weaving Preparatory Processes

Major Global Equipment Manufacturers: Benninger (Switzerland), Karl Mayer (Germany), Sucker Muller (Germany), Staubli (Switzerland)

Table 10 - Technology Adoption in Pre-Weaving Preparatory Processes

Stage	Equipment Category	Technology Range Available	India Adoption (2026)
WARPING	Sectional/Pattern warping machines	• Automated creel loading with electronic stop motions • Electronic length control • Hydraulic tension systems	• Large integrated mills have moved to automated systems • Small-medium units majorly using manual creel loading • Barrier: High capital (30-50L), technical expertise
	Direct/Beam warping machines	• Automated tension control with servo systems • Electronic stop motions vs. Conventional mechanical tension • Manual monitoring	• Large mills have installed electronic tension control • Medium/small units use mechanical systems instead of electronic stop motions • Barrier: Maintenance skill requirements
SIZING	Multi-cylinder sizing machines	• Automated size dosing with digital control • Steam injection heating systems • Double size box with zone temperature control • Humidity/temperature precision control	• Organized mills moving towards automated dosing systems • Some Medium units have steam injection system in place. • Small units predominantly use conventional heating • Barrier: High capital (50L-2Cr), water/steam infrastructure
		• Conventional heating (direct steam) • Single size box • Manual tension and dosing	• Small-medium powerloom units continue to rely on conventional sizing systems facing limitations including size pickup variation that affects fabric quality, higher chemical wastage from manual dosing inconsistencies, and energy consumption above automated systems due to inefficient heating.
DRAWING & KNOTTING	Automated drawing-in machines	• Fully automated threading through heddles/reed • Electronic pattern control	• Large mills are gradually adopting automated drawing-in machines, driven by frequent design changes and growing jacquard fabric production requiring rapid pattern modifications • Barrier: Very high cost (80L-1.2Cr), limited flexibility
	Automated knotting machines	• Automated warp end tying • Electronic knot verification	• Organized mills have adopted automated knotting machines, primarily for same design continuation where the cost-benefit is clear for large continuous production runs. • Barrier: Capital cost (25-40L)

5.2.2 Weaving Technologies - Fabric Formation

Weaving machines classified by weft insertion mechanism:
- Shuttle Looms (Conventional)
- Shuttleless Looms[18]

Air-jet and water-jet are 4-5 times faster than shuttle looms, but air-jet needs expensive compressed air infrastructure while water-jet works only for polyester/nylon fabrics.

Table 11 - Weaving Loom Technologies - Technical Comparison

Loom Type	Speed (picks/min)	Productivity	Fibre Suitability	Energy Level	Fabric Weight Range	Key Advantage	Key Limitation
Shuttle	180-250	LOW (Baseline)	All fibres	High	All weights	Low investment, versatile	Low speed, high noise
Rapier	400-600	2-3× shuttle	All fibres	Moderate	Up to 1,500 gsm	Most versatile	Moderate weft waste
Air-Jet	800-1,200	HIGHEST (4-6× shuttle)	Cotton, synthetics (light)	Very High	30-550 gsm	Fastest production	High energy, compressed air needed
Waterjet	800-1,000+	Very High (4-5× shuttle)	Synthetics ONLY	Lower than air-jet	Light-medium	Energy efficient for synthetics	Cannot use natural fibres
Projectile	600-700	2-3× shuttle	All fibres	High (inefficient)	Extra-wide (up to 540cm)	Wide fabrics	Expensive, energy inefficient



[18] Textile Engineering - Shuttleless Looms Techno-Economics

Table 12 - Weaving Loom Technologies - India Adoption Status

Loom type	India status (2026)	Major locations (indicative)	Adoption trend	Key constraint
Shuttle / plain looms	Dominant in decentralized powerloom base; being replaced gradually	Decentralized powerloom clusters	Declining	Upgradation requires capital + disruption of livelihoods
Rapier (shuttleless)	Largest shuttleless category; policy-led upgradation pathway	Bhiwandi belt and other powerloom clusters	Growing	High capex; adoption supported by lower-cost Asian looms
Air-jet	Limited diffusion; concentrated in organized mills	Organized mills	Slow growth	Very high capex + compressed air energy/ maintenance needs
Waterjet	Concentrated in synthetic-focused ecosystems	Surat belt (synthetic hub)	Stable / selective growth	Synthetic-only suitability + water quality + effluent/ TDS
Projectile	Negligible presence	Few niche users	Stagnant	Technology largely superseded

Challenge

- Majority of Indian powerlooms are still old shuttle technology producing only 1/3 the output of modern shuttleless looms
- India's shuttleless penetration is very less compared to the major global textile manufacturing countries
- China is modernizing 3-5 times faster: Water-jet loom shipments grew +63%, rapier +38%, air-jet +30% in 2024 alone.

Opportunity

- Chinese rapier looms (25-40L) have made shuttleless accessible to medium powerlooms—Bhiwandi added 25,000 rapier looms primarily with Chinese machines at 40-50% lower cost than European brands
- Productivity gain: 2-6× output depending on loom type, directly improving weaver incomes and fabric production capacity

Barrier

- Capital investment: Modern shuttleless looms cost 25-60 lakh (vs. 5-15 lakh for shuttle), a significant barrier for 60-70% of powerlooms operated by small units with limited access to capital
- Air-jet looms require 50L-1Cr additional investment in compressed air infrastructure, limiting adoption to large mills despite 4-6× productivity advantage
- Technical skills: Maintenance and operation of modern looms require training, lacking in many powerloom clusters

5.3 Global Technology Benchmarking

As of 2026 baseline, India's weaving sector demonstrates systematic technology gaps across six critical dimensions when benchmarked against global leaders (China, Turkey, Vietnam) and international best available techniques (BAT). These gaps create compounding competitive disadvantages: older loom vintages constrain productivity, limited shuttleless penetration reduces speed-to-market capability, minimal digitalization prevents efficiency optimization, and higher energy consumption erodes profitability.



Table 13 - Comparative Country wise Weaving Benchmarking

Country/Region	Shuttleless penetration (2026)	Strategic focus / narrative
India	Low–Medium (highly uneven; concentrated in organized sector; decentralized sector still plain loom-heavy)	Gradual replacement via capex support; Chinese loom cost advantage accelerating upgrades
China	High	Modernization at scale; major investor in weaving machinery
Turkey	High	Premium positioning; stronger automation + EU proximity supply chain
Vietnam	Medium–High	Export-oriented capacity build-up linked to garment/textile exports
Bangladesh	Medium	Backward integration to support RMG; expanding processing + weaving investment

5.3.1 Technology Adoption Gap

As shown in table above, India's 60-70% shuttle dominance14 creates a structural productivity ceiling. Global competitors operating at higher shuttleless capacity produce 2-3x more fabric per loom, enabling faster delivery, lower per-unit costs, and better speed-to-market for fashion and seasonal products. This gap directly impacts India's competitiveness in time-sensitive export markets (EU, US apparel brands requiring 4–6-week lead times).

5.3.2 Industry Automation

India's digital infrastructure gap is more severe than mechanical technology gap. Even mills with modern shuttleless looms operate with minimal production monitoring (15-20% have centralized systems), creating data blind spots that prevent efficiency optimization, quality prediction, and predictive maintenance. China and Turkey's 60-70% real-time monitoring enables data-driven loom utilization improvements, downtime reduction, and energy optimization.

Digital infrastructure gaps (connectivity, IT skills), lack of in-house capabilities, uncertain ROI perception, and limited vendor support ecosystems slow adoption even when technology is available.

Table 14 - India's Weaving Industry Automation Status

Automation Category	India Adoption	Global Leaders (China, Turkey)	Gap Severity
Electronic Jacquard (design systems)	20-25%	50-60%	MEDIUM-HIGH
Electronic Dobby (shedding mechanisms)	30-35%	60-70%	MEDIUM-HIGH
Real-time Production Monitoring (loom efficiency tracking)	15-20% (large mills only)	60-70%	CRITICAL
IoT Sensors (predictive maintenance, energy monitoring)	<2%	30-40%	CRITICAL
AI-Integrated Design Systems (pattern generation, quality prediction)	<1% (experimental)	15-25% (Turkey operational)	CRITICAL
Overall Automation Index	20-30%	55-65%	HIGH

5.3.3 Barrier Analysis

Barrier Type	Key Issues	Who It Affects Most
Financial	• Shuttleless costs ₂25-70L vs. ₂5-15L for shuttle • Air-jet needs additional ₂50L-1Cr compressed air infrastructure • Small units (60-70% of sector) cannot access finance	Small powerloom units with limited capital
Technical	• Maintenance skills for electronic systems lacking • Compressed air optimization expertise needed • Design/CAD skills for jacquard absent in clusters	Medium and small units without technical staff
Institutional	• Limited financing despite ATUF scheme availability • No quality standards for Chinese machinery • Poor power quality damages electronics in clusters	Decentralized powerloom sector across all sizes

5.3.3.1 Leading Weaving Machinery Manufacturers

- Picanol (Belgium)
- ITEMA Group (Italy)
- Tsudakoma (Japan)
- Toyota Industries Corporation (Japan)
- Dornier (Germany)
- Chinese Manufacturers



5.4 Resource Efficiency and Sustainability Considerations

5.4.1 Energy Consumption in Weaving

Weaving is energy-intensive, with electricity consumption varying significantly by loom type and technology generation.

Table 15 - Energy Consumption by Loom Type (Relative)

Loom Type	Energy Efficiency Drivers	Efficiency Remarks
Shuttle looms (conventional)	Very high due to reciprocating shuttle motion (mechanical inefficiency)	25-35% higher than modern rapier equivalent
Rapier looms	Moderate consumption: • Mechanical weft transfer (no compressed air) • Electronic controls enable optimization • Servo motors available in modern models	Can be higher with servo drives and optimized electronics
Air-jet looms	High consumption primarily from: • Compressed air generation (major energy sink) • Air compressor efficiency critical with leak management	Optimized air-jet with leak prevention, pressure control, air recycling
Water-jet looms	Lower than air-jet: • Water circulation less energy-intensive than air compression Pumping and filtration systems • Closed-loop systems reduce consumption	Increases with efficient pumps and heat recovery
Projectile looms	High specific energy: • Only 15% of projectile acceleration energy effectively utilized • Mechanical inefficiency inherent to technology	Technology inherently inefficient; replacement preferred over optimization

5.4.1.1 Water Consumption

Sizing Process:

- Major water consumer in pre-weaving: Steam generation for size paste heating, size mixing, equipment cleaning
- Efficiency improvements: Closed-loop steam condensate recovery, automated size dosing reducing waste, modern sizing machines with better thermal insulation

Water-Jet Looms:

- Continuous water circulation for weft insertion
- Recirculation systems: Water filtered and recirculated, makeup water for losses
- Environmental consideration: Wastewater treatment if water discharged, increasingly closed-loop systems

Other weaving processes:
Minimal direct water consumption

Table 16 - Sizing Water Efficiency Improvements

Technology	Water Saving Potential	India Adoption	Key Benefit
Closed-loop steam condensate recovery	30-40% steam/water savings	Can be majorly seen in organized mills	Recirculates steam condensate, reduces boiler makeup water
Automated size dosing	10-20% size chemical + water savings	Large and medium mills	Precise dosing reduces waste from over-preparation
Modern sizing machines with thermal insulation	15-25% steam/energy savings (indirectly reduces water)	Greenfield mills with modern systems	Better heat retention reduces steam/water consumption



5.4.1.2 Waste Generation and Circularity

Sizing Waste:

- Size paste waste: Leftover size, cleaning waste containing starch, PVA, chemicals
- Desizing wastewater (downstream in processing): High BOD/COD from size removal
- Waste reduction: Automated dosing systems, optimized size recipes, bio-based sizes (easier degradation)

Weaving Waste:

- Weft waste: Broken weft yarns, end cuts, weft insertion rejects
  - Rapier looms: Higher weft waste (yarn return mechanism)
  - Air/waterjet: Lower weft waste
- Selvage waste: Edge trimmings, narrow strips (some fabrics)
- Warp waste: Loom waste (initial setup), warp breaks

Total weaving waste:
2-5% of input yarn depending on loom type, fabric complexity, operational efficiency.[19]

Table 17 - Weaving Waste Generation by Stage

Stage	Waste Type	Characteristics	Current Utilization
Sizing	Size paste waste, cleaning waste	Contains starch, PVA (polyvinyl alcohol), acrylic-based chemicals	Limited recovery; wastewater treatment challenge (high BOD/COD in desizing downstream)
Weaving (Weft waste)	Broken weft yarns, end cuts, insertion rejects	Clean yarn waste, suitable for recycling	Sold to recyclers for low-grade yarn, non-wovens, filling material (cotton/natural fibres); synthetic waste more challenging
Weaving (Selvage waste)	Edge trimmings, narrow strips	Continuous strips of woven fabric edge	Minimal value; often discarded or used as filling
Weaving (Warp waste)	Loom waste (set-up), warp breaks	Mixed fibre content	Typically discarded or minimal recycling
Total weaving waste	Combined yarn waste	Primarily clean yarn waste (cotton, synthetics)	Cotton/natural: Recycling into low-grade yarns, non-wovens Synthetic: Limited mechanical recycling, some polymer recovery

5.4.1.3 Global trends toward sustainable weaving:

- Energy-efficient loom technologies (manufacturer focus area)
- Water recycling in sizing and water-jet operations
- Bio-based sizing agents replacing synthetic chemicals
- Digital design systems reducing sampling waste
- Longer fabric runs reducing changeover waste

Indian sector faces opportunity in sustainability compliance for export markets and challenge in capital investment for efficient technologies.

5.4.2 Circularity Opportunities

Table 18 - Circularity Opportunities in Weaving

Circularity Opportunity	Current Challenge	Pathway Forward
Post-Industrial Weaving Waste Recycling	• No systematic collection infrastructure • Quality consistency issues for recyclers • Small units lack aggregation systems	• Cluster-level collection centres (Bhiwandi, Surat, Erode) • Grading systems for waste quality • Digital tracking for traceability Technology ready: Mechanical recycling operational; rotor spinning accepts recycled content
Upstream Integration with Spinning	• Weaving-spinning disconnect: Waste sold to middlemen (40-60% margin capture) • No direct weaving-to-spinning recycling loops • Spinning mills lack weaving waste collection capability	Model: Weaving cluster waste, Aggregation centre, Local spinning mills, New yarn supply back to cluster Bhiwandi example: • 25,000 shuttleless looms = 10-15 tons/day clean weft waste • Nearby Malegaon/Mumbai spinning capacity available • Closed-loop reduces logistics, improves traceability Advantage: Rotor spinning tolerates 47% short fibre (vs. ring 25%), ideal for recycled content
Sizing Waste Management	• Conventional sizing: 65-70% of units use starch/PVA with manual dosing • Over-preparation waste: 1-2% of chemicals • High BOD/COD wastewater from desizing (if done downstream) • Limited bio-based sizing adoption (10-15%)	Technology pathway: 1. Automated dosing systems: Reduce over-preparation by 10-20% (Investment: ₂15-30L per unit) 2. Bio-based sizing agents: Replace PVA with starch/modified starch/natural polymers (easier biodegradation, lower wastewater treatment load) 3. Closed-loop size recovery: Reclaim unused size paste Barrier: Bio-based alternatives cost 15-25% more; awareness gap on long-term savings
Fabric Reject Recycling	• Quality rejects (1-3% of production) often landfilled or incinerated • Mixed fibre fabrics (poly-cotton blends) difficult to separate • No chemical recycling infrastructure for blended fabrics	Emerging technologies: • Chemical recycling pilots (fibre-to-fibre for polyester) • Mechanical shredding for non-woven applications • Downcycling to industrial wipers, insulation Challenge: Economic viability unclear; requires aggregation at scale

[19] Industrial Consultations

5.5 Weaving Sector Baseline

India's weaving sector is the world's largest and most diverse, combining heritage handloom craftsmanship with modern industrial capacity, but faces critical challenges: technological fragmentation (60-70% outdated shuttle looms), energy inefficiency (higher consumption than global best practices), and limited automation (digital monitoring), creating competitive disadvantages despite massive scale advantages.

The sector operates a unique duality: preserving 31 lakh handlooms employing 43.3 lakh artisans while simultaneously modernizing 25 lakh powerlooms toward shuttleless technologies. This dual identity—heritage preservation alongside industrial modernization—defines India's strategic positioning but requires differentiated policy interventions to address structural productivity gaps while maintaining employment-intensive character.

5.5.1 Baseline Characterisation

Table 19 - Geographic Distribution and Cluster Characteristics[18,20]

Cluster	Shuttleless Looms	Technology Profile	Fibre/Fabric Focus	Key Characteristics
Bhiwandi (Maharashtra)	~25,000 units	90% Chinese rapier looms 10% other shuttleless	Grey sheeting, synthetic fabrics, blends	Cost-competitive Chinese machinery; grey fabric for processing
Surat (Gujarat)	~22,600 units	90% water-jet looms 10% rapier/others	Synthetic filament (polyester, nylon)	Polyester value chain hub; water-jet looms specialization
Erode (Tamil Nadu)	~3,200 units	Majority rapier (Indian + imported)	Shirting & pants materials	Design focus; multi-colour capability; jacquard adoption
Ichalkaranji (Maharashtra)	Mix shuttle + shuttleless	Traditional + modern coexistence	Cotton fabrics, handloom-powerloom overlap	Heritage handloom presence alongside powerloom modernization
Panipat (Haryana)	Limited shuttleless	Mix of shuttle and rapier	Home textiles, blankets, carpets	Recycled fibre focus; traditional technologies dominant
Coimbatore (Tamil Nadu)	Organized mills (data limited)	Higher shuttleless penetration (50-60% in large mills)	Export-oriented fabrics	Better automation, modern technologies in organized sector

[20] Indian Textile Journal (December 2021) - "Crisis in Bhiwandi powerloom sector"

5.5.2 Global Position

Digital monitoring and automation gap (15-20% adoption) is more severe than mechanical shuttleless loom gap (28-40%), creating “blind production” in most units—no real-time data for optimization, quality tracking, or predictive maintenance. The sector faces a dual challenge—both in technology generation and automation depth—versus global leaders China, Turkey, and Vietnam.

- Technology generation lag:

Latest looms (23% energy efficient) limited penetration vs. China (water-jet growth, 38% rapier growth in 2024)

- Automation gap:

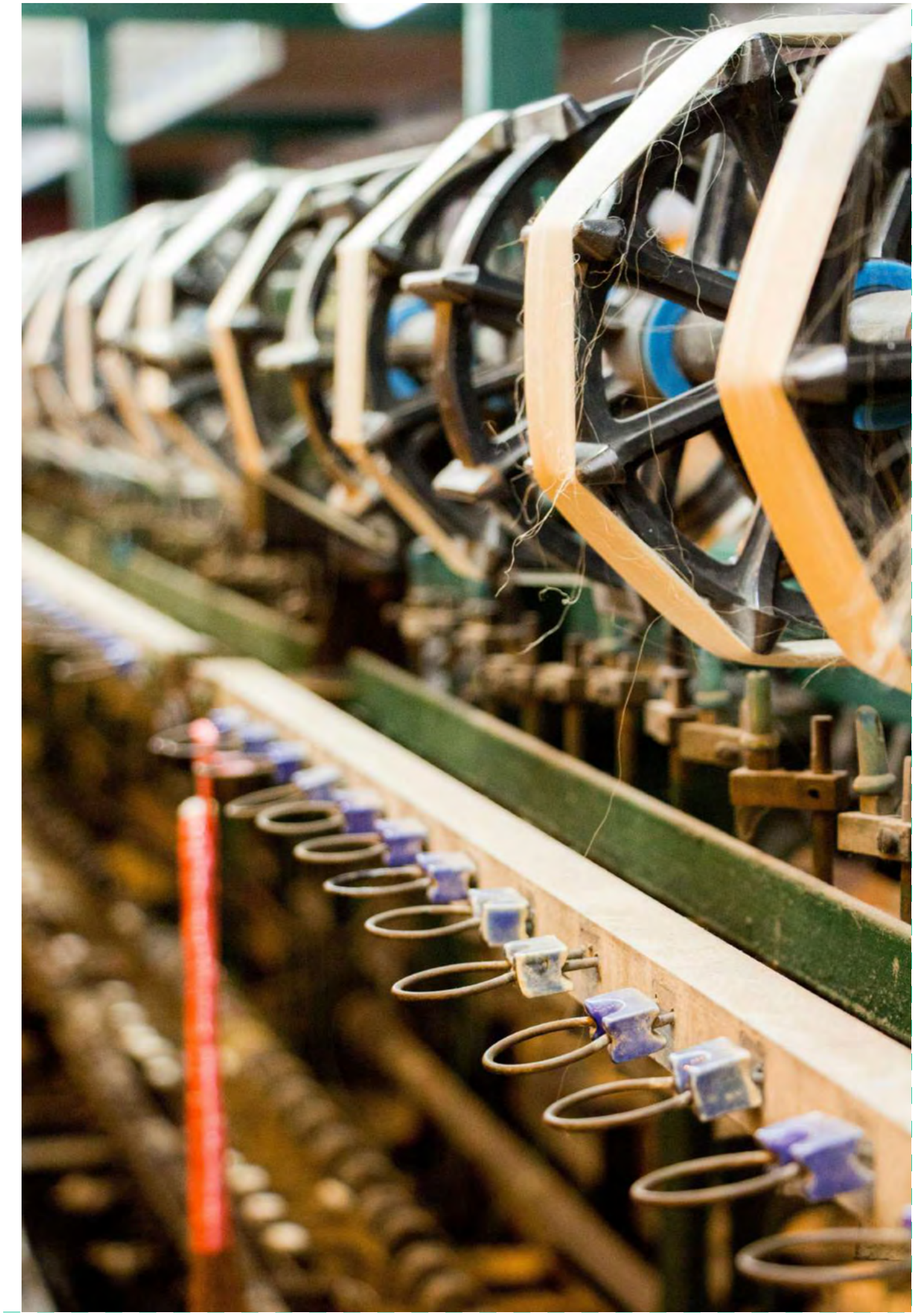
Turkey’s AI-integrated systems, China’s comprehensive digitalization vs. India’s basic monitoring.

The weaving sector’s modernization from 2026 baseline toward 2030 requires phased technology upgrades balancing clustered powerloom needs with organized mill advancements. Shuttleless loom penetration, energy-efficient technologies, and selective automation represent priority areas for enhancing global competitiveness while preserving handloom heritage and powerloom employment.

The sector’s transformation directly impacts downstream processing (dyeing, finishing) capacity by enabling higher-quality fabrics requiring advanced dyeing/finishing and upstream spinning yarn specifications such drives demand for consistent yarn quality (lower hairiness, uniform strength), positioning weaving as the critical bridge in India’s textile value chain evolution toward Viksit Bharat 2047.

Table 20 - Strategic Modernization Priorities for Weaving Sector

Priority	Approach	Impact	Importance
Shuttleless Penetration	Leverage Chinese rapier cost advantage while building Indian machinery upto world class level	2-3× productivity gain addresses structural ceiling	Critical (Foundation for productivity leap; enables downstream quality processing)
Digital Infrastructure	Demonstration centers showing ROI, initial subsidies, IT skill development	Data-driven optimization, EU traceability compliance, predictive maintenance foundation	Critical (Solves “transparency issue”; mandatory for EU export access post-2027)
Energy Efficiency	Low-hanging fruit with 1-3 year paybacks; awareness campaigns	15-25% energy reduction = 1.5-2.5% fabric cost reduction	High (1–3-year paybacks make this economically attractive; climate regulation compliance)
Air-Jet Capacity Building	Shared compressed air infrastructure	High-volume light fabric competitiveness	High (Addresses specific fabric segment gap; cluster approach reduces individual capital burden)





6. Knitting

6. Knitting

6.1 Overview: Knitting in India's Textile Manufacturing

India's knitting sector in 2026 demonstrates strong export competitiveness anchored by Tirupur's "Knitwear Capital" dominance (55% of India's knitwear exports, ₂40,000 Cr in FY25[21]), but faces technology modernization challenges, and minimal Industry 4.0 integration (IoT-connected machines) creating competitive gaps versus China's automation leadership and Bangladesh's cost advantage.

The sector exhibits clear cluster differentiation: Tirupur's export-oriented circular knitting ecosystem (European machines, vertical integration) versus Ludhiana's domestic-focused flat knitting base (Chinese/Indian semi-automatic machines, winter wear specialization).

This geographic specialization requires cluster-specific technology interventions to maintain global competitiveness while capturing domestic market growth.

6.1.1 India's Knitting Industry Profile

6.1.1.1 Market Size:

The Indian knitwear market is a high-growth segment, projected to more than double from USD 9.1 billion to USD 21.5 billion by 2027, sustaining a high 9% growth rate.[22]

Furthermore, knitwear constitutes a significant portion of India's total textile and apparel exports, often acting as the largest component within the Ready-Made Garment (RMG) basket. The rapid modernization of knitwear clusters is therefore essential to capture both this strong domestic demand and enhance global export competitiveness.

6.1.1.2 Major Knitting Hubs:

India's knitwear production is dominated by two distinct, geographically specialized clusters: Tirupur and Ludhiana.

Table 21 - India's Major Knitting Clusters—Comparative Profile

Cluster	Brief Introduction	Key Products	Technology & Market Orientation
Tirupur (Tamil Nadu)	Known as the Knitwear Capital of India, contributing ~56% of India's knitwear exports. A highly export-driven and vertically integrated cluster, spanning spinning, knitting, processing/dyeing, and garment manufacturing.	T-shirts, innerwear, casualwear, sportswear	Uses advanced imported circular knitting machinery (e.g., Mayer & Cie, Santoni, Terrot). Strong integration with global value chains, supplying large international buyers such as Walmart, H&M, Gap, etc.
Ludhiana (Punjab)	A major hub for winter wear manufacturing, dominating India's woollen and acrylic knitwear production. Cluster output is largely driven by and supplied to the domestic Indian market.	Sweaters, pullovers, cardigans, jackets, mufflers	Relies largely on semi-automatic flat knitting machines, including lower-cost Chinese and domestic equipment. Overall, lower automation and capex intensity compared to export clusters like Tirupur.

[21] Business Standard, April 2025: "Knitwear capital Tiruppur scales record Rs 40K cr exports in FY25"

[22] Indian Textile Magazine, December 2024 "How Modern Machines and Innovations are Transforming India's Knitting Industry."

The technological divergence between the two—Tirupur's focus on high-speed circular knitting for global exports vs. Ludhiana's flat knitting for domestic volume—highlights the need for cluster-specific technology interventions within the national roadmap.

Emerging clusters in Mumbai, Bengaluru, and Delhi exhibit a mixed knitting profile. Other Clusters: Mumbai, Bengaluru, Delhi are emerging knitwear manufacturing with mixed circular/flat knitting.

6.2 Knitting Technology Landscape

Knitting machines are classified by fabric construction method (weft vs. warp) and bed configuration (circular vs. flat). This classification determines production characteristics, fabric properties, applications, and technology requirements.

Table 22 - Knitting Technology Classification—Primary Distinctions

Primary Classification	Fabric Formation Method	Key Characteristics	India Adoption
Weft Knitting	Yarn runs horizontally (weft direction); loops formed across fabric width	• Dominant technology worldwide • 95%+ of India's knitting capacity[1]	DOMINANT in India Circular (Tirupur) + Flat (Ludhiana)
Circular Knitting	Needles arranged in circular bed; tubular fabric produced continuously	• High-speed production • Minimal waste • T-shirts, sportswear, innerwear	Tirupur cluster export focus European + Asian machines
Flat Knitting	Needles arranged in flat beds; fabric produced in panels	• Shaped garment panels • Fashion knitwear • Intricate patterns	Ludhiana cluster winter wear Chinese semi-automatic dominant
Warp Knitting	Yarn runs lengthwise (warp direction); loops formed along machine length	High-speed, stable fabrics Technical textiles Less stretch, run-resistant	MINIMAL in India Technical textiles niche <5% capacity

6.2.1 1. Weft Knitting Machines

Yarns run horizontally (weft direction), forming loops across the fabric width.

Table 23 - Circular Knitting Machine Types and Specifications

Machine Type	Fabric Characteristics	Applications	Adoption in India
Single Jersey	• Lightweight, basic construction • One-sided face appearance • Maximum stretch	T-shirts, underwear, basic apparel	Most widely adopted in Tirupur due to high volumes and export demand. Globally, single circular machines hold the larger share (~53.4% in 2024)[23].
Double Jersey (Rib/Interlock)	• Thicker, more stable fabrics • Better dimensional stability • Two-sided appearance Enhanced stretch retention	Polo shirts, sports-wear, heavier T-shirts, underwear waistbands	Growing adoption in Tirupur export houses, driven by product diversification (sportswear/ premium categories) and buyer expectations.
Jacquard Cir-cular	• Multi-color designs • Intricate patterns • Color changes programmed	Fashion knitwear, designed T-shirts, branded apparel	Fastest-growing and premium segment. (design capability, higher ASP, branded requirements). Jacquard capability is increas-ingly integrated into modern circular knitting portfolios (single + double jersey categories).
Terry/Fleece	• Loop pile fabrics • Soft, absorbent • Thermal insulation	Sweatshirts, hoodies, toweling, winter innerwear	Terry and fleece variants are typically pro-duced using dedicated circular knitting config-urations

Leading Manufacturers:

- Mayer & Cie (Germany): Premium circular knitting machines, high reliability, widely used in Tirupur
- Santoni (Italy): Innovative seamless technology, jacquard capabilities
- Terrot (Germany): Quality machines for knitwear
- PaiLung (Taiwan): Cost-effective, growing presence in India
- Fukuhara, Tayu (Japan): High-speed machines
- Chinese manufacturers: Cost-competitive alternatives (Baiyuan, Wellmade)

[23] Industry Research, "Large Circular Knitting Machine Market Size, Share, Growth, and Industry Analysis"

6.2.1 2. Flat Knitting Machines (Dominant in Ludhiana)

Working Principle: Needles arranged in straight (flat) beds, fabric produced in flat panels.

Table 24 - Application & Adoption of Flat Knitting Machines

Machine Type	Control Level	Productivity	Applications	India Adoption
Manual Flat	Hand-operated Pattern cards	LOWEST ~5-10 kg/day	Basic sweaters, Traditional knitwear	Labor scarcity, rising wages making uneconomical
Semi-Automatic Flat	Mechanical + basic electronic Pattern cards or basic programming	MEDIUM ~20 kg/day[1₂]	Winter wear (sweaters, cardigans, pullovers) Standard patterns	Cost-effective for winter wear production Chinese machines dominant (40-50% cost advantage)[24]
Fully Automatic / Computerized Flat	Electronic control Pattern programming Shape knitting capability	HIGH 40-60 kg/day Complex patterns feasible	Fashion knitwear, Intricate designs, Premium segments Shaped panels	High-end fashion knitwear segment Export-oriented units only
WHOLEGARMENT® / Seamless Flat	Advanced computerized 3D garment knitting No sewing required	HIGHEST (per garment) Minimal post-production Near-zero waste	Premium knitwear, Seamless garments, Technical sportswear, Fashion innovation	ABSENT in India, Very high capital cost ROI unclear for Indian market

Leading Manufacturers:

- Shima Seiki (Japan): World leader in computerized flat knitting, WHOLEGARMENT® seamless technology
- Stoll (Germany, Karl Mayer Group): High-end flat knitting, CMS series
- Indian manufacturers: Omex, Mastana, Apex, Vishwakarma (semi-automatic machines)
- Chinese manufacturers: Cixing, Kauo Heng, Ningbo Yuren Knitting Machine and so on which are cost-competitive, widely adopted in India

[24] Apparel Resources, "Flat Knitting Technology Options"

6.2.2 Warp Knitting Machines

Yarns run lengthwise (warp direction), each yarn forming loops along machine length.

Table 25 - Warp Knitting Machine Types and Applications

Machine Type	Fabric Characteristics	Typical Applications
Tricot Machines	Lightweight, smooth fabrics Stable, less stretch Run-resistant	Lingerie, linings, sportswear (base layers), activewear
Raschel Machines	Heavier, open-structure fabrics Net-like constructions Strong, durable	Lace, nets, automotive upholstery, geotextiles, agrotextiles, industrial textiles
Double Needle Bar	3D spacer fabrics Sandwich structures Cushioning properties	Footwear (shoe uppers, insoles), mattresses, sports equipment, protective gear

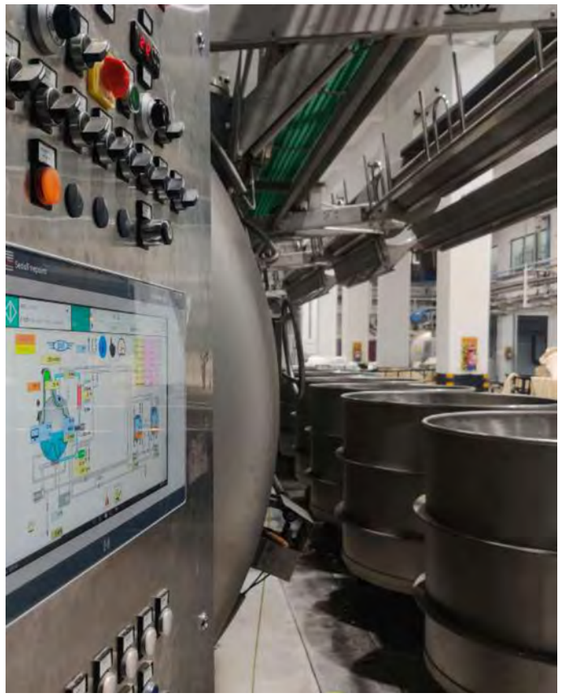
Leading Manufacturers:

Karl Mayer (Germany): Dominant global player in warp knitting technology

India Adoption:
Limited compared to weft knitting, concentrated in technical textiles sector, automotive applications, specialized manufacturers.

India currently has a significant gap in warp knitting adoption, with warp knitting estimated to constitute less than 5% of India's overall knitting capacity (industry estimates).

Most warp knitting capacity is concentrated in niche, high-performance segments, especially technical textiles such as automotive textiles, functional fabrics, and industrial applications, rather than mainstream apparel production.

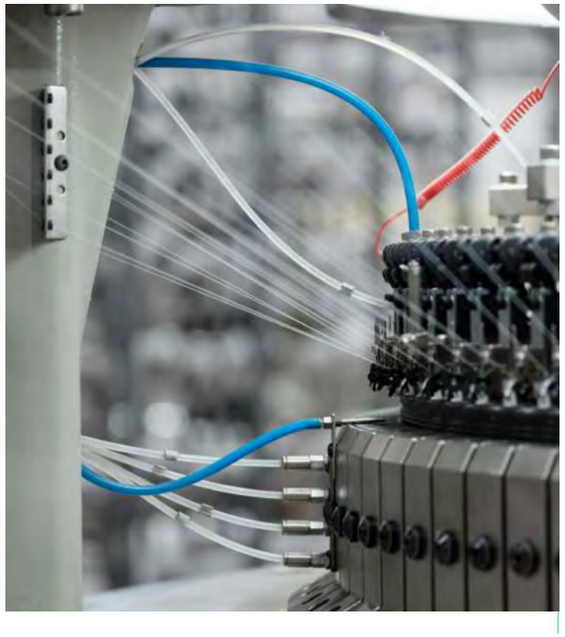


[25] PIB, "Weaving the Fabric of Innovation"

6.3 Current Technology Adoption in India - Baseline 2026

India's knitting sector demonstrates extreme technology heterogeneity driven by cluster specialization: Tirupur's export-oriented circular knitting ecosystem operates with European premium machines alongside growing Asian adoption, while Ludhiana's domestic winter wear production relies predominantly on Chinese and Indian semi-automatic flat knitting machines.

This geographic differentiation creates distinct technology profiles, adoption patterns, and modernization imperatives.



6.3.1 Technology Penetration by Cluster

Table 26 - Knitting Technology Penetration by Cluster

Parameter	Tirupur Cluster (Circular Knitting-led)	Ludhiana Cluster (Flat Knitting-led)
Dominant machine base	• Single jersey & double jersey circular knitting machines dominate (high-volume cotton knitwear) • High presence of export-oriented capacity	• Semi-automatic flat knitting machines remain most common (cost-effective for winterwear production) • Cluster suited to domestic market-driven product cycles
Machine brands / sourcing trend	• European machines (e.g., Mayer & Cie, Terrot, Santoni) preferred by large exporters due to quality consistency, reliability, and buyer compliance needs • Asian machines (PaiLung / Chinese brands) growing in medium units due to capex advantage	• Chinese flat knitting machines dominate due to strong cost advantage (typical market perception: large gap vs European/Japanese) • Strong presence of Indian manufacturers like Omex and Mastana due to affordability + quick service support
Automation / digital adoption	Moderate and rising: computerized circular machines growing, but auxiliary operations still have high manual dependence (handling, inspection, fabric movement, etc.)	Mixed: coexistence of manual + semi-automatic + computerized flat knitting; automation adoption higher in select larger units
Technology vintage / upgradation	• Mixed machine age (approx. 5–15 years) with progressive exporters investing in latest models	• Larger portion of the base is older / semi-automatic equipment, with gradual upgrades toward computerized machines in pockets

6.3.1.1 India's Knitting Sector:

• Weft knitting dominance:
95%+ capacity (circular + flat)

• Warp knitting:
Niche segment, technical textiles, limited installations

• Seamless/3D knitting:
Virtually absent (very high capital cost, limited ROI clarity for Indian manufacturers)

• Import dependency:
High reliance on imported machines (Europe, Asia)
- European: Premium segment (quality, reliability, after-sales support)
- Chinese/ Taiwanese: Volume segment (cost competitiveness)



6.4 Global Technology Benchmarking

6.4.1 Technology Gap Analysis

Table 27 - Gaps between India and global leaders

Area	Gap	Global Benchmark / Leaders
Seamless knitting (WHOLEGARMENT® / similar)	Negligible adoption in India; seamless knitting is still rare and not mainstream in Indian knitwear clusters	Seamless / whole-garment knitting has growing penetration in advanced markets (China, Turkey, Europe) driven by efficiency + reduced stitching operations.[26]
Digitalization (3D design + virtual sampling)	Limited use of 3D garment design, virtual prototyping, and digital sampling; sampling largely physical	3D sampling / virtual prototyping is becoming mainstream in developed markets to reduce cost, time, and waste[27]
Automation (production + material handling)	High dependence on manual operations across knitting preparation, handling, inspection, and auxiliary processes	Competitive markets are moving toward higher end-to-end automation (higher output, consistency, traceability)
Machine vintage / modernization	Machinery base is older on average (industry estimates often cite ~8–12 years), leading to productivity and quality gap	Competitive producers typically operate newer machinery (often ~3–5 years in high-performance export settings)
Warp knitting capacity	Minimal warp knitting base (industry estimates <5% of knitting capacity), mostly limited to niche technical textiles	China/Europe have matured warp knitting ecosystems, enabling advanced technical textile production
IoT / Smart factory systems	Mostly reactive maintenance and manual production tracking; limited real-time visibility	Global leaders increasingly use IoT-based monitoring, predictive maintenance and digital dashboards

[26] Shima Seiki's WHOLEGARMENT ®
[27] Textile World, March 2024: "Game-Changing Benefits Of 3D Digital Sampling"

Table 28: Competitive Position of India in Knitting

Country	Competitive Advantage	Implication for India
Bangladesh	Low labor cost advantage + strong capacity in basic circular knitwear	India cannot compete only on cost; must improve productivity + technology
China	Strong automation, large-scale manufacturing, leadership in seamless + warp knitting, and speed	Largest technology benchmark; India needs upgradation + scale + technical textiles push
Turkey	Advanced knitting technologies, fashion/ value-added focus, and proximity to EU markets	Highlights the value of technology-led positioning and faster design-to-market cycles

6.5 Resource Efficiency and Sustainability

Knitting is intrinsically more resource-efficient than weaving across multiple dimensions: lower energy consumption per kg fabric (knitting bypasses preparatory steps like sizing/ warping), near-zero water use in the knitting process itself (vs. weaving's sizing water), and lower fabric waste potential (shaped panels, seamless technology). However, India's knitting sector operates with significant efficiency gaps versus global benchmarks due to older machine vintages, underutilized digitalization (<5% IoT active use), and minimal seamless adoption (<1%)—leaving substantial sustainability improvements untapped.

This section quantifies energy consumption by machine type, waste generation patterns, water usage, and circularity opportunities, then identifies priority interventions to realize India's resource efficiency potential by 2030.





[28] Knitting Industry Creative, October 2018 "Seamless Knitting: Is The Skilled Handwork of Garment Finishers At Risk?"
[29] Singh, R., Yadav, V., Gaur, T.S. et al. Barriers to adopting industry 4.0 in Indian textile and clothing industries. Discov Appl Sci 7, 560 (2025).

6.5.1 Material Efficiency

Fabric Waste:

Yarn consumption:
Knitted fabrics generally use 10-15% less yarn per meter vs. equivalent woven fabrics (loop structure vs. interlacing)

Table 29 - Material Efficiency Opportunities in Knitting

Aspect	Circular Knitting	Flat Knitting (Conventional Cut & Sew)	Seamless Knitting (Whole Garment)
Fabric waste generation	Low – fabric is produced in tubular form, leading to efficient material use and lower wastage in standard knit garments.	Moderate to High – panels/shapes are typically cut and assembled, leading to cutting waste similar to woven apparel production.[28]	Near-zero waste – garment is knitted in 3D / whole form, with minimal cutting and offcuts[29]
Material utilization efficiency	High	Medium (cutting loss depends on pattern/size mix)	Very high (largest material efficiency benefit)

6.5.2 Energy Consumption

Table 30 - Energy Efficiency Opportunities in Knitting

Energy Parameter	Summary
Relative energy intensity	Knitting generally consumes less energy per kg fabric compared to upstream/downstream textile stages like spinning, weaving and wet processing (where thermal and process energy loads are much higher).
Key energy consumption points in knitting units	• Motor electricity (main driver – knitting machine running) • Compressed air requirement in some machine configurations using pneumatic systems
Efficiency improvement pathways	Modern machines increasingly use: • Servo motor drives / efficient motors and energy-saving modes (reducing energy use during idle/stoppage) • Replacement of old motors with efficient motors is a widely recognized industrial energy improvement measure

6.6 Knitting Sector Baseline 2026

India's knitting sector demonstrates strong export competitiveness.

- Tirupur 40,000 Cr FY25 exports (55% of India's knitwear)[22]
- Structural resource efficiency advantages:
  - Near-zero water knitting process
  - Lower energy vs. weaving

However, the knitting and knitwear ecosystem continues to face significant technology and modernization gaps compared to global leaders—particularly China.

India's industry structure still reflects slower diffusion of advanced manufacturing practices, including limited adoption of Industry 4.0/IoT-enabled systems, where barriers such as cost, skills, and fragmented MSME capacity remain prominent.[29]

Seamless/3D knitting (e.g., WHOLEGARMENT®-type whole-garment manufacturing) is emerging in India, but remains at a nascent stage, while global markets are accelerating investment in automated, low-waste 3D/seamless[30] production systems.

In parallel, India's overall textile industry modernization momentum is visible in rising machinery imports and upgrade cycles, but the pace of upgrading and digital transformation still lags leading competitors that have undertaken large-scale modernization and automation at scale.

If India does not accelerate knitting modernization now, the global competitiveness gap will widen by 2030. However, targeted investments can position India as a sustainable, technology-ready knitwear leader.

Risk

- Global knitwear is rapidly shifting toward automation + digital production + advanced knitting (including seamless/3D systems).
- China continues strengthening competitiveness through large-scale industrial automation, 1,40,000 industrial robots are added to textile production lines[31], improving output efficiency and export resilience.
- India's modernization remains import-dependent, with industry evidence showing China contributes ~66% of India's textile machinery imports[32]—underlining the urgency to upgrade faster and build domestic capability

Opportunity

- Invest strategically in equipment modernization, digital infrastructure (IoT + real-time monitoring), and seamless/advanced knitting pilots, combined with sustainability-led productivity gains.
- This can strengthen India's positioning as a future-ready + sustainable knitwear hub by 2030.

[30] Future Market Insights, "3D Knitting Machines Market"

[31] Canada China Business Council, "The New Era of Chinese Manufacturing"

[32] Dr. Gurudas Aras, "Indian Textile Machinery Sector: Emerging Opportunities"

6.6.1 Strategic Imperatives toward 2030:

Table 31 - Gaps/Weaknesses in Knitting

Weakness / Gap	Why it is a problem	Evidence / Anchor Source
Technology upgradation gap (machine vintage + slower refresh cycle)	Lower efficiency, inconsistent quality, reduced competitiveness for premium buyers	India shows modernization but still lags top competitors; ITMF data shows China remains dominant investor in textile machinery.[19]
Seamless / whole-garment capability remains limited	If global buyers shift toward seamless/3D knitting for speed + waste reduction, India risks premium segment loss	Global knitting machinery narrative indicates increasing move toward advanced categories; technology leaders pushing higher automation and advanced systems.[19]
Digitalization / Smart factory gap (IoT, monitoring, predictive maintenance)	Impacts productivity, traceability, compliance reporting, speed-to-market	China's digital manufacturing and automation scale provides productivity advantage.[33]
Warp knitting capacity gap (technical textiles readiness)	Technical textile growth needs warp knitting capacity; India risks missing import substitution opportunity	Strategic relevance of technical textiles growth is recognized under India's development focus; warp knitting is foundational for many technical textiles.[34]
Ludhiana modernization drag (flat knitting upgrade lag)	Domestic market will shift to premium knits; risk of import substitution failure	ITMF shows electronic flat knitting machine shipments are rising globally (135k units in 2024), indicating fast modernization globally.[19]

The knitting sector's next phase of growth requires selective technology upgradation that aligns investment decisions with market positioning and buyer requirements.

Global buyers are increasingly selecting suppliers not only on cost and capacity, but also on speed-to-market, consistent quality, digital product development capability, and compliance-readiness (traceability / sustainability reporting). Digitization—especially 3D design and virtual sampling—is therefore becoming a competitiveness enabler rather than an optional efficiency tool, as it shortens sampling cycles and reduces development time.

In parallel, automation and IoT adoption support buyer expectations for reliable delivery performance, traceable production records, and measurable compliance, which are increasingly linked to market access in regulated regions.

Table 32 - Technology Recommendations for Knitting

Buyer Requirement (What brands expect)	Why it matters	Technology Response (What India must adopt)
Speed-to-market (shorter development cycles)	Brands are compressing seasons; suppliers selected on responsiveness	3D design + virtual sampling in export houses (faster approvals, fewer physical samples)
Consistent quality + repeatability	Reject rates/variance impact contracts and trust	Latest-generation circular/flat knitting machines + better QC automation
Traceability + compliance-readiness	Buyer compliance & regulations demand evidence, not claims	Digital tracking / IoT/ERP integration for production records, chain-of-custody support.
Lower impact products (water, waste, carbon)	"Preferred supplier" status increasingly linked to measurable improvements	Energy efficient machines + seamless pilots (waste reduction) + circularity integration
Design differentiation / premiumisation	Buyers pay premiums only for unique capability	Jacquard + seamless knitting pilots (premium segments, functional apparel)

Tirupur's position as knitwear export hub remains our strength, but technology upgradation is essential to compete with Bangladesh costs and China automation.

Ludhiana's domestic focus provides buffer but modernization needed for quality improvement and premium segment capture toward Viksit Bharat 2047.

[33] Financial Times (Sept 2025),"Homegrown robots help drive China's global export surge"

[34] The Times of India (July 2025),"Synthetic Takeover"

7. Wet Processing

7. Wet Processing

Wet processing represents the most water, energy, and chemically intensive stage of textile manufacturing, encompassing pre-treatment (desizing, scouring, bleaching), dyeing, printing, and finishing.

India's textile production remains heavily skewed towards Cotton (60-65%), a dominance that fundamentally shapes the nation's wet processing infrastructure.

This reliance necessitates extensive pre-treatment facilities (desizing, scouring, bleaching), resulting in structurally high water and salt consumption—a critical bottleneck in water-stressed hubs like Tirupur and Rajasthan where Zero Liquid Discharge (ZLD) is becoming mandatory.

Simultaneously, the Polyester segment (30-35%) is growing rapidly, presenting a different set of challenges. While polyester dyeing consumes less water than cotton, it is highly energy-intensive, requiring High-Temperature High-Pressure (HTHP) jet dyeing machines operating at 130-140°C. Furthermore, Indian adoption of advanced, energy-efficient alternatives like supercritical CO_2(waterless) dyeing remains limited, keeping the carbon footprint of this segment high.

The most complex operational challenge, however, lies in the rising Poly-Cotton (PC) blends (15-20%). Processing these blends creates a "compound inefficiency" because it typically requires two distinct dyeing steps (one for cellulose, one for synthetic) or inefficient carrier methods. This pathway is currently the most resource-intensive, exposing a significant technology gap in India's adoption of efficient, single-bath processing chemistries that could streamline production and reduce effluent loads.

India's wet processing sector faces a critical paradox: serving as the essential value-addition gateway that transforms grey fabric into finished textiles, while simultaneously generating 70% of total textile industry water pollution and consuming 40-50% of sector energy use.

The wet processing impacts are not isolated to a few units—they are cluster-scale risks with shared infrastructure and regulatory exposure (ETP/CETP/ZLD, hazardous sludge logistics, boiler emissions). To address this structurally, interventions cannot remain confined to end-of-pipe treatment alone. Instead, modernization must extend upstream into dye and chemical production, since input quality and chemical profile directly influence wastewater toxicity, treatability, sludge volumes, and buyer compliance readiness (RSL/MRSL audits).



[21] Business Standard, April 2025: "Knitwear capital Tiruppur scales record Rs 40K cr exports in FY25"
[22] Indian Textile Magazine, December 2024 "How Modern Machines and Innovations are Transforming India's Knitting Industry."

Strategic Importance for This Roadmap	
Environmental Intensity Implication: wet processing modernization is a license-to-operate requirement—driven by regulation, community pressure, and export buyer audits.	Wet processing is the largest environmental hotspot in textiles—driven by high water, chemicals, hazardous sludge and boiler emissions. Dyeing water use is typically ~110–130 L/kg (knits) and ~130–150 L/kg (wovens), making it structurally water-intensive. Wet processing is widely reported to contribute ~70–80% of textile water pollution due to high chemical load and wastewater generation.
	Wastewater treatment through ETP/CETP/ZLD generates ETP/ZLD sludge, classified as hazardous waste, requiring compliant storage, transport and disposal (TSDF / incineration / co-processing).
	Boilers/TFHs used for steam/heat emit PM, SO_2, NOx, creating local air compliance risk. CPCB has tightened PM norms for 'baby boilers' (<2 TPH)—a key regulatory signal for clusters.
Value Addition and Export Competitiveness	Knitting creates volume; wet processing creates value. Dyeing/printing/finishing determines: • shade accuracy & repeatability • colour fastness performance • handfeel and functional finishes • defect levels, rejections, buyer claims
	As buyer procurement tightens, units without strong process control + chemical management systems + traceability lose premium programs first—because wet processing is the stage most linked to audit failure and quality variability
Resource Efficiency Opportunity Implication: wet processing modernization simultaneously improves unit cost, carbon intensity, quality consistency, and export market access.	Because wet processing drives most of the water/chemical footprint, it offers the highest ROI efficiency opportunity. The modernization package should prioritise: • LLR / ultra-low liquor ratio dyeing: advanced machines can operate at liquor ratios as low as ~4:1, reducing water use and associated thermal energy demand. • Digital textile printing: can substantially reduce water consumption (reported up to ~95% reduction compared to conventional wet printing workflows). • ZLD and advanced recovery for clusters facing freshwater stress and high regulatory scrutiny (where compliance failures translate into shutdown risk)

Dyes and Dyestuff: Strategic enabler of India's Wet Processing Roadmap

India is a globally significant dye producer, contributing ~16–18% of world dyestuff exports[36], positioning it among the leading dye manufacturing countries globally (after China). Market estimates indicate that India's dye and dyestuff industry is valued at around USD ~7 billion (2024) and is projected to grow at approximately ~9–10% CAGR over the medium term.[37]

Production Base and Demand Profile

- Textiles are the anchor end-use sector, widely cited as consuming ~70%+ of global dye production.
- India's dye manufacturing is strongly aligned to wet processing demand, with reactive dyes supporting cotton/cellulosics and disperse dyes supporting synthetics (polyester-dominant processing hubs).

Strategic Implication of the Roadmap

Modernizing dye manufacturing (cleaner production, ZLD readiness, safer formulations, and digital ink innovation) in parallel with wet processing upgrades creates a value-chain multiplier:

- Higher export compliance readiness (chemical management + buyer audits)
- Reduced pollution load in processing clusters
- Stronger domestic value addition and import competitiveness
- Improved positioning in sustainability-driven markets by 2030.



[36]PIB (Feb 2025), "CHEMEXCIL's Export Award Ceremony Held at Mumbai"
[37]Indian Chemical News (Aug 2025), "Colors of Opportunity: India's expanding dye and dyestuff industry"

Table 33 - Major Wet Processing Countries (Global)[38]

Country	Global Positioning (Wet Processing)	Typical Wet Processing Focus	Compliance / Sustainability Profile
China	World's largest wet processing base (scale advantage)	Cotton + synthetics dyeing/finishing; printing at massive scale	Increasing automation + LCA focus; still large pollution footprint due to scale
India	One of the largest wet processing ecosystems (cluster-led)	Knitwear dyeing, cotton processing, synthetics processing; ZLD in select clusters	Strong regulatory evolution in clusters (e.g., ZLD models); high modernization opportunity
Bangladesh	Export-led processing hub (garments)	Knit dyeing, fabric finishing supporting RMG exports	High buyer pressure (compliance programs), wet processing intensification risk
Vietnam	Fast-growing wet processing country	Export-oriented dyeing/finishing; synthetics	Increasing capacity as textiles exports grow; environmental scrutiny rising
Pakistan	Major cotton-based wet processing hub	Cotton dyeing/printing/finishing	Compliance tightening due to export reliance; cluster-level interventions relevant
Turkey	Premium/value-added processing hub for EU proximity	Fashion knitwear processing, denim, home textiles	Higher compliance expectations due to EU market linkages (World Trade Organization)
Indonesia	Large ASEAN processing base	Fabric dyeing/printing for regional supply chains	Chemical management & pollution reduction programs increasing



[38] World Trade Centre, "Global Value Chains Sectoral Profiles"

7.1 India's Wet Processing Capacity and Scale

India's wet processing sector serves the one of the world's largest wet processing industry and is equipped with both integrated as well as individual dyeing, printing, and finishing facilities.

Table 34 - Major Wet Processing Clusters

Cluster / Region	Specialization	Processing Capacity / Scale	Technology / Environmental Profile
Tiruppur (Tamil Nadu)	Knitwear bleaching, dyeing & finishing	Large wet processing base supported through CETP network	ZLD transition achieved through CETPs + RO recovery systems; progressive chemical/process optimisation
Surat (Gujarat)	Synthetic fabric dyeing & finishing (polyester/nylon)	Major hub for man-made textiles and processing ecosystem	High TDS effluent challenge; modernization needs include recovery systems and ZLD-ready infrastructure
Faridabad–Ballabgarh (Haryana/NCR)	General fabric dyeing/printing/finishing	High concentration of wet processing units	Water-risk exposure (groundwater stress); modernization needed for pollution and water governance
Ludhiana–Jalandhar (Punjab)	Knitwear dyeing for winterwear (woollen/acrylic blends)	Major base supporting winterwear value chain	Conventional exhaust dyeing prevalent in many units; modernization required for quality + compliance
Ahmedabad–Patan–Mehsana belt (Gujarat)	Cotton/blended processing + dyeing/printing	Traditional as well as woven dyeing & printing processing	Conventional wet processing base; transition push due to water scarcity and compliance tightening
Erode–Karur (Tamil Nadu)	Yarn dyeing + home textile processing	Established regional processing ecosystem	Mix of conventional dyeing + selective upgrades; compliance tightening via TNPCB norms
Balotra–Pali–Sanganer belt (Rajasthan)	Cotton cloth dyeing, printing, washing and traditional processing	wet processing belt with cluster-based processing (Balotra/Pali) and printing concentration (Sanganer)	High effluent load from dyeing/printing; high chemical + TDS/COD concerns; CETP/cluster compliance measures are central

7.2 Wet Processing Technology Landscape and Value Chain

Wet processing follows sequential stages: Pretreatment > Dyeing/Printing > Finishing.

Each employs specific technologies, chemicals, and machinery. This section provides a comprehensive overview of wet processing equipment, technologies, and manufacturers available globally.

Technology adoption patterns in India are detailed separately in Section 6.3.
Wet processing technologies vary fundamentally by fibre chemistry.
The tables below indicate fibre suitability for each process.

Table 35 - Wet Processing Pathways by Fibre Type

Fibre Type	Pre-Treatment Required	Dyeing Method	Typical Water Consumption	Key Challenge
COTTON (Cellulosic)	• Desizing (remove starch/PVA) • Scouring (remove waxes, pectins, oils) • Bleaching (achieve whiteness) • Mercerizing (optional - luster/strength)	• Exhaust dyeing (batch) • Continuous (pad-batch, pad-steam) • Garment dyeing	High: 150-200 L/kg (conventional) 80-120 L/kg (LLR) 40-60 L/kg (ULR)	High water/chemical use Salt/alkali in effluent Color fixation 60-90% (dye hydrolysis)
POLYESTER (Synthetic)	• Heat-setting (dimensional stability) • Light scouring (remove spinning oils only)	• Exhaust HTHP (130-140°C) • Continuous thermosol • Supercritical CO_2 (emerging)	Lower: 80-120 L/kg (conventional HTHP) 40-60 L/kg (LLR HTHP) ZERO (CO_2dyeing)	Requires high temperature (130-140°C = high energy) Oligomer migration (surface defects) Dye sublimation issues
POLYESTER-COTTON BLENDS	Cotton pre-treatment needed • Desizing • Scouring • Bleaching (polyester unaffected)	• Two-bath process (separate dye for each fibre) OR • Single-bath (disperse + reactive dyes together)	Very High: 180-250 L/kg (two-bath conventional) 100-150 L/kg (single-bath LLR)	Process complexity Color matching both fibres High water/chemical use Shade reproducibility
NYLON (Polyamide)	Minimal • Heat-setting • Light scouring	Exhaust (neutral or acidic pH)	80-120 L/kg (conventional) 50-80 L/kg (LLR)	pH control critical Level dyeing challenges
WOOL / SILK (Protein)	Minimal - Gentle • Scouring (remove grease/sericin) • Chlorination (wool - shrink resist, optional)	Exhaust (acidic pH, low temp 60-100°C)	100-150 L/kg (wool sensitive to mechanical action)	Temperature sensitivity (protein degradation >100°C) Shrinkage control Gentle handling required
VISCOSE / MODAL (Regenerated Cellulosic)	Like cotton but more sensitive • Desizing • Scouring (gentle) • Bleaching	Exhaust Continuous	120-180 L/kg (similar to cotton but more sensitive to alkali)	Fibre strength loss when wet Caustic damage risk Careful alkali control

7.2.1 Stage 1: Pretreatment (Preparation)[39]

Pre-treatment prepares grey fabric for dyeing/ printing by removing impurities (sizing agents, natural oils/waxes, pectins), improving wettability, and achieving desired whiteness. Technology choices determine water consumption, chemical usage, and processing time

Table 36 - Pre-Treatment Equipment & Processes (Fibre-Specific)

Process	Fibre Applicability	Technology/Technique Available	Equipment Types	Key Features
Desizing	• Cotton, Cotton Blends, Viscose (ONLY - removes starch/PVA sizing)	• Enzymatic (amylase enzymes) • Oxidative (H_2O_2,persulfates) • Acid desizing (dilute acids) • Combined (enzyme + chemical)	Continuous desizing range J-box Jigger	• Enzymatic: 50-70% chemical reduction, lower temp (50-60°C), biodegradable • Oxidative: Faster, higher temp, harsher
Scouring	• Cotton, Linen, Viscose (remove waxes, pectins, oils) • Polyester/Nylon: Light scouring ONLY (remove spinning oils - much gentler, lower alkali)	• Alkaline scouring (NaOH-based) • Bio-scouring (pectinase enzymes) • Combined scour-bleach (H_2O_2+ alkali)	Continuous bleach range J-box Winch	• Bio-scouring: 30-50% alkali reduction, softer fabric hand-feel, easier effluent treatment • Alkaline: Established, reliable, higher chemical/ temp
Bleaching	• Cotton, Linen, Viscose (achieve whiteness 80-85% brightness) • Polyester: Generally NOT bleached (naturally white) Wool/Silk: Gentle bleaching (H_2O_2only, lower conc.)	• H_2O_2(Hydrogen peroxide) bleaching • Sodium hypochlorite (limited use) • Enzyme-assisted bleaching • Ozone bleaching (emerging)	Continuous bleach range Pad-steam J-box Jigger Winch	• H_2O_2:Industry standard, good whiteness, fabric-friendly • Enzyme-assisted: 10-20% H_2O_2reduction,lower environmental load
Mercerizing (Cotton)	• Cotton ONLY (cellulosic swelling under tension)	• Chain mercerizer (open-width, woven) • Chainless mercerizer • Tubular mercerizer (knits)	Continuous mercerizing range	• Increases luster, strength, dye affinity; 18-25% NaOH solution; caustic recovery systems reduce chemical cost
Heat-Setting	• Polyester, Nylon ONLY (thermoplastic fibres)	• Stenter frame (dry heat 180-220°C)	Stenter (pin/ clip stenter)	• CRITICAL for synthetics: Done BEFORE dyeing to avoid fabric shrinkage in HTHP dyeing at 130°C

[39] Indian Textile Journal. "Emerging technologies in the field of textile processing." February 21, 2024.

7.2.2 Stage 2: Dyeing

Dyeing applies color to fibres, yarns, fabrics, or garments using dyes and chemicals. Most water and energy-intensive stage.

Table 37 - Dyeing Methods by Substrate[40,41]

Dyeing Pathway	What is dyed	Most common equipment / systems	Key applications	Baseline (India relevance)
Fibre / Stock Dyeing	Loose fibres before spinning	Paddle dyeing / pressurised fibre dyeing vessels	Woollen yarns, melange effects, deep penetration	Niche but premium. Used for blending/ styling effects
Yarn Dyeing	Cone/package, hank, beam (warp yarn)	Package dyeing machine; Hank dyeing machine; Beam dyeing machine	Yarn-dyed fabrics, checks/ stripes, embroidery threads	High value-add; supports premium woven & knitting yarn segments.
Fabric Dyeing (Most Common)	Knitted/woven fabric	Batch/exhaust: Jet/ softflow/overflow; Beam; Jigger Continuous: Pad-batch / Pad-steam / Thermosol	Bulk fabric lots, export orders	Primary modernization lever (water/energy/chemicals + compliance) (Textile Learner)
Garment Dyeing	Finished garments	Garment dyeing machines (tumbling/low abrasion)	Fashion garments, casualwear	High value-add; cluster relevance (e.g., Tiruppur)



[40] Cottonworks, "Textile Dyeing"
[41] Textile Learner (Dec 2011), "Methods of Dyeing | Different Types of Dyeing Methods"

Fabric dyeing is the dominant wet processing pathway in India and the primary modernization lever for water/energy/chemical reduction. The technologies used are further elaborated in the below table to understand the baseline better.

Table 38 - Fabric Dyeing Processes & Equipment Baseline

Sub-Category	Process / Method	Typical Equipment	Fibre Suitability	Baseline Notes (India relevance)
Batch / Discontinuous (Exhaust)	Jet / Softflow / Overflow (Rope Form)	Jet / softflow / overflow dyeing machines	Cotton, synthetics, blends	Dominant for knit clusters (e.g., Tiruppur); highest leverage for LR modernization
	Jigger Dyeing (Open Width)	Jigger dyeing machine	Mostly woven fabrics	Legacy technology; lower capex but limited for modern quality/compliance
	Beam Dyeing (Fabric form)	Beam dyeing machine	Wovens requiring uniform penetration	Better uniformity & handling; selective use
High Temp. High Pressure Dyeing	High Temp High Pressure Dyeing	HTHP dyeing machine (sealed vessel)	Polyester, nylon, acetate	Essential for synthetic hubs (e.g., Surat); linked to steam/TFH energy and TDS/effluent management
Continuous Dyeing	Cold Pad-Batch	Padding mangle + batching unit	Reactive dyes on cotton	High uniformity, suitable for volume
	Pad-Steam	Padding mangle + steamer	Reactive/vat/sulphur dyes on cotton	Faster fixation and better repeatability
		Padding mangle + dryer + stenter/ thermofix	Disperse dyes on polyester	Competitiveness tech for synthetics; fastest high-volume route

7.2.2 Stage 3: Printing

Applying localized colour patterns to fabrics.

Note: Water consumption depends strongly on ink chemistry and post-print fixation (steaming/washing). Rotary screen printing can require significantly higher water than digital workflows; as measured comparisons show rotary at ~50–60 L/linear meter vs digital ~14–20 L/linear meter (~70% saving).[42]

Table 38 - Fabric Dyeing Processes & Equipment Baseline

Printing method	Technology range	Water intensity (indicative)	Equipment type	Production speed	Typical application
Rotary screen printing	Conventional rotary (6–24+ colour stations), auto registration	High (significant water + chemicals in print fixation & washing route)	Rotary screen-printing machine	High (typically tens of m/min)	Mass fashion prints, home textiles
Flat screen printing	Manual tables, semi-automatic	High	Flat screen-printing tables	Low	Artisanal / small batches, handloom prints
Digital textile printing – multi-pass (scan-type)	Moving printheads scanning across width	Low (measured reductions vs rotary)	Multi-pass inkjet printers	Medium (model dependent)	Sampling, customization, short runs, D2C
Digital textile printing – single-pass	Fixed head arrays across width (industrial digital line)	Low	Single-pass inkjet printers	Very High (industrial)	High-volume digital fashion + home textiles
Direct-to-Garment (DTG)	Inkjet printing on finished garments	Low (route-dependent)	DTG printers	Medium (garments/hr)	On-demand tees, e-commerce fulfilment
Discharge printing (analog)	Rotary with discharge chemistry	Medium–High	Rotary + discharge system	High	Denim, dark fabrics
Pigment printing (analog)	Rotary/flat with pigment paste	Medium	Rotary/flat screen	High	General fashion; avoids heavy washing (depends on binder system)

[42] SPGPrints (Nov 2021), "Sustainable Textile Printing: digitally reducing the ecological footprint"

7.2.4 Stage 4: Finishing

Imparting specific functional or aesthetic properties to fabrics.

D. Advanced Finishing Technologies:

Nano-coatings: Functionalization using nanoparticles for enhanced properties. Microencapsulation: Embedding fragrances, phase-change materials, moisturizers. Plasma finishing: Surface modification without water/chemicals, activating surfaces, depositing coatings. Laser finishing: Surface modification, denim fading, pattern creation.

Finishing Type	Equipment Types	Process Temp/Conditions
MECHANICAL FINISHING		
Calendering	Calender machine	120-220°C, high pressure rollers
Sanforizing	Sanforizing machine	Steam + pressure + rubber blanket
Raising / Shearing	Raising machine, Shearing machine	Mechanical action
Emerizing / Sueding	Emerizing machine	Dry mechanical abrasion
CHEMICAL FINISHING		
Softening	Padding mangle + Stenter	Pad application + 140-180°C stenter
Water/Oil Repellent	Padding + Stenter	Pad + 150-170°C curing
Flame Retardant	Padding + Stenter	Pad + 150-180°C
Anti-Microbial	Padding + Stenter	Pad + 120-160°C
Easy-Care / Wrinkle-Free	Padding + Stenter + Curing	Pad + 150-170°C + post-cure
BIO-BASED FINISHING (Emerging)		
Enzyme-Based Softening	Conventional padding/exhaust equipment	50-60°C enzyme treatment
Plant-Based Water Repellents	Padding + Stenter	Pad + 140-160°C
HEAT-SETTING (Synthetics)		
Stenter Frame	Stenter (thermosol range)	180-220°C (polyester), 160-180°C (nylon)

7.3 Current Technology Adoption in India

7.3.1 Technology Status by Process Stage

Table 39 - Key Technology Gaps in Wet Processing[43]

Process stage	Current dominant technologies (India baseline)	BAT / advanced technology direction	Key technology gap (why it matters)
Pretreatment	Alkaline scouring + peroxide bleaching remain standard; batch systems still operate in decentralized sector; gradual shift to continuous pretreatment ranges in organized mills	Enzymatic pretreatment: amylase-based desizing; pectinase bio scouring[1]; improved chemical efficiency and effluent load reduction	Sizing & fibre content testing remains almost nil at MSME level leading to higher water & chemical consumption.
Dyeing	Predominantly batch/exhaust dyeing: jet + soft-flow machines dominate, particularly in knit clusters	Liquor ratio reduction ladder: Conventional LR > LLR > ULR/airflow smartflow	High water/steam intensity driven by conventional liquor ratios; ULR adoption limited to advanced installations. Verified OEM benchmarks show ULR can reach ~1:2.5 (synthetics) and ~1:3.7 (cotton).
Printing	Screen printing (flat & rotary) dominates commercial volumes	Digital printing (multi-pass / single-pass) expanding rapidly for short runs, sampling, design-intensive output	Chinese Digital Printers are dominating Polyester Dyeing i n Surat due to favourable capex, but remains nascent for cotton substrate
Finishing	Conventional mechanical finishes (calendering, sanforizing, compacting) + chemical finishes widely used	Shift away from legacy chemistries: PFC-free / fluorine-free repellents, reduced hazardous chemistries, improved compliance systems	Sustainability compliance pressure is driving substitution: strong global movement toward PFC-free DWR alternatives.

[43] Textilchemie Dr. Petry GmbH, "Bioscouring: Preteatment of Cotton with Pectinase Enzymes

7.3.2 Automation and Process Control

7.3.2.1 Digitalization & Automation

The sector operates mostly at a semi-automated level, highlighting a major technology gap towards Industry 4.0. Manual operations persist widely, particularly for fabric loading/unloading and chemical dosing in smaller units.

While computerized color matching (Macbeth, Datacolor) is growing, especially in Tirupur processors, the adoption of fully automatic dosing and chemical dispensing systems is still limited to large scale industry due to investment.

Process Monitoring:

- Basic monitoring: Temperature, time, pH sensors standard
- Real-time monitoring: Limited IoT sensors, predictive systems
- Laboratory testing: Physical testing (color fastness, strength, shrinkage) standard in Tirupur labs (ITS, SGS, Textile Committee)
- In-line quality control: Minimal automated systems

Digitalization:

- Recipe management: Digital systems in progressive mills
- Production tracking: ERP integration limited to large mills
- Industry 4.0: Nascent stage, minimal AI/ML applications

7.3.2.2 Cluster-Specific Patterns

Ahmedabad Cluster (Gujarat):

- Historical textile hub: One of India's oldest and largest textile processing centers
- Specialization: Cotton and blended fabric dyeing and finishing, woven fabric processing
- Infrastructure: Mix of large integrated mills and standalone processing houses
- Technology: Conventional and modern dyeing equipment, continuous processing ranges
- Environmental infrastructure: Multiple CETPs serving cluster units
- Challenges: Aging equipment in many units, water stress issues, pollution control compliance

Tirupur Cluster:

- Specialization: Knitted fabric dyeing, garment dyeing, finishing
- Technology: Soft-flow dyeing dominant, open-width finishing emerging trend (Shakthi Mills, Chaya Industries, Victus Dyeing leading)
- Yarn mercerizing: In-house facilities emerging (GTN Textiles specializing)
- Garment washes: Extensive capabilities (perfume wash, pigment dye, silicon wash, UV protection treatments)
- Quality infrastructure: Multiple testing labs (ITS, SGS, Textile Committee, supporting laboratories)
- Rejection rates: Improved from 5% to 1.5% through better quality control

Surat Cluster:

- Specialization: Synthetic fabric dyeing
- Technology: Jet dyeing Machine
- Scale: Large-volume production orientation

Integrated Mills:

- Higher technology levels, modern dyeing machines, better process control
- In-house R&D capabilities in largest mills
- Vertical integration enabling quality consistency

Standalone Processing Houses:

- Technology heterogeneity, mix of conventional and modern equipment
- Capital constraints limiting latest technology adoption
- Job-work model serving multiple customers

7.4 Global Technology Benchmarking

India's wet processing sector exhibits significant technology gaps relative to global leaders in water efficiency, digital printing penetration, zero liquid discharge implementation, liquor ratio achievement, process digitalization, and sustainable chemistry adoption. These gaps translate directly into higher operating costs, regulatory vulnerability, market access constraints, and missed premium positioning opportunities.

This section quantifies each gap, assesses severity, and defines strategic implications for India's readiness to 2030.

7.4.1 Technology Availability vs. Adoption in India

Readily Available:

- Conventional jet dyeing machines, jiggers
- Standard continuous ranges for synthetics
- Screen printing equipment (domestic and imported)
- Basic finishing equipment (calendars, sanforizing)
- Chemical finishing auxiliaries

Available Internationally, Limited Indian Adoption:

- Ultra-low liquor dyeing machines: Latest models (Benninger FabricMaster, Thies Signature) available but high capital cost limits adoption. Requires significant infrastructure investment, skilled operators.

- Waterless dyeing technologies:
  • Supercritical CO2: Technology exists (DyeCoo), virtually no Indian installations due to very high capital cost (~10x conventional), limited to 100% polyester, infrastructure requirements
  • Foam dyeing: Limited pilots, technology demonstration stage

Advanced digital printing:
Latest high-speed single-pass printers available but significant capital investment. Growing adoption for short-run/customization but conventional screen printing still dominant.

Plasma treatment systems:
Surface modification technology available, minimal adoption (high cost, technical complexity, unclear ROI for conventional textiles).

Comprehensive automation:
SCADA systems, automated chemical dispensing, in-line quality monitoring available but capital intensity and skilled personnel requirements limit adoption.



7.4.2 Technology Gap Analysis

Gaps between India and global leaders:

1. Water efficiency gap: Conventional liquor ratios (1:8-1:12) vs. global best practice (1:2.3-1:4), limited water recycling penetration
2. Energy efficiency gap: Older dyeing machines, inefficient heating systems vs. latest energy-optimized equipment (heat recovery, insulation)
3. Chemical efficiency gap: Higher chemical consumption per kg fabric, limited Right-First-Time dyeing penetration, re-dyeing waste
4. Automation gap: Manual operations, limited process control vs. comprehensive automation, real-time monitoring in advanced markets
5. Digital gap: Minimal Industry 4.0, IoT, AI applications vs. digital integration in European/Chinese leading mills
6. Sustainable technology gap: Limited waterless, low-impact technologies vs. growing adoption globally (Europe leading)

Effluent Treatment:

- Common Effluent Treatment Plants (CETPs) in clusters (Tirupur, others)
- Individual ETPs in integrated mills
- Challenges: Treatment effectiveness varies, occasional clandestine discharge issues (Tirupur litigation history), capital-intensive upgrades needed



7.5 Resource Efficiency and Sustainability

7.5.1 Water Consumption

Water consumption by process:

- Pretreatment (scouring, bleaching): High water for washing, rinsing
- Dyeing: Highest consumption - bath preparation, rinsing, washing after dyeing.
  • Liquor ratio directly determines water: 1:12 = 12L water per kg fabric vs. 1:3 = 3L water per kg
- Printing: Lower than dyeing but screen washing consumes water (digital printing eliminates this)
- Finishing: Washing after chemical application, padding processes

Water efficiency improvements:

- Low-liquor dyeing: 60-75% water reduction (1:12 > 1:3 liquor ratio)
- Water recycling: Closed-loop systems, RO treatment for reuse (limited adoption)
- Counter-current washing: Using final wash water for initial rinse (reduces fresh water)
- Digital printing: Eliminates screen washing water

Tirupur context: Water-stressed region, significant environmental litigation. Zero Liquid Discharge (ZLD) mandates for some operations, driving CETP investments and water conservation.

7.5.2 Energy Consumption

Wet processing is energy-intensive due to water heating, steam generation, drying.

Energy consumption by process:

- Water heating: Major consumer (60-90°C for dyeing/scouring/bleaching)
- Steaming: Fixation in printing, mercerization, continuous dyeing
- Drying: Stenters, dryers after wet processes (high energy)
- Mechanical finishing: Motors for calendars, compactors

Energy efficiency drivers:

- Heat recovery systems: Capturing exhaust heat for water preheating (limited adoption)
- Insulated equipment: Reducing heat loss
- High-efficiency burners: Modern stenters
- VFD motors: Variable speed drives (growing adoption)
- Low-temperature processes: Enzymatic treatments vs. high-temperature alkaline

7.5.3 Chemical Usage and Waste

Chemicals consumed:
Dyes, alkalis (caustic soda), acids, oxidizing agents (peroxide), reducing agents, detergents, softeners, specialty chemicals.

Waste minimization:

- Right-First-Time dyeing: Avoiding re-dyeing reduces chemical/water waste
- Precise dosing systems: Automated chemical dispensing reduces excess
- Green chemistry: Bio-based auxiliaries, biodegradable chemicals (growing segment)
- Natural dyes: Sustainable alternative but performance limitations
- Effluent Characteristics and Treatment

Wet processing effluent:
High BOD/COD (organic load), color (residual dyes), pH variations, dissolved solids, heavy metals (some dyes), temperature.

7.6 Wet Processing Sector Baseline 2026

India's wet processing sector in 2026 demonstrates critical environmental and technology transformation needs. As the most resource-intensive and polluting stage in textiles, wet processing faces dual pressures: stringent environmental regulations domestically and sustainability requirements from global buyers.

7.6.1 Baseline Characterization

The baseline status of India's textile processing sector is defined by a dual structure and significant technological gaps, particularly in resource efficiency. The sector is organized around major clusters (Tirupur, Ahmedabad, Surat) and features a dual structure: modern Integrated Mills coexisting with numerous standalone units that display high technology heterogeneity.

7.6.1.1 Technology and Automation Status

Conventional processes remain dominant, highlighted by widespread Batch Dyeing (often utilizing high liquor ratios of 1:8 to 1:12), alkaline pretreatment, and peroxide bleaching.

Modern, resource-efficient technology is limited: Ultra-low liquor dyeing is minimal, and advanced concepts like waterless dyeing are virtually absent.

The most significant technological momentum is seen in specific segments: Digital Printing is expanding rapidly for short-run flexibility, enzymatic processes are increasing, and computerized color matching is standardizing quality in larger units.

However, a major automation gap persists, characterized by prevalent manual operations, limited real-time process monitoring, and a nascent Industry 4.0 presence.

7.6.1.2 Resource Consumption and Environmental Challenges

Resource consumption remains high and inefficient. Conventional processes require an estimated 80-150 liters of water per kg of textile[44], with limited penetration of advanced water recycling systems.

Energy consumption is high in heating and drying stages, compounded by limited deployment of heat recovery systems.

This intensity translates directly into a significant Environmental Challenge: While pollution is managed through CETPs in clusters and individual ETPs, their effectiveness varies. The sector faces constant regulatory pressure from Pollution Control Boards and litigation, driving the slow but certain emergence of Zero Liquid Discharge (ZLD) mandates.

7.6.1.3 Competitive Positioning

Despite these challenges, India maintains strong Competitive Positioning through cost competitiveness, pronounced cluster specialization (e.g., Tirupur knitwear), and the growing adoption of digital printing.

This is supported by adequate Quality Infrastructure, with key testing labs (ITS, SGS, Textile Committee) present, which has led to marked improvements in quality control.

The primary Challenges for the roadmap remain bridging the substantial water/energy efficiency gaps versus global best practice, accelerating the adoption of sustainable technologies, ensuring effective effluent treatment, and overcoming the pervasive automation lag.

7.6.2 Strategic Imperatives towards 2030

The wet processing sector's transformation from 2026 baseline requires prioritized investments in:

- **Water efficiency:** Low-liquor dyeing machines, water recycling, Right-First-Time processes
- **Energy efficiency:** Heat recovery, insulation, efficient stenters, low-temperature processes
- **Sustainable chemistry:** Bio-based auxiliaries, natural dyes (niche), green chemistry adoption
- **Effluent treatment:** Enhanced CETP effectiveness, advanced oxidation, ZLD where mandated
- **Digital printing expansion:** Replacing conventional printing for short-medium runs
- **Process automation:** Automated dosing, real-time monitoring, reducing human error

The sector's environmental performance directly impacts India's textile export competitiveness as global brands impose stricter sustainability requirements. Wet processing modernization represents both compliance necessity and competitive opportunity toward Viksit Bharat 2047.



[44]BREF of Gujarat



8. Ready-Made Garment

8. Ready-Made Garment

8.1 Overview: Garment Manufacturing in India's Textile Value Chain

Garment manufacturing represents the final value-addition stage in textiles, converting fabrics into finished apparel for domestic and export markets. India's garment industry is characterized by extreme fragmentation, labor intensity, and rapid technology evolution driven by global competitiveness pressures and automation trends.

Strategic Importance for this Roadmap

1. Employment and inclusive growth engine (highest socio-economic leverage)
Garment manufacturing is India's most employment-intensive textile segment and a key lever for inclusive industrial growth.

Implication: Modernizing garment production is not only a competitiveness agenda—it is fundamentally a livelihood security and job quality agenda.

2. Export competitiveness depends on speed, quality and compliance (not cost alone)
While upstream modernization improves input competitiveness, export outcomes are ultimately determined at the garment stage through:

Fit and aesthetics | quality consistency | rejection rates | delivery reliability

Global fashion models increasingly compete on shortened trend cycles and lead times, where even a few days of delay affects vendor selection.

Implication: The garment chapter is central because the global competition is shifting from unit cost to speed-to-market + reliability.

3. Garments are the "traceability and due diligence bottleneck" for future market access
India's export competitiveness will increasingly depend on digital proof of compliance—not just physical compliance. The EU is advancing Digital Product Passport (DPP) concepts for textiles to strengthen traceability, circularity and transparency.

For exporters, this pushes garment factories (and their job-work networks) toward standardized data capture, bill-of-material traceability, process transparency, and digital integration with buyers.

Implication: Roadmap investments in RFID/WMS/ERP + supplier traceability become a market access requirement—not an optional efficiency upgrade.

4. Technology diffusion has the highest ROI in garments
Unlike spinning and weaving (where capex is very high and largely mill-driven), garment manufacturing has multiple technology upgrades with a favourable ROI

Implication: The roadmap must prioritize technology diffusion models (cluster/CFC-based systems + skilling), not only factory-level capex support.

8.1.1 India's Garment Manufacturing Capacity and Scale

India's garment sector operates through a highly decentralized structure serving both domestic consumption and significant export markets.

Dimension	Baseline status (India)	What it indicates	Policy implication
Industry structure	Highly decentralized and fragmented, with layered production networks (manufacturers + fabricators/job contractors)	Flexibility and scale-through-subcontracting, but uneven capabilities	Productivity and compliance improvements require cluster/association-led modernization, not unit-level only
Manufacturing base	~27,000 domestic manufacturers and ~1,000 manufacturer-exporters[1]	Export capability concentrated in a smaller organized segment	Support export firms to absorb MSMEs into compliant supply networks (common standards, digital systems)
Technology intensity	Large installed base (indicative: ~1.5 million sewing machines across units)45	Scale exists but uneven modernization (automation/CAD/QA varies)	Shift from "machines count" to "productivity per machine" approach
Capacity concentration	Small fabricators dominate (often cited ~72% of manufacturing capacity)[45]	Structure supports employment but caps standardization	Introduce common facility centres, QA labs, and shared digital tools for MSME job-work clusters
Employment significance	Textile/apparel is the 2nd largest employer after agriculture. ~45 million employed directly	High socio-economic impact	Policy must treat garment sector modernization as livelihood protection + competitiveness + Skilling + productivity investments have high multiplier impact
Gender & inclusion	High participation of women, especially sewing operations; significant presence in semi-urban/rural clusters	Inclusion-driven manufacturing	Focus on safe workplaces, hostels, transport, retention, and supervisor training

[45] Department of Scientific and Industrial Research (DSIR), Government of India. "Garment Manufacturing".

8.1.1.1 Market Size, and Growth

The market size provides a strong incentive for capacity expansion and technological investment. India's overall textile manufacturing market is projected to grow substantially from USD 128.28 billion in 2024 to USD 190.57 billion by 2033, representing a steady 4.15% CAGR. The domestic apparel segment is a key growth driver, particularly the Direct-to-Consumer (D2C) apparel market, which is expected to hit USD 10 billion by 2025 and is growing rapidly at 20% annually. This growth is heavily accelerated by e-commerce platforms (Myntra, Flipkart, Ajio), which consistently report double-digit apparel sales growth.[46]

8.1.2 Major Garment Manufacturing Clusters

Garment manufacturing in India is decentralized but specialized, with distinct regional hubs driving different segments of the market—from large-scale exports to specialized domestic winter wear.

Mumbai-Thane (Maharashtra) is a historical garment manufacturing center with a varied mix of both domestic-oriented and export-oriented units. And, Kolkata (West Bengal) differentiates itself with a focus on handloom-based garment production and ethnic wear, alongside an emerging ready-made garment sector.

Table 40 - Garment Manufacturing Clusters

Cluster / Region	Product specialization	Market orientation	Competitive positioning (what it is known for)	Key note for baseline
Tiruppur (Tamil Nadu)	Cotton knitwear: T-shirts, innerwear, casualwear	Export-led	High-volume knitwear hub with established global buyer linkages	Strong export engine; highly buyer-compliance driven (quality + delivery + sustainability).
NCR (Delhi–Gurugram–Noida)	Mixed garment manufacturing base (woven + knit)	Domestic + Export	Strong presence of export houses, buying offices, sampling & design interface; logistics advantage	Functions as a key commercial interface with global supply chains; scale supported through industrial parks.
Bengaluru (Karnataka)	Woven garments and export-grade manufacturing; some denim value chain linkage	Export-led	Compliance-focused ecosystem; larger factory-based production base	Strong global supply chain integration; compliance and labour standards pressure shapes competitiveness.
Ludhiana (Punjab)	Winter knitwear: sweaters, pullovers, acrylic/wool blends	Domestic-led (with export niche)	India's major winterwear manufacturing hub; seasonal demand-driven	Domestic market anchor; faces competitive pressure from imports and quality differentiation requirements.

[46] IMARC Group. "India Textile Manufacturing Industry: Market Size, Share 2033

8.1.3 Global Competitive Context

India is the 6th largest exporter of textiles globally, contributing 8.21% to total exports (2023-24). Textile and apparel hold 4.5% share in global trade. United States and European Union account for 47% of India's textile/apparel exports.

Technology Transformation Imperative: McKinsey report suggests AI-driven solutions could reduce production costs by 20-30% over next 5 years. Automation, robotics, and digital technologies becoming competitive necessities. [48]

Table 41 - Garment Global Competitive Context

Competitor	What makes them competitive	Why it matters for India
Bangladesh	Lower labour costs + strong export specialization; duty-free, quota-free EU access under EBA due to LDC status[47]	Creates a cost+tariff advantage in price-sensitive garment categories; strengthens buyer preference for volume programs
Vietnam	Preferential trade agreements (e.g., EU–Vietnam FTA) and strong export-oriented manufacturing ecosystem	Tariff pathway improves long-term market access; accelerates investment into textiles/garments and supply chain upgrades
China	Scale, deep supplier ecosystem, and fast industrial upgrading including digital transformation and automation	Speed, consistency, and productivity advantage; difficult to compete on cost without modernization and differentiation
Cambodia / Myanmar (emerging)	Low-cost manufacturing alternatives for basic apparel	Competition on entry-level products increases pressure on India's cost competitiveness

Table 42 - India's Competitive Advantages in Garment Industry

Advantage	What it enables	Policy relevance
Presence across the full value chain (fibre > yarn > fabric > apparel)	Vertical integration potential, faster domestic sourcing, resilience vs supply chain shocks	Strategic leverage vs "cut-make-trim" countries; needs cluster coordination to unlock
Large workforce across textile segments	Ability to scale across multiple product categories	Needs skilling modernization (CAD/CAM, digital, automation operations)
Design capability and sampling flexibility	Growing domestic design talent, fashion education infrastructure	Key advantage for premium/export programs and domestic value fashion growth
Operational flexibility	Ability to handle small/medium orders	Competitive in fragmented buyer landscape
Quality & compliance ecosystem	Testing labs and compliance support (ITS, SGS, Bureau Veritas	Supports buyer confidence and reduction in rejections/claims

[47] European Commission, "Bangladesh - Trade and Economic Security"

8.2 Garment Manufacturing Technology Landscape

Garment manufacturing involves sequential processes:

Design > Pattern Making > Grading > Marker Making > Fabric Spreading > Cutting > Sewing > Finishing > Quality Control > Packaging

Each stage shows varying automation adoption. The initial stages of garment manufacturing—Design, Spreading, and Cutting—represent a critical juncture where technology adoption directly impacts speed-to-market and cost efficiency.

Table 43 - Garment Manufacturing Technologies & BATs

Stage	Current Technologies	Technology ladder (Modern > BAT)	Why it matters
Design & Product Dev	Manual sketching, paper patterns, physical sampling	CAD/CAM pattern making > 3D virtual prototyping > PLM integration	Speed-to-market + sampling cost
Fabric spreading	Manual spreading dominates in decentralized units	Manual > semi-automated spreaders > automated tension-free spreading with edge alignment	Quality + cutting efficiency
Cutting	Manual cutting (straight/ band/round knife)	Manual > mechanized straight knife > computerized auto cutting; laser / water-jet / ultrasonic as niche	Fabric waste + precision
Sewing/ stitching	Traditional machine set: single needle lockstitch, overlock/flatlock, bartack, buttonhole	Traditional > computerized machines > programmable pattern sewing (PPS) / automated sewing units (ASU) > robotic sewing work lines	Productivity ceiling
Finishing	Manual trimming and steam pressing; QC via visual checks + AQL sampling	Manual > semi-automatic trim/press aids > tunnel finishers > automated folding/packing aids; emerging AI defect detection	Defect risk + claims
Packaging & logistics	Manual/semi-automatic polybagging/cartoning; manual warehouse operations	Manual > WMS + RFID tagging > EDI integration with buyers	Traceability + buyer integration

8.2.1 Stage 1: Design and Product Development

The sector is undergoing a necessary transition from traditional methods (manual sketching, paper patterns, physical sampling) to sophisticated CAD/CAM Technologies.

Modern systems, including digital pattern creation, grading, marker making software, 3D garment design for virtual prototyping, and PLM (Product Lifecycle Management) solutions, enable significant benefits: reduced sampling time and cost, better fit accuracy, and faster design iteration.

Adoption in India is polarized: Export Houses and large manufacturers have made significant investments in systems like Gerber, Lectra, and Optitex, while adoption is only growing in medium units (driven by clear ROI and export compliance needs) and remains limited to manual methods in small fabricators.[49]

8.2.2 Stage 2: Fabric Spreading

The laying of fabric layers for simultaneous cutting is still dominated by Manual Spreading in smaller Indian units, which is labor-intensive and quality-variable.

Technological progression moves through Semi-automated spreading machines to Fully Automated Spreading systems (e.g., Gerber, Lectra, Bullmer). These modern systems offer computer-controlled laying with precise tension and edge alignment, but their high capital cost means the manual method remains predominant across the broader industry base.[21]

8.2.3 Stage 3: Cutting

The sector utilizes a dual system for cutting. Manual Cutting using straight, band, and round knives is prevalent in small fabricators due to its low capital cost, despite its operator-dependent accuracy and quality variability.

The future of cutting lies in Computerized Cutting Technologies, which offer high precision and better material utilization. These include computer-controlled straight knife cutters, and advanced methods like:

- Laser Cutting
  For high precision/complex patterns
- Water-jet Cutting
  For delicate fabrics and
- Ultrasonic Cutting
  For synthetic fabrics that seal edges

While Computerized Cutting systems are standard in large and export-oriented units, the vast majority of small-scale production capacity still relies on the labor-intensive manual method.

Leading Manufacturers:

- Gerber: Automated cutting solutions (Z7, S-Series cutters)
- Lectra: Vector cutters, laser systems
- Bullmer: Cutting systems popular in Europe/Asia
- Chinese manufacturers: Cost-effective solutions (growing in India)



[49] Textile Sphere. "Garment Automation in the Textile Industry." September 27, 2024

8.2.4 Stage 4: Sewing/Stitching

The core assembly stage is dominated by Traditional Machines such as the single needle lockstitch, various overlock and flatlock machines, and specialized units (buttonhole, bartack). This suite of conventional machinery remains dominant across all unit sizes in India.

However, a technological transition is underway, marked by the growth of Computerized Sewing Machines in medium-to-large units and export houses.

These advanced units offer programmable stitches, automatic threading, and built-in patterns.

Furthermore, highly specialized automation, such as Programmable Pattern Sewing (PPS) and Automated Sewing Units (ASU) for specific operations (e.g., pocket setting), is confined to the largest manufacturers.[21]

The Robotic Sewing (Sewbots) technology, representing the global frontier (e.g., Soft-Wear Automation), is capable of end-to-end garment assembly with AI-driven precision and reduced manual intervention.[21]

Critically, this technology is virtually absent in India due to high cost and its pilot stage globally, presenting the most significant technology gap in core manufacturing. The market, defined by top export states like Maharashtra, Gujarat, and Tamil Nadu, shows a rising demand for technological advancements, with trends focusing on automatic bobbin changing and IoT connectivity for machine monitoring.[50]

India Adoption Status:

- Traditional machines: Dominant across all unit sizes
- Computerized machines: Growing in medium/large units, export houses
- Specialized automated units: Limited to large manufacturers, specific operations
- Robotic sewing: Virtually absent (high cost, technology demonstration stage)

8.2.5 Stage 5: Finishing Operations

Finishing operations—covering thread trimming, pressing, inspection, and packaging—are predominantly manual across the Indian sector.

Pressing/Ironing is largely dependent on manual steam pressing.
While Automated Tunnel Finishers are present in the largest export units, they are not widespread.
Quality Control (QC) remains labor-intensive, relying heavily on visual end-line 100% inspection and statistical AQL sampling, though in-line inspection during the sewing stage is a growing trend.
The limited adoption of automated systems (e.g., auto-folders) confirms that finishing is one of the least automated stages of the manufacturing process.

8.2.6 Stage 6: Packaging and Logistics

The final stage of Packaging and Logistics also shows limited automation. Packaging relies on manual or semi-automated processes for individual poly bags and cartons, with fully Automated Packaging Lines having limited adoption.

Digital integration is, however, slowly growing: RFID tagging for inventory management is increasing in larger units, alongside the adoption of Warehouse Management Systems and EDI/AS2 integration for seamless communication with international buyer systems.



[50] Gartex India. "How Automation and AI are Transforming Garment Manufacturing." August 28, 2024

8.3 Current Technology Adoption in India

8.3.1 Automation and Digitalization Status

Process area	Automation status (2026 baseline)	Digitalization status (2026 baseline)	Strategic gap / competitiveness impact
Spreading & cutting room	Moderate automation in export factories (spreading + automated cutting); manual dominant in MSMEs	Marker optimization and cutting workflow digitization in organized units	Cutting-room modernization yields immediate ROI via fabric savings and consistency
Sewing / stitching (core bottleneck)	Minimal automation globally and in India; sewing remains highly labour-dependent; programmable units only in select operations	Limited machine monitoring / IoT in most factories	Sewing is the global automation frontier; robotic sewing exists but remains limited commercially (textileworld.com)
Material handling (intra-factory)	Largely manual bundle handling and fabric movement	Limited real-time tracking	Hidden productivity loss (WIP delays, mix-ups, rehandling)
Production planning / shopfloor control	-	ERP usage concentrated in organized sector; MSME planning is manual/spreadsheet-driven	Weak production visibility affects delivery reliability
Traceability & inventory systems	-	RFID/barcode adoption emerging in large units; WMS in exporters; buyer system integration via EDI in select factories	Traceability becoming buyer requirement; RFID improves real-time inventory accuracy and speed
Industry 4.0 readiness (overall)	Mechanization is widespread; automation uneven	Digital adoption uneven; some pilots in IoT/AI	Sector sits largely in Industry 2.0–3.0 with pockets of 4.0, consistent with global apparel readiness studies

Training Infrastructure:

- Apparel Training & Design Centres (ATDC): Over 400,000 candidates trained (government initiative)
- NIFT (National Institute of Fashion Technology): Design education, technology training
- Polytechnic and ITI programs: Technical training in garment manufacturing
- Industry-specific training: Buyer-sponsored programs, NGO initiatives (Shahi Exports, others)

Skill Challenges:

- Technology gap: Workforce trained on traditional methods, limited exposure to automation
- Operator turnover: High attrition rates affecting continuity
- Upskilling needs: AI, robotics, digital systems require new competencies

8.4 Global Technologgy Benchmarking

8.4.1 Technology Gap Analysis

Table 44 - India vs Global Trajectory[51,52]

Gap Area	India Baseline (2026)	Global Trajectory	Competitiveness Impact
Operational Automation	Predominantly manual; automation limited to large-scale exporters.	Widespread use of automated units for repetitive tasks (pocket setting, bartacking).	Productivity ceiling; higher unit costs; delivery variability.
Robotic Sewing	Virtually absent in domestic production.	Pilots/Early commercialization (e.g., Sewbots) for simple product groups (T-shirts).	Risk of long-term obsolescence as global adoption accelerates.
Digital Design & 3D Sampling	Limited adoption of 3D prototyping beyond top-tier exporters.	Standardized use of virtual sampling for faster approvals and zero-waste design.	Slower sampling cycles; higher development costs; reduced buyer agility.
Smart Factory (IoT)	Minimal real-time visibility; fragmented digitization across the floor.	Industry 4.0 integration; real-time monitoring and predictive maintenance.	Lower OEE (Overall Equipment Effectiveness); weaker buyer transparency.
Speed & Throughput	Lower operator throughput due to manual handling and poor line balancing.	Engineered SMV (Standard Minute Value) systems and modular production.	Extended lead times; incompatible with “Fast Fashion” requirements.
Quality Consistency	Labor-intensive QC; high dependence on manual visual inspection.	AI-based defect detection and real-time quality analytics.	Higher defect leakage; increased rework costs and buyer claims.

Comparative Labor Costs:

While India maintains labor cost advantage over developed markets, Bangladesh labor costs 20-30% lower, creating competitiveness pressure. Automation partially offsets labor costs but requires capital investment.

8.4.2 Leading Garment Technology Manufacturers

- Gerber Technology (USA, part of Lectra Group)
- Lectra (France)
- Juki (Japan)
- Brother (Japan)
- Jack Sewing Machine (China)
- SoftWear Automation (USA)
- Indian Manufacturers

[51] SewBots: https://softwearautomation.com/sewbots/
[52] Smartex: https://apparelimpact.org/solutions/smartex-ai-enabled-real-time-quality-control/

8.5 Resource Efficiency and Sustainability

8.5.1 Material Efficiency

Table 45 - Material Efficiency in Ready-Made Garment Unit

Parameter	Baseline / Conventional	Optimized / Modern	Efficiency gain (credible range)
Cutting waste (fabric offcuts)	~10–15%[53] fabric waste commonly generated during cutting (cut-and-sew)	Reduced waste via CAD marker planning + automated cutting + better lay planning	Reduction possible (site dependent). Range improvement is typically a few percentage points
Marker efficiency / fabric utilization	Manual marker making; depends on skill & size mix	CAD marker planning and optimization	CAD economizes fabric use; quantified % improvement varies by style/ order mix
Thread / trim waste	Higher trim waste due to manual trimming & inconsistent cut width	Automated trimming systems / improved trimming guides	Reduction possible but varies by operation type
Total textile waste potential (India)	India accumulates ~7,793 ktons (~7.8 million tonnes) textile waste annually (pre + post consumer)	Higher capture through sorting + circular value chains	Potential shift from disposal > recycling/upcycling
Pre-consumer waste relevance (cutting floor scrap)	Significant pre-consumer waste generated in cut-and-sew operations	Segregation + valorization (wipers, stuffing, recycled fibre pathways)	High circularity potential if collected cleanly



[53]Maeen Md. Khairul Akter, Upama Nasrin Haq, Md. Mazedul Islam, Mohammad Abbas Uddin, Textile-apparel manufacturing and material waste management in the circular economy: A conceptual model to achieve sustainable development goal (SDG) 12 for Bangladesh, Cleaner Environmental Systems, Volume 4, 2022

8.5.2 Energy Consumption

Garment manufacturing relatively low energy intensity vs. spinning/weaving/wet processing.

Energy consumer	Baseline	Efficient / BAT technology	Verified energy saving potential
Sewing machines (motors)	Sewing operations are a major electricity user in garment lines; one study notes sewing machines can account for ~70% of energy in apparel manufacturing in their studied context	Direct-drive servo motors replacing clutch motors	~45% lower energy for servo vs clutch motors (documented case study);[54]
Lighting	Lighting can be materially reduced via retrofit (widely proven across industries)	LED retrofit + task lighting	LED retrofits often deliver ~50% energy savings vs fluorescent in retrofit contexts[55]
Compressed air	Compressed air is among the costliest utilities and offers large saving potential via system optimization	VSD compressors + leak reduction + pressure optimization	Compressed air optimization can improve efficiency ~20–50% (often more with poor baseline)
Pressing / finishing (steam + irons)	Energy demand varies heavily by finishing route and steam system efficiency; steam losses common	Boiler efficiency improvement, condensate recovery, insulation, steam management	Qualitative high potential (site dependent; avoid fixed % unless audited)
HVAC / ventilation	Increasing relevance due to heat stress and worker productivity	VRF systems, ventilation design, evaporative cooling (where suitable)	Site dependent (do not fix % without audit); but HVAC upgrades are a known lever
Cutting room (automated cutting)	Energy share varies widely; savings depend more on utilization and scheduling	Efficient cutters + optimized cutting schedules (laser/ultrasonic = niche)	Site dependent

[54]Partnership for Cleaner Textile - Installation of Energy Efficient Servo Motor-based Sewing Machines Hamza Clothing Ltd.

[55]R. Saidur, N.A. Rahim, M. Hasanuzzaman, A review on compressed-air energy use and energy savings, Renewable and Sustainable Energy Reviews, Volume 14, Issue 4,2010,

8.5.3 Compliance Framework

- Buyer codes of conduct: Social compliance audits (Walmart, H&M, Gap standards)
- Certifications: SA8000, WRAP, SEDEX, BSCI
- Monitoring: Third-party audits, corrective action plans
- India performance: Better in organized export sector, challenges in subcontractor networks

8.5.4 Environmental Footprint

Garment manufacturing lower environmental impact vs. wet processing, but considerations include:

Waste generation:
- Fabric cutting waste: 10-15% (recycling potential for wipers, stuffing, low-value applications)
- Thread, packaging waste: Disposal/recycling systems needed
- Hangers, poly bags: Plastic waste (reusable/recyclable alternatives emerging)

Chemical usage:
- Spot cleaning chemicals: Limited use
- Adhesives: Fusible interlinings (heat-activated)
- Finishing sprays: Starch, stain protection (minimal vs. fabric processing)

Circularity:
- Garment recycling: Post-consumer garment collection, textile-to-textile recycling (emerging)
- Design for recycling: Mono-material garments, easy disassembly
- Upcycling: Fabric scrap utilization for accessories, patchwork

8.6 Garment Manufacturing Sector Baseline 2026

India's garment manufacturing sector in 2026 stands at a technology transformation inflection point. As a labor-intensive, fragmented industry with over 45 million employed, the sector faces dual imperatives: maintaining cost competitiveness while adopting automation to compete globally.

8.6.1 Baseline Characterization:

The garment sector's evolution from 2026 baseline requires phased automation adoption balancing capital availability with competitiveness:

1. Selective automation:
   Automated cutting, specialized sewing units for repetitive operations

2. Digital transformation:
   CAD/CAM expansion, 3D design adoption, ERP penetration to medium units

3. Skill development:
   Workforce upskilling for technology operation, Industry 4.0 readiness

4. Quality systems:
   Automated inspection systems, in-line quality control expansion

5. Compliance strengthening:
   Social/environmental standards across supply chain including subcontractors

6. Innovation: Smart textiles integration, customization capabilities, quick response manufacturing

The sector's labour intensity remains strength and challenge—automation enhances productivity without full labour replacement in medium term, but long-term competitiveness requires technology adoption to match global efficiency while leveraging India's skilled workforce advantage toward Viksit Bharat 2047.



9.
Way Forward

9. Way Forward

This comprehensive baseline assessment has documented the current state (2026) of technology adoption across India's textile value chain, establishing a foundation for strategic technology and innovation planning toward Viksit Bharat 2047.

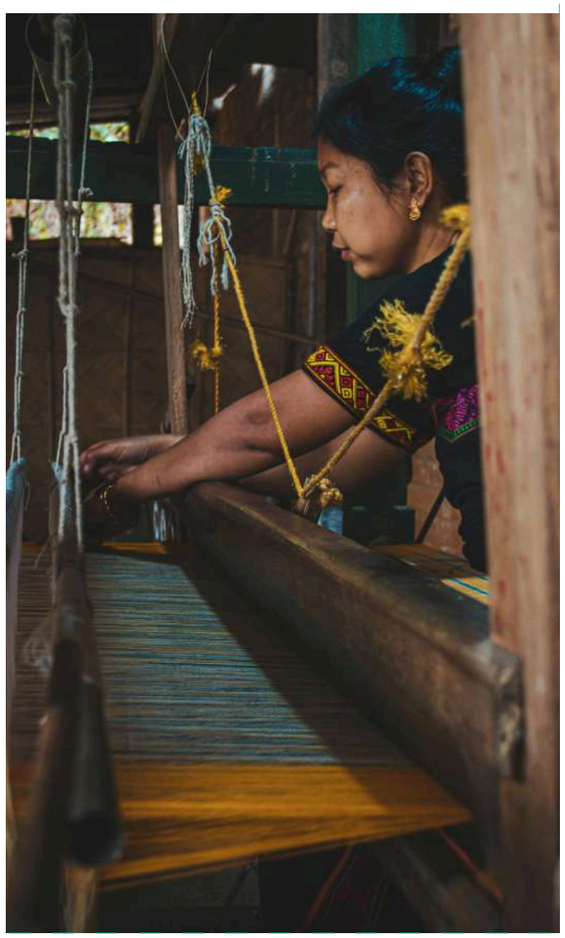
9.1 Green Manufacturing and Technology Imperative

Global textile manufacturing faces mounting environmental pressure. India's sector must address water stress (textile clusters in water-scarce regions), energy intensity, chemical pollution from dyeing/finishing, and low recycling rates. International buyers increasingly mandate ESG compliance—water/energy reduction targets, chemical restrictions (ZDHC, REACH), carbon commitments, supply chain transparency.

- Technology as the Critical Bridge:
  Technology enables transformation from current state to sustainable excellence through four pathways:
- Manufacturing Technologies:
  Energy-efficient spinning (VFD-equipped motors), water-saving dyeing (low liquor ratio machines, air dyeing), automated handling reducing waste, digital printing minimizing water/chemical use.
- Process Innovation:
  Enzymatic treatments replacing harsh chemicals, plasma treatment, ozone washing, closed-loop resource recovery.
- Digital Technologies:
  IoT for real-time monitoring, AI-driven quality control reducing rejections, ERP optimizing resources, blockchain for transparency.
- Sustainability Technologies:
  Zero-liquid discharge effluent treatment, renewable energy integration, waste heat recovery, fibre-to-fibre recycling.

Technology adoption is both environmental obligation and economic necessity.

Improving cost competitiveness through resource efficiency, enabling quality premiums, ensuring market access through compliance, enhancing productivity, and building innovation capacity for long-term competitiveness.



9.1.1 Global Competitive Positioning

India ranks 6th globally (2023) facing competition from China (advanced automation, massive scale), Bangladesh (apparel focus, preferential EU access, lower labor costs), Vietnam (FTA network, high FDI, fast fashion), and Turkey (technical textiles, EU proximity).

Based on the comprehensive baseline assessment, five strategic imperatives emerge as critical for India's textile technology transformation:

1. Selective Automation and Productivity Enhancement

2. Resource Efficiency and Sustainability Transformation

3. Quality Upgradation and Value Addition

4. Digital Integration and Industry 4.0 Readiness

5. Innovation Ecosystem and R&D Strengthening

9.2 Steps for Transformation

9.2.1 Selective Automation and Productivity Enhancement

Rationale: Maintaining employment (45M+ jobs) while improving competitiveness requires selective automation targeting productivity bottlenecks without wholesale labor displacement.

Priority Actions: Detailed priority actions are provided at the end of each value chain chapter.

- Spinning:
  Automate blow room (70% target) and winding (80% target), expand rotor spinning to 15-20% capacity
- Weaving:
  Increase shuttleless penetration to 60%, focus on automated quality monitoring
- Garment:
  Automated cutting expansion (60%), selective robotic sewing for repetitive operations (10-15%)
- Wet Processing:
  Automated chemical dosing (70%), digital color matching (80%)

Outcome:

20-30% productivity improvement without proportional employment reduction through labor redeployment to value-added operations.

9.2.2 Resource Efficiency and Sustainability Transformation

Rationale: Environmental regulations tightening domestically (Pollution Control Boards) and internationally (buyer requirements, carbon border adjustments), making sustainability both compliance necessity and competitive advantage.

Priority Actions: Detailed priority actions are provided at the end of each value chain chapter.

- Water:
  Low-liquor dyeing (1:4 liquor ratio 50% adoption), water recycling (60% units), ZLD where mandated
- Energy:
  Replace 20+ year machines, renewable energy 30% by 2030, heat recovery systems
- Chemicals:
  Bio-based auxiliaries (30%), natural dyes for niche segments, green chemistry adoption
- Waste:
  Fabric waste reduction through optimized cutting (CAD markers), circular economy models

Outcome:

50% water reduction, 40% energy reduction in wet processing; positioning India as sustainable textile producer.

9.2.3 Quality Upgradation and Value Addition

Rationale: Moving up value chain from volume to value requires consistent quality, design capabilities, and brand positioning.

Priority Actions: Detailed priority actions are provided at the end of each value chain chapter.

- Quality systems: In-line inspection (50% capacity), automated testing, real-time monitoring
- Design capabilities: CAD/3D design (70% export units), virtual sampling, rapid prototyping
- Technical textiles: Warp knitting capacity expansion, specialized finishing, performance fabrics
- Certification: International standards (OEKO-TEX, GOTS, BCI) adoption 60%

Outcome:

Premium positioning in global market, higher realization per unit, reduced dependence on price competition.

9.2.4 Digital Integration and Industry 4.0 Readiness

Rationale: Fourth Industrial Revolution technologies (IoT, AI, cloud, analytics) becoming competitive necessities for efficiency, traceability, and rapid response.

Priority Actions: Detailed priority actions are provided at the end of each value chain chapter.

- Production monitoring:
  IoT sensors, real-time dashboards (40% organized sector)
- Predictive maintenance:
  AI/ML for machine downtime reduction (30% large units)
- Supply chain digitization:
  ERP integration, digital procurement, blockchain traceability pilots
- Skill development:
  Data analytics, digital literacy, cyber-physical systems operation

Outcome:

Industry 4.0 foundation in organized sector, digital-ready workforce, smart factory demonstrations.

9.2.5 Innovation Ecosystem and R&D Strengthening

Rationale: Sustainable competitiveness requires indigenous technology development, not just adoption, and continuous innovation culture.

Priority Actions:

- R&D investment:
  Increase from current <0.5% to 2% of turnover
- Innovation centers:
  Technology demonstration facilities, pilot plants, testing centers
- Industry-academia:
  NIFT, NITs, IITs collaboration, textile engineering programs expansion
- Patent culture:
  Incentivize IP creation, protect innovations, commercialize research

Outcome:

Indigenous technology development, reduced import dependency, export of textile machinery/technology.

9.3 Enabling Ecosystem Requirements

Technology transformation imperatives cannot succeed without supportive enabling ecosystem:

9.3.1 Financial Mechanisms: De-Risking Technology Adoption

Financial support must be structured to target specific gaps—from capital subsidy to high-risk frontier technologies.

- Re-engineer the ATUF Successor Scheme to be output-focused, linking higher interest subvention/capital subsidy to measurable outcomes like energy reduction ($>25\%$), water savings ($>50\%$), or labor productivity improvement ($>30\%$) achieved through the new machinery.
- Institute a high-cap Viability Gap Funding (VGF) mechanism specifically for first-of-a-kind, high-capex technologies (e.g., waterless dyeing, full-scale digital printing, advanced recycling) where public de-risking is essential to attract private investment.
- To develop technology leasing models through specialised non-banking financial companies (NBFCs) and simplify lending criteria for small-scale technology purchases ($<_{2}50$Lakh) to enable phased modernization in MSMEs.
- Create a tiered concessional credit window (e.g., lower interest rates, longer moratorium) linked directly to third-party validated environmental scores (e.g., ZDHC compliance, Higg Index scores) achieved through technology investments.

9.3.2 Policy and Regulatory Support: Incentivizing Digital & Green

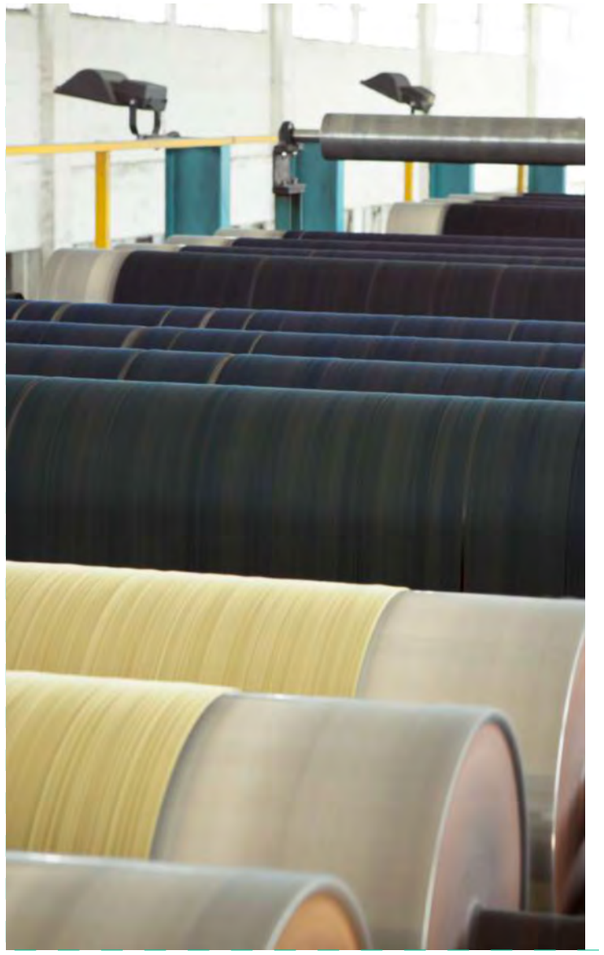
Policy must actively drive the shift towards Industry 4.0 and global environmental standards.

- Subsidies/Incentives for investments solely in Industry 4.0 technologies (e.g., IoT sensors, MES systems, AI-driven process optimization) to accelerate data-driven manufacturing.
- Rationalize (reduce) import duties on state-of-the-art textile machinery and critical components/spares not manufactured domestically, while maintaining protection for viable local machinery production.
- Progressively mandate international quality and traceability standards for exported items and certain domestic segments, thereby creating a market pull for compliant technology and process upgrades.
- Establish a ‘Single-Window Technical Assistance Cell’ to proactively support MSMEs in taking lead in setting the targets in ESG areas focusing on technical solutions over punitive measures.

9.3.3 Institutional Strengthening: Access and Demonstration

With help of TRAs across India, focus on creating shared infrastructure to democratize technology access, especially for MSMEs.

- Evolve TRAs into “Technology Incubation and Digital Readiness Centers” offering not just basic machinery access, but also subscription-based access to high-end design software, advanced data analytics tools, and Industry 4.0 pilots.
- Partner with leading global machinery manufacturers and domestic R&D institutes to establish Thematic Technology Demonstration Centers (e.g., one for Technical Textiles, one for Sustainable Processing) for large-scale, pre-investment pilot testing and operator training.



9.3.4 Skill Development: Future-Ready Workforce

By introducing short and long term courses, the focus must shift from operating old machinery to managing complex, data-driven systems.

- Overhaul the curriculum of ITIs, Polytechnics, and Textile Engineering Colleges to mandate Industry 4.0 modules on data analytics, robotics, cybersecurity in manufacturing, and process automation.
- Strengthen “Prime Minister’s Internship Scheme 2025” with industry partners focused on on-the-job training for operating and maintaining advanced textile machinery and IT/OT integration.
- Launch a nationally recognized, modular certification program for existing workers, leveraging online platforms and local clusters to train on energy efficiency, lean manufacturing, and basic digital literacy.
- Design specialized ‘Women-in-Tech’ training programs (flexible timings, local delivery) to upskill the large female workforce in areas like CAD/CAM, advanced quality control, and data entry/analysis roles within the modern textile factory.

9.4 Way Forward

The sector’s strengths are substantial: complete value chain integration, skilled workforce, cluster specialization, quality infrastructure, and domestic market resilience. However, challenges are equally significant: technology vintage lag, automation deficit, sustainability pressures, import dependency, skill gaps, and fragmentation.

This baseline assessment provides the evidence base for Balanced Transformation that positions India as a global textile technology leader while preserving the sector’s employment generation and social significance.

The roadmap phase will translate this vision into actionable pathways, timelines, investments, and institutional mechanisms to guide India’s textile sector toward technology excellence, sustainability leadership, and global competitiveness by 2047.



The United Nations Partnership for Action on Green Economy (PAGE) puts sustainability at the heart of global economic policymaking for a shift in finance and investment towards a just, circular, and green economic transformation.

The partnership brings together five United Nations agencies: UNEP, UNDP, ILO, UNIDO, and UNITAR, whose expertise and support assist and lead partner countries towards their transition to an Inclusive Green Economy (IGE) by providing policy advice, assessments, capacity building and analytical tools outputs.

PAGE was launched in 2013 as a response to the call at Rio+20 to support countries addressing one of the greatest challenges of our time: building economies that improve human well-being and social equity, while significantly reducing environmental risks and ecological scarcities.

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